UNIVERSIDADE DE SÃO PAULO
INSTITUTO DE FÍSICA

**Determinação do fator $S(E)$ astrofísico
para a reação $^{16}\text{O}+^{16}\text{O}$**

JEREMIAS GARCIA DUARTE

ORIENTADOR: PROF. DR. LEANDRO ROMERO GASQUES

Dissertação apresentada ao Instituto de Física
da Universidade de São Paulo para a obtenção
do título de Mestre em Ciências.

Banca Examinadora:

Prof. Dr. Leandro Romero Gasques (Orientador, IF-USP)

Prof. Dr. Nemitala Added (IF-USP)

Prof. Dr. Pedro neto de Faria (IF-UFF)

São Paulo
2014

FICHA CATALOGRÁFICA
Preparada pelo Serviço de Biblioteca e Informação
do Instituto de Física da Universidade de São Paulo

Duarte, Jeremias Garcia

Determinação do fator $S(E)$ astrofísico para a reação $^{16}\text{O}+^{16}\text{O}$; Determination of the astrophysical S-factor for the $^{16}\text{O}+^{16}\text{O}$ reaction. São Paulo, 2015.

Dissertação (Mestrado) – Universidade de São Paulo.
Instituto de Física. Depto. de Física Nuclear

Orientador: Prof. Dr. Leandro Romero Gasques

Área de Concentração: Física Nuclear

Unitermos: 1. Física nuclear; 2. Interações nucleares; 3. Reações nucleares; 4. Evolução estelar.

USP/IF/SBI-010/2015

UNIVERSITY OF SÃO PAULO
INSTITUTE OF PHYSICS

**Determination of the astrophysical $S(E)$ factor
for the $^{16}\text{O}+^{16}\text{O}$ reaction**

JEREMIAS GARCIA DUARTE

ADVISOR: PROF. DR. LEANDRO ROMERO GASQUES

Dissertation submitted to the Institute of Physics of
the University of São Paulo for the Master of Science
degree.

Examining committee:

Prof. Dr. Leandro Romero Gasques (Orientador, IF-USP)
Prof. Dr. Nemitala Added (IF-USP)
Prof. Dr. Pedro neto de Faria (IF-UFF)

São Paulo
2014

Jeremias Garcia Duarte: *Determination of the astrophysical $S(E)$ factor for the $^{16}\text{O}+^{16}\text{O}$ reaction*, December 2014.

This work was financially supported by Fundação de Amparo à Pesquisa do Estado de São Paulo.

Este trabalho foi apoiado financeiramente pela Fundação de Amparo à Pesquisa do Estado de São Paulo.

Ó profundidade da riqueza da sabedoria e do conhecimento de Deus! Quão insondáveis são seus juízos, e inescrutáveis os seus caminhos!

“Quem conheceu a mente do Senhor? Ou quem foi seu conselheiro?”

“Quem primeiro lhe deu, para que ele o recompense?”

Pois dele, por ele e para ele são todas as coisas. A ele seja a glória para sempre! Amém.

Paulo, Ap., Carta aos Romanos, 11.

Agradecimentos

Ao Prof. Dr. Leandro Romero Gasques, meu orientador e amigo, pela confiança, pelo empenho e dedicação, que foram fatores decisivos para a realização deste trabalho.

Aos meus pais, Paulo e Leila pelo suporte, amor e carinho que desde o meu nascimento demonstraram. Foram eles, sem dúvida, os grandes alicerces desta e de muitas outras conquistas em minha vida.

À minha esposa, linda e preciosa Ana Paula, pelo apoio, paciência, cuidado, compreensão, amor e carinho que sempre demonstrou.

Ao meu irmão Mateus, sempre do meu lado para o que der e vier, pelo carinho e amizade.

Aos meus amigos e companheiros de laboratório, sempre dispostos a ajudar, Valdir, Vitor, Renatão, Erich, Vinícius, Hellen, André, Rubén, Caio e Elienos.

Aos professores Chamon, Medina, Zero, Nemi, Julian, Marcos, Suaide, Ribas, Alinka, Rubens, Valdir, Ernesto, Marcia Rodrigues, Marcia Rizzutto e Chubaci.

Aos meus amigos técnicos e funcionários, Tiago, Abreu, Otávio, Luis, Eurípedes, Rone, Wanda, Messias, Edmilson, Celso, Antônio e Tromba.

Às secretárias, Gilda, Andréia e Zenaide, pela presteza e dedicação.

A todas as pessoas que de alguma maneira contribuíram para a realização dessa dissertação de mestrado.

À FAPESP pelo apoio financeiro em todas as etapas deste trabalho.

Resumo

DUARTE, J. G. **Determinação do fator $S(E)$ astrofísico para a reação $^{16}\text{O}+^{16}\text{O}$** . Dissertação (Mestrado) - Instituto de Física, Universidade de São Paulo, São Paulo, 2014.

O objetivo deste trabalho é obter uma função de excitação para o sistema $^{16}\text{O}+^{16}\text{O}$ através de medidas de espectroscopia- γ e coincidência γ -partícula carregada, utilizando o sistema Saci-Perere montado no final da linha de feixe 30A do Laboratório Aberto de Física Nuclear da Universidade de São Paulo (LAFN). Testes com o sistema de detecção γ -partícula carregada indicaram sua inviabilidade devido ao curto tempo de medida e a perda do canal de nêutrons. Para superarmos este problema, uma nova configuração experimental foi utilizada. Dois detectores de radiação γ foram posicionados a 55° e 125° e um detector de barreira de superfície foi posicionado a 130° para monitorar os núcleos de ^{16}O retroespalhados. As seções de choque parciais relativas aos canais de saída da reação de fusão $^{16}\text{O}+^{16}\text{O}$ foram medidas através da detecção de seus raios- γ característicos para $E_{cm} = 8.27, 9.27, 10.77$ e 12.27 MeV. Três dificuldades foram encontradas ao longo e após o experimento: contaminação do alvo por carbono, radiação natural de fundo e baixa intensidade do feixe. Esforços foram direcionados com sucesso para superar estas dificuldades. A normalização relativa foi realizada por dois caminhos, utilizando os raios- γ a 279 keV(^{197}Au) e a 536 keV(^{100}Mo), e seus resultados concordam muito bem. A seção de choque de fusão total foi obtida somando as seções de choque parciais para cada energia de feixe medida. Sua normalização absoluta foi feita usando a seção de choque de fusão teórica total obtida com cálculos de canais acoplados, utilizando o modelo *zero point motion* (ZPM), para $E_{cm} = 12.27$ MeV. De posse da seção de choque de fusão total calculamos o fator S-astrofísico, e ambos os resultados concordam bem com a literatura.

Palavras-chave: seção de choque de fusão, espectroscopia gama, fator S-astrofísico.

Abstract

DUARTE, J. G. **Determination of the astrophysical $S(E)$ factor for the $^{16}\text{O}+^{16}\text{O}$ reaction.** Dissertation (Master of Science degree) - Institute of Physics, University of São Paulo, São Paulo, 2014.

This work aims to obtain the fusion excitation function for the $^{16}\text{O}+^{16}\text{O}$ system through γ -spectroscopy measurements and γ -charged particle coincidence, using the Saci-Perere system mounted at the end of the 30A beamline of the Open Laboratory of Nuclear Physics of the University of São Paulo (LAFN) LAFN Laboratório Aberto de Física Nuclear. Tests with the γ -charged particle detection system indicated its unfeasibility due to the short measurement time and loss of the neutron channel. To overcome this problem, a new experimental setup was used. Two γ -ray detectors were placed at 55° and 125° and a surface barrier detector was placed at 130° to monitor the ^{16}O nuclei backscattered. The partial fusion cross sections related to the exit channels from the $^{16}\text{O}+^{16}\text{O}$ fusion reaction were measured by detecting their characteristic gamma rays at $E_{cm}=8.27, 9.27, 10.77$ and 12.27 MeV. Three difficulties were faced during and after the experiment: carbon contamination of the target, natural background and low beam intensity. Efforts were made to successfully overcome these difficulties. The relative normalization was made by two ways, using the γ -rays at 279 keV (^{197}Au) and 536 keV (^{100}Mo), and their results agree very well with each other. The total fusion cross section was obtained by summing the partial cross sections for each beam energy. Its absolute normalization was performed with the total theoretical fusion cross section obtained using coupled channel calculations, using the zero point motion model (ZPM), at $E_{cm}=12.27$ MeV. With the total fusion cross section we calculated the astrophysical S-factor, and both results are in good agreement with the literature.

Keywords: fusion cross section, gamma spectroscopy, astrophysical S-factor.

Contents

List of Abbreviations	ix
List of Symbols	xi
List of Figures	xiii
List of Tables	xv
1 Introduction	1
2 Theoretical Aspects	5
2.1 Nuclear Potential	5
2.1.1 Coulomb Potential	5
2.1.2 Nuclear Potential	6
2.2 Nuclear Fusion	6
2.2.1 A Classical View of the Nuclear Fusion	7
2.2.2 A Quantum View of the Nuclear Fusion	7
3 Experimental Procedure	11
3.1 Equipament Used	11
3.1.1 Laboratory Overview	11
3.1.2 Ion Source	13
3.1.3 Pelletron Accelerator	13
3.1.4 Detectors	16
3.2 Experimental Methods - First Experiment	20
3.2.1 Energy and Charge States	20
3.2.2 Target	21
3.2.3 Detection System	21
3.2.4 Acquisition Electronics - Coincidence Method	22
3.2.5 Acquisition Electronics - Single Detection Method	23
3.2.6 Data Acquisition	23
3.3 Experimental Methods - Second Experiment	23
3.3.1 Energy and Charge States	23
3.3.2 Target	23
3.3.3 Detection System	26
3.3.4 Acquisition Electronics	26
4 Data Reduction and Analyzis	27
4.1 First Experiment	27
4.2 Second Experiment	28

4.2.1	Processing of the Spectra	28
4.2.2	Identification of the γ -ray Peaks	30
4.2.3	Carbon Contamination	31
4.2.4	Integration of the Peaks	32
4.2.5	Relative Normalization	41
4.2.6	Partial Fusion Cross Section	42
4.2.7	CC calculation	43
4.2.8	Energy Loss in the Target	43
4.2.9	Total Fusion Cross Section	44
4.2.10	Astrophysical S(E) Factor	45
4.2.11	Partial Fusion Cross Section - Normalization	46
5	Conclusions and Outlook	51
5.1	Conclusions	51
5.2	Outlook	51
5.2.1	Carbon Contamination	51
5.2.2	Natural Background	52
5.2.3	Low Beam Intensity	52
A	Acquisition Electronics	53
A.1	Coincidence Method	53
B	Spectra of the First Experiment	55
C	Fresco Inputs	61
C.1	Input for ^{100}Mo	61
C.2	Input for ^{197}Au	61
	Bibliography	63
	Index	66

List of Abbreviations

32 MC-SNICS	32 Sample Multi-Cathode Source of Negative Ions by Cesium Sputtering
ADC	Analogic to Digital Converter
BGO	Bismuth Germanate
BPM	Barrier penetration model
CAMAC	Computer Aided Measurement And Control
CFD	Constant Fraction Discriminator
GG	Gate and Delay Generator
HPGe	Hyperpure Germanium
LAFN	Open Laboratory of Nuclear Physics of the University of <i>São Paulo</i> (<i>Laboratório Aberto de Física Nuclear do Instituto de Física da USP</i>)
LAMFI	Laboratory of Materials and Ionic Beams of the University of <i>São Paulo</i> (<i>Laboratório de Materiais e Feixes Iônicos da Universidade de São Paulo</i>)
LIN FI/FO	Linear Fan In / Fan Out
LOG FI/FO	Logic Fan In / Fan Out
ME-20	Mass-energy product = 20
ME-200	Mass-energy product = 200
NEC	National Eletrostatics Corporation
QDCA	Charge Analogic to Digital Converter
QDCW	Charge ADC with Wide Gates
REGe	Reverse Electrode detector
Saci-Perere	Ancillary System of plastic scintillators and Small Spectrometer with Rejection of Electromagnetic Radiation Scattering (<i>Sistema Ancilar de Cintiladores plásticos e Pequeno Espectrômetro de Radiação Eletromagnética com Rejeição de Espalhamento</i>)
SIMNRA	Simulation Program for the Analysis of NRA, RBS and ERDA
SPP	São Paulo potential
TDC	Time to Digital Converter
TFD	Timing Discriminator
TFA	Timing and Filter Amplifier
USP	University of <i>São Paulo</i> (<i>Universidade de São Paulo</i>)
ZPM	Zero point motion
WKB	Approximation developed by Wentzel, Kramers and Brillouin
WS	Wood-Saxon

List of Symbols

M	Mass of a star
$M_{\odot}$	One solar mass
T_9	10^9 Kelvin
E_G	Energy of the Gamow peak
V_C	Coulomb potential
V_N	Nuclear potential
V_F	Folding potential
E_{cm}	Energy in the center-of-mass frame
V_{eff}	Effective potential
μ	Reduced mass
V_b	Coulomb barrier potential
$\mathcal{R}$	Reflection factor, where the reflection coefficient is $R = \mathcal{R} ^2$
$\mathcal{T}$	Transmission factor, where the transmission coefficient is $T = \mathcal{T} ^2$
SF_6	Sulfur hexafluoride
psi	Pound per square inch
m_A	Atomic mass of a nucleus A
C1	Detector placed at a backward angle of 125°
C2	Detector placed at a forward angle of 55°
E_γ	Energy of the gamma-ray
E_{lab}	Energy in the laboratory frame
ϵ_γ	Relative efficiency of detection of a gamma-ray at E_γ
Y_γ	Yield of a gamma-ray peak
β_γ^{ch}	Branching factor of a channel related to its characteristic gamma-ray
σ^{ch}	Partial fusion cross section of a reaction channel
σ^{CE}	Coulomb excitation cross section
σ_{tot}	Total fusion cross section
N_i	Number of incident nuclei
N_t	number of atoms per unit of area of the target
ϵ_γ^{abs}	Absolute efficiency of detection of a gamma-ray at E_γ
E_0	Bombarding energy of the projectile
Δ	Total energy loss in the target
η	Sommerfeld parameter

List of Figures

1.1	The S-factor as a function of the center-of-mass energy for the $^{16}\text{O}+^{16}\text{O}$ reaction. The curve was obtained by the coupled channel calculation using the ZPM model. The arrow indicates the Coulomb barrier.	2
2.1	Illustration of the one-dimentional barrier penetration model for $E < V_B$	7
3.1	Detailed scheme of the Pelletron Laboratory beamline (Author: J. C. Terassi). . . .	12
3.2	Scheme of the Experimental Hall, showing the seven experimental beamlines available at the LAFN (Author: J. C. Terassi).	13
3.3	Operational scheme of the Multi-Cathode Source of Negative Ions by Cesium Sputtering [30].	14
3.4	On the left we have a scheme of the Pelletron Charging System [33], that was adapted from [34], and on the right a scheme of the acceleration tube.	15
3.5	Scheme of a basic combination of fast and slow phosphors with a photomultiplier [35].	16
3.6	Current pulse from complete traversal (XX) of double phosphor [35].	16
3.7	Scheme of the procedure used to integrate the charge of the two light outputs [36].	17
3.8	Scheme of the Reverse Electrode detector [37].	18
3.9	Cross section of the cryostat used for the storage of the liquid nitrogen [37].	18
3.10	Illustration of the background generated by the Compton scattering of the gamma ray inside the detector.	19
3.11	Scheme of the Compton Suppressor used in this experiment.	19
3.12	Simplified diagram of surface barrier Si detector manufacturing [38].	20
3.13	^{16}O target used in the experiment.	21
3.14	Depth profile resulting from the fit made in the backscattering spectrum by Cleber L. Rodrigues of LAMFI.	22
3.15	Saci-Perere system.	22
3.16	Alpha spectrum from the Rutherford backscattering method. The black dots are the data points and the red line is the fitting.	24
3.17	Proton spectrum from the Rutherford backscattering method. The black dots are the data points and the red line is the fitting.	25
3.18	Schematic illustration of the target.	25
3.19	Configuration of the detectors used in the second experiment.	26
4.1	Spectrum of the background observed during the experiment with detector C2. . .	29
4.2	Spectra of detector C2 for the beam energy of 19 MeV with (black line) and without background (red line).	30
4.3	Spectra of detector C2 for the beam energy 22 MeV with (black line) and without background (red line).	31
4.4	Spectra of detector C1 for the beam energy 15 MeV without background, shifted in counts by a factor 1000.	32

4.5	Q-value diagram for the $^{16}\text{O}+^{16}\text{O}$ reaction showing the energy in the center of mass frame required to open each exit channel [14].	33
4.6	Typical Doppler shift observed in the spectra obtained with detectors C1 and C2 for the beam energy of 19 MeV.	34
4.7	Branching factor curves calculated theoretically using the Hauser-Feshbach statistical model formalism [14].	35
4.8	Part of the spectra from detector C1 observed at 25 MeV bombarding energy at the beginning (black line) and end (red line) of the experiment.	36
4.9	Curves obtained from the fitting of the relative efficiency measured with the ^{152}Eu radioactive source.	37
4.10	Spectrum of the ^{152}Eu radioactive source observed at a backward angle (55°). . . .	38
4.11	Spectrum obtained with the backward (C1) detector at 22MeV.	39
4.12	Spectrum obtained with the forward (C2) detector at 22MeV.	40
4.13	Spectra obtained with the backward (blue line) and the forward (red line) detectors at $E_{lab}=17$ MeV. The head-head arrows show the expected Doppler peaks position.	41
4.14	Spectra with no background subtraction obtained at $E_{lab}=17$ and 25 MeV.	42
4.15	Cross sections obtained from the BPM and ZPM model calculations.	43
4.16	Partial cross sections obtained for each exit channel analyzed.	45
4.17	(Left) Total fusion cross sections obtained from normalization with ^{197}Au (279 keV) (salmon and brown dots) and with ^{100}Mo (536 keV) (orange and black dots). (Right) Total fusion cross sections obtained from the average of the four sets of cross sections obtained. Just for a reference, the results from reference [14] (grey dots) are shown.	46
4.18	Averaged total fusion cross sections compared with references [12, 13, 14, 15, 24], and theoretical predictions from ZPM model (solid line) and BPM model (dashed line).	47
4.19	Astrophysical S-factors obtained with the averaged total fusion cross sections compared with references [12, 13, 14, 15, 24], and theoretical predictions from ZPM model (solid line) and BPM model (dashed line).	48
4.20	Partial cross sections obtained for each exit channel analyzed.	50
B.1	Spectrum obtained for a beam energy of 18.6 MeV with the single detection method, for an energy range of 660 to 1420 keV.	55
B.2	Spectrum obtained for a beam energy of 18.6 MeV with the single detection method, for an energy range of 1480 to 2460 keV.	56
B.3	Spectrum obtained for a beam energy of 18.6 MeV with the coincidence detection method, for an energy range of 640 to 1400 keV.	56
B.4	Spectrum obtained for a beam energy of 18.6 MeV with the coincidence detection method, for an energy range of 1740 to 2300 keV.	57
B.5	Spectrum obtained for a beam energy of 25 MeV with the single detection method, for an energy range of 580 to 1800 keV.	57
B.6	Spectrum obtained for a beam energy of 25 MeV with the single detection method, for an energy range of 1760 to 2860 keV.	58

List of Tables

1.1	Evolutionary Stages of a $25 M_{\odot}$ Star [1].	1
3.1	Thickness values from the simultaneous fitting of the spectra of Figures 3.16 and 3.17.	25
4.1	Values of the time of measurement and counts in the integrator for the four measured energies.	27
4.2	Normalization factors.	29
4.4	Threshold for the exit channels ^{26}Al and ^{23}Na [45].	32
4.5	Gamma rays integrated for the calculation of the partial cross sections.	34
4.6	Parameters obtained for the fitting of the relative efficiency data.	35
4.7	Effective energy calculation.	44
4.8	Γ values.	44
4.9	Averaged total fusion cross section.	45
4.10	S-factor obtained with the averaged total fusion cross section.	46
4.11	Averaged partial fusion cross sections presented in (mb).	47
4.3	Gamma peaks used for the analyzis.	49
B.1	Peaks identified in the spectrum for the beam energy of 25 MeV.	59

Chapter 1

Introduction

Most of the chemical elements that we can observe in nature come from nuclear reactions that occur inside of stars. The evolution of a star, since its birth (a cloud of gas essentially formed by hydrogen) to its death (for example, white dwarfs or supernovae explosions), strongly depends on its mass. Other factors, such as abundance of elements that compose a particular star, density and temperature, are also important in this evolutionary process. Therefore, knowledge of the mechanisms of reaction plays a fundamental role in understanding the different phases associated with stellar evolution.

The fuel of a main sequence star are the elements that compose it, and its engine are the thermonuclear reactions that occur inside, which maintain the gravitational and thermal pressure in equilibrium. When the fuel exhausts, the star collapses transforming gravitational potential energy into heat, opening the possibility for new reactions to take place, so that the ashes of the previous burning can become fuel for the next.

These thermonuclear reactions begin with the hydrogen burning. If a star has enough mass ($M > 1.5 M_{\odot}$ (solar mass)), after the core hydrogen has been completely exhausted, the gravitational force causes a contraction of the star providing the heat for the next burning phase, the helium burning. One possible scenario indicates that, for even more massive stars ($M > 10 M_{\odot}$), immediately after the helium burning, starts the carbon, neon and oxygen burning phases, and finally the silicon burning, after which the star collapses and explodes quickly. How long a main sequence star lives depends on how massive it is. The more massive the star, greater its gravitational pull inwards, so its core gets hotter. Then, low massive stars spend more time on the main sequence. Table 1.1 shows the time, temperature and density scales of the evolutionary stages of a $25 M_{\odot}$ star obtained from reference [1].

Table 1.1: *Evolutionary Stages of a $25 M_{\odot}$ Star [1].*

Stage	Time Scale	Temperature (T_9)	Density (g cm^{-3})
Hydrogen burning	7×10^6 y	0.06	5
Helium burning	5×10^5 y	0.23	7×10^2
Carbon burning	600 y	0.93	2×10^5
Neon burning	1 y	1.7	4×10^6
Oxygen burning	6 months	2.3	1×10^7
Silicon burning	1 d	4.1	3×10^7
Core collapse	seconds	8.1	3×10^9
Core bounce	milliseconds	34.8	$\simeq 3 \times 10^{14}$
Explosive burning	0.1–10 s	1.2–7.0	Varies

In the past decades, great efforts were concentrated in the experimental determination of reac-

tion rates for a large number of systems. Despite the considerable progress made in this field, many of the reactions that are important for the complete understanding of the astrophysical processes have still not been fully investigated [2, 3]. In particular, the burning process of elements like carbon and oxygen has drawn enormous interest in the field of astrophysics, since not only influence the formation of heavier elements in massive stars, as well as the subsequent evolution of stars, resulting or not in a number of different explosive processes that can lead to formation of supernovae [4, 5]. During the carbon burning phase, the fusion between two ^{12}C nuclei is the most important reaction, typically occurring at temperatures of the order of $(6-8)\times 10^8\text{K}$ and density around 10^5 g/cm^3 [6]. Depending on the ratio between ^{12}C and ^{16}O , determined by the $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ reaction, additional processes such as $^{12}\text{C}+^{16}\text{O}$ and $^{16}\text{O}+^{16}\text{O}$ may occur [7, 8].

Despite the important progresses achieved in determining the fusion cross sections for the $^{12}\text{C}+^{12}\text{C}$, $^{12}\text{C}+^{16}\text{O}$ and $^{16}\text{O}+^{16}\text{O}$ systems [5, 9, 10], there are considerable discrepancies among different experimental data sets available in the literature. Typically, the reactions of astrophysical interest occur at energies far below the Coulomb barrier (around the Gamow energy) [1], leading to extremely low cross sections, making difficult to obtain experimental data with high accuracy.

In particular, the $^{16}\text{O}+^{16}\text{O}$ reaction was widely studied between the years 1960 and 1990, by using different experimental techniques [11, 12, 13, 14, 15]. Most of them were planned to measure secondary γ -rays from the evaporation residues, while some experiments detected the evaporated light particles from the compound nucleus. Despite of the large number of experiments performed, most of the data were taken in an energy region around 6.7 to 14.0 MeV in the center-of-mass reference frame. The available data around the Gamow peak, corresponding to temperatures typical for core oxygen burning ($T \sim 2.2\text{ GK}$; $E_G \sim 6.6 \pm 1.3\text{ MeV}$) and explosive oxygen burning ($T \sim 3.6\text{ GK}$; $E_G \sim 9.2 \pm 2\text{ MeV}$), are in poor agreement reaching a factor of 3 in the lowest energy region, as shown in figure 1.1.

Figure 1.1: The S -factor as a function of the center-of-mass energy for the $^{16}\text{O}+^{16}\text{O}$ reaction. The curve was obtained by the coupled channel calculation using the ZPM model. The arrow indicates the Coulomb barrier.

From the theoretical point of view, different models lead to different results for the $^{16}\text{O}+^{16}\text{O}$

astrophysical S-factor. This characteristic is brought to the fore at energies a few MeV below the Coulomb barrier, where the calculated values can present large discrepancies. Typically, for the $^{16}\text{O}+^{16}\text{O}$ reaction, the calculated S-factor is flat in the entire range of energy (from very below up to far above the Coulomb barrier). In a recent paper [16], the $^{16}\text{O}+^{16}\text{O}$ reaction was studied within a molecular framework, using a formalism based on the two-center shell model. In this model, two Woods-Saxon nuclear potentials were used to describe the interaction between the ^{16}O nuclei, and molecular configurations were used to describe the compound nucleus. At energies below the Coulomb barrier, the radial motion of the interacting nuclei is adiabatically slow compared to the rearrangement of the mean field of the protons and neutrons that compose the nuclei. It is interesting to notice that, when the mass of the compound nucleus varies as a function of the distance between the interacting nuclei (cranking mass), a local maximum in the astrophysical S-factor is predicted around 4.5 MeV. On the other hand, on the energy region below 3.0 MeV, the astrophysical S-factor is suppressed by a factor of 5 compared to the curve obtained by a constant reduced mass parameter ($\mu=8$). To disentangle these discrepancies, more good quality data are needed in the energy region varying from very below up to a few MeV above the Coulomb barrier. Extending the fusion cross section data toward lower energies, despite very difficult, is important to: (i) nuclear astrophysics, since different theoretical predictions and extrapolations lead to huge uncertainties in the reaction rate between the ^{16}O nuclei, and (ii) nuclear physics, bringing information about dynamic effects in fusion reactions at energies below the Coulomb barrier.

This work aims to measure the fusion excitation function for the $^{16}\text{O}+^{16}\text{O}$ system through γ -spectroscopy measurements and γ -charged particle coincidence, using the Saci-Perere system (Ancillary System of plastic scintillators and Small Spectrometer with Rejection of Electromagnetic Radiation Scattering)[17, 18] mounted at the end of the 30A beamline of the Open Laboratory of Nuclear Physics of the University of *São Paulo* (LAFN). The experimental measurements were performed at $E_{cm} = 8.27, 9.27, 10.77$ and 12.27 MeV.

Chapter 2

Theoretical Aspects

2.1 Nuclear Potential

When two nuclei approach, they feel the presence of each other through the action of two forces, the Coulomb force (long range) and the strong force (short range). The Coulomb force arises from the electromagnetic interaction between the protons, and the strong force from the interaction between the nucleons. The description of these interactions is given in the form of a potential. Here we present a brief description of the Coulomb and nuclear potentials, as well as a short discussion about the fusion process.

2.1.1 Coulomb Potential

In a description of a nuclear interaction between two heavy ions, the Coulomb potential plays an important role. In a vast number of studies, the Coulomb potential between two nuclei is obtained in an approximate manner. A very often adopted procedure to calculate the Coulomb potential is done considering that one of the interacting nuclei is well described by a point charged particle. Then, assuming that the other nucleus is an uniformly charged sphere, the interaction between them is given by the relation:

$$V_C(r) = \begin{cases} \frac{Z_1 Z_2 e^2}{r} & ; \text{for } r > R, \\ \frac{Z_1 Z_2 e^2}{2R} \left(3 - \frac{r^2}{R^2} \right) & ; \text{for } r \leq R, \end{cases} \quad (2.1)$$

where R is the sphere radius.

In 1975 Devries and Clover obtained an analytical solution for the Coulomb potential considering the interaction between two uniformly charged spheres [19]. Almost three decades after, in 2004, Chamon *et al.* [20] proposed a method to calculate exactly the Coulomb potential between two heavy nuclei using a systematics for the nuclear charge densities obtained from [21]

$$V_C(R) = \iint \frac{e^2}{|\vec{R} + \vec{r}_2 - \vec{r}_1|} \rho_1(\vec{r}_1) \rho_2(\vec{r}_2) d\vec{r}_1 d\vec{r}_2, \quad (2.2)$$

where $\vec{R}$ is the position vector measured from the center of mass of nuclei 1 and 2. This exact calculation gives very similar results in comparison with the other methods previously presented in the surface region. However, at inner distances, which are typically probed in nuclear reactions at relatively high energies, the results can be very different. For the present work, any method gives satisfactory results for the Coulomb interaction.

2.1.2 Nuclear Potential

Knowledge of the nuclear potential is crucial to describe many aspects of nuclear collisions. However, the exact treatment of this problem represents a very complex task, so that a description of the reaction mechanisms is usually treated in an approximate way. In general, an average nuclear potential is considered in the description of two reacting nuclei. Very often, for heavy ion reactions, the Woods-Saxon (WS) potential, which is characterized by the depth (V_0), radius (r_0) and diffuseness (a) parameters, is used in the study of nuclear reactions. However, the consistency among different reaction channels, such as elastic and inelastic scattering, fusion and fission processes, described by the same nuclear interaction, has been tested only in a few particular cases [22].

In the present work, we have used the so-called São Paulo potential (SPP), which is a parameter free model for the nuclear interaction that takes into account the effects of the Pauli nonlocality. The energy dependence of the SPP is expressed in terms of the square of the relative velocity v^2 between the two interacting nuclei

$$V_N(R, E) = V_F(R) e^{-4v^2/c^2}, \quad (2.3)$$

where c is the speed of light and

$$v^2(R, E) = \frac{2}{\mu} [E - V_C(R) - V_N(R, E)]. \quad (2.4)$$

The folding potential depends on the matter densities of the colliding nuclei

$$V_F(R) = \iint \rho_1(r_1) \rho_2(r_2) V_0 \delta(\vec{R} - \vec{r}_1 + \vec{r}_2) d\vec{r}_1 d\vec{r}_2, \quad (2.5)$$

where $V_0 = -456 \text{ MeV fm}^3$. The matter densities can be obtained from a systematics as given in reference [21].

2.2 Nuclear Fusion

In the occasion that two heavy ions approach each other, the nucleons that compose the nuclei experience the competition between the long range Coulomb interaction and the strong short range attractive force, giving rise to a barrier containing a pocket located inside it (the so-called Coulomb barrier). Fusion cross section is related with the probability for the formation of a compound nucleus in a collision involving two nuclei [23]. Typically, the lifetime of the compound nucleus lies between 10^{-19} s and 10^{-16} s , which is a long time as compared to the time required for the incident energy to be shared among nucleons. The compound nucleus is almost always formed in excited states with large angular momentum values. Following the hypothesis of Bohr, the hot and rapidly rotating compound nucleus decays in such a way that barely depends on how it has been formed. Conversely, the probability of a certain mode of decay is strongly related to the amount of excitation energy at the formation of the compound nucleus. It can decay emitting one or more light particles, such as neutrons, protons or α -particles, giving rise to a certain number of different nuclei. Those are very often formed in excited states, so they decay emitting γ -rays in their transitions to lower-lying nuclear levels. Another possibility is that the compound nucleus undergoes fission, splitting in two nuclei of more or less equal size. In the present case of $^{16}\text{O} + ^{16}\text{O} \rightarrow ^{32}\text{S}$ reaction at $E_{cm} = 6-13 \text{ MeV}$, the ^{32}S compound nucleus decays mainly by evaporation of light particles, despite Spinka *et al* have been reported in [24] that the $^{32}\text{S} \rightarrow ^{12}\text{C}_{g.s.} + ^{20}\text{Ne}_{g.s.}$ fission reaction gives a contribution for the total fusion cross section of about 2.5(3) %.

2.2.1 A Classical View of the Nuclear Fusion

Let us consider a classical picture, where the radial motion of a projectile around the target nucleus is governed by an effective potential given by the relation

$$V_{eff}(r) = V(r) + E \frac{b^2}{r^2} , \quad (2.6)$$

where $V(r)$ is a central potential of the form $V(r) = V_N(r) + V_C(r)$, and b is the impact parameter, which is the perpendicular distance between the initial classical trajectory of the projectile and a parallel line passing through the center of the target nucleus. The impact parameter is given by $b = l/\sqrt{2\mu E}$, where μ is the reduced mass of the system, and l is the angular momentum. If the impact parameter is sufficiently large, the Rutherford elastic scattering is the dominating process. On the other hand, central collisions result predominantly in the fusion of the projectile with the target nucleus, provided that the two colliding nuclei can overcome the Coulomb barrier. Within the classical formalism, projectile and target can fuse only if the center-of-mass energy of the system is larger than the height of the Coulomb barrier. Hence, for l waves resulting in effective barrier heights above the center-of-mass energy, the fusion process is forbidden. However, substantial fusion cross sections have been observed at energies below the Coulomb barrier for a vast number of systems. To explain this phenomenon, it is necessary to invoke the quantum mechanics, which takes into account the quantum tunneling of the nuclei through the Coulomb barrier.

2.2.2 A Quantum View of the Nuclear Fusion

Transmission in the WKB approximation

Let us consider the one-dimensional barrier penetration model (BPM) as illustrated in figure 2.1. The Hamiltonian H for the relative motion of two collision partners is given by

Figure 2.1: Illustration of the one-dimensional barrier penetration model for $E < V_B$.

$$H = \frac{|\vec{p}|^2}{2\mu} + V(r) = -\frac{\hbar^2}{2\mu} \nabla^2 + V(r) , \quad (2.7)$$

where $\vec{p}$ is the relative momentum, μ the reduced mass and $V(r)$ the central potential composed by the Coulomb and the nuclear parts. The wave function $\psi(\vec{r})$ describing the relative motion satisfies the stationary one-body Schrödinger equation

$$H \psi(\vec{r}) = E \psi(\vec{r}) = \left(-\frac{\hbar^2}{2\mu} \nabla^2 + V(\vec{r}) \right) \psi(\vec{r}) , \quad (2.8)$$

where E is the energy of the relative motion. Solving this equation one obtain that the wave function $\psi(r, \theta)$ expanded in Legendre polynomials could be given by

$$\psi(r, \theta) = \frac{1}{kr} \sum_{l=0}^{\infty} (2l+1) i^l \psi_l(r) P_l(\cos\theta) , \quad (2.9)$$

where $\psi_l(r)$ is the radial wave function and $P_l(\cos\theta)$ is the Legendre polynomials. The WKB approximation is obtained by considering a large number of waves contributing to the collision, thus substituting the discrete partial wave sum of equation 2.9 by an integration over the angular momentum l , and by using asymptotic expressions (valid for large l) of the Legendre polynomials $P_l(\cos\theta)$. The Schrödinger equation becomes

$$\left(\frac{d^2}{dr^2} - \frac{l(l+1)}{r^2} - \frac{2\mu}{\hbar^2} V(r) + k^2 \right) \psi_l(r) = 0 . \quad (2.10)$$

The real solution of equation 2.10 in the region I is of the form

$$\psi_I(r) = \frac{1}{[p(r)]^{1/2}} \cos \left(\frac{1}{\hbar} \int_a^r p(r') dr' - \frac{\pi}{4} \right) , \quad (2.11)$$

where $p(r)$ is the local momentum

$$p(r) = \sqrt{2\mu[E - V(r)]} , \quad (2.12)$$

and in the region II continues as

$$\psi_{II}(r) = \frac{1}{2[p(r)]^{1/2}} e^{\frac{1}{\hbar} \int_a^r |p(r')| dr'} . \quad (2.13)$$

Using the linearly independent partners of equations 2.11 and 2.13, and reflecting this solutions to the region III, one obtain that the outgoing wave function in region III is given by

$$\psi_{III}^{(out)}(r) = \frac{1}{[p(r)]^{1/2}} e^{i \left[\frac{1}{\hbar} \int_r^b p(r') dr' - \frac{\pi}{4} \right]} , \quad (2.14)$$

and the incoming part propagating from the right to the left has the form

$$\psi_I^{(in)}(r) = \frac{1}{i[p(r)]^{1/2}} e^{\frac{1}{\hbar} \int_b^a |p(r')| dr'} e^{-i \left[\frac{1}{\hbar} \int_a^r p(r') dr' - \frac{\pi}{4} \right]} . \quad (2.15)$$

As the transmission coefficient is defined by

$$T = \frac{|\psi_{III}^{(out)}|^2}{|\psi_I^{(in)}|^2} , \quad (2.16)$$

the transmission coefficient in the WKB approximation valid for energies below the barrier is therefore

$$T = \exp \left(-\frac{2}{\hbar} \int_b^a \left| \sqrt{2\mu[E - V(r')]} \right| dr' \right) , \quad (2.17)$$

and with the partial wave expansion of the fusion cross section

$$\sigma_F = \frac{\pi}{k^2} \sum_{l=0}^{l_{max}} (2l+1) T_l(E) , \quad (2.18)$$

one obtain

$$\sigma_F^{(WKB)} = \frac{\pi \hbar^2}{2\mu E} (l_{max} + 1)^2 \exp \left(-\frac{2}{\hbar} \int_b^a \left| \sqrt{2\mu[E - V(r')]} \right| dr' \right), \quad (2.19)$$

where l_{max} is the greatest angular momentum which results in a barrier pocket.

Transmission in the Hill-Wheeler approximation

Alternatively, applying the full quantum theory, one can consider a potential barrier having the form of an inverted parabola [25, 26, 27],

$$V(r) = V_b - \frac{1}{2} \mu \omega^2 r^2, \quad (2.20)$$

for which the equation 2.8 becomes

$$\left(-\frac{d^2}{d\delta^2} - \delta^2 \right) \psi = 2\epsilon \psi, \quad (2.21)$$

with the parametrization $\delta = r(\mu\omega/\hbar)^{1/2}$ and $\epsilon = (E - V_b)/\hbar\omega$.

Considering the asymptotic solution, the scattering situation illustrated in figure 2.1 could be described by the wave function

$$\psi(\delta) = \begin{cases} e^{-i\delta^2/2} \delta^{-i\epsilon-1/2} + \mathcal{R} e^{i\delta^2/2} \delta^{i\epsilon-1/2} & \text{for } \delta \rightarrow \infty, \\ \mathcal{T} e^{-i\delta^2/2} |\delta|^{i\epsilon-1/2} & \text{for } \delta \rightarrow -\infty, \end{cases} \quad (2.22)$$

where $\mathcal{R}$ and $\mathcal{T}$ are the reflection and transmission factors. Connecting the two asymptotic solutions and considering the flux conservation one obtain

$$|\mathcal{T}|^2 = T(E) = \frac{1}{1 + \exp[2\pi(V_b - E)/\hbar\omega]}, \quad (2.23)$$

which is an exact quantum result that holds for all energies. The fusion cross section then can be written as

$$\sigma_F^{(HW)} = \frac{\pi \hbar^2}{2\mu E} \left(\frac{1}{1 + \exp[2\pi(V_b - E)/\hbar\omega]} \right), \quad (2.24)$$

which gives satisfactory results for l waves with effective barrier heights below the center-of-mass energy.

It is well known that the one-dimensional BPM is adequate for describing light systems. However, in the case of heavier systems, an increasing number of non-elastic channels have to be taken into account. For example, inelastic excitations can take place so higher-energy states of the nuclei may become populated. These inelastic interactions cause the incoming wave to split up into various inelastic waves with different transmission probabilities. The combination of these transmission probabilities gives the total transmission into the interior of the compound system. The coupling of inelastic channels leads to a loss of flux of the elastic channels, resulting in an enhancement of the transmission coefficients for the fusion.

The total Hamiltonian H for the relative motion of two collision partners which undergoes inelastic interactions can be represented as

$$H = -\frac{\hbar^2}{2\mu} \nabla^2 + h(\delta) + V_0(r) + V_{coupl}(\vec{r}, \delta), \quad (2.25)$$

where V_0 is the barrier potential, $h(\delta)$ is the internal hamiltonian for the target nucleus, and $V_{coupl}(\vec{r}, \delta)$ is the nuclear interaction, which couples the relative motion and the internal degrees of freedom.

For heavy-ion reactions, fusion cross sections at energies below the Coulomb barrier present

large enhancements in comparison with the predictions obtained from the BPM. To explain this effect, one possible solution is to take into account the internal structure of the colliding nuclei using a coupled-channel formalism. In this work, we adopted a zero point motion (ZPM) model that couples the complete sets of inelastic states related to the quadrupole 2^+ and octopole 3^- vibrational bands [28]. This theoretical approach has advantages as at relatively low energies the usual coupled-channel codes may present numerical problems when dealing with a large number of inelastic states. The effect of the couplings is to replace the Coulomb barrier height, which is coupled to an harmonic oscillator, by a set of barriers, where the total transmission coefficient is given by a weighted average of the transmission for each effective barrier. For deformed nuclei, the fusion cross section depends strongly on the barrier height, which varies depending on the orientation of the colliding partners. The Coulomb barrier parameters have been obtained using the SPP [21], which assumes a two-parameter Fermi distribution to describe the density of a given nucleus [20].

Chapter 3

Experimental Procedure

As already mentioned, the main goal of this work was to determine the fusion cross section of the $^{16}\text{O}+^{16}\text{O}$ reaction, which is related to the probability of two heavy nuclei overcome the Coulomb barrier. This probability varies strongly with the bombarding energy, so the use of a particle accelerator was needed to accomplish our task.

A common method used in nuclear physics experiments consists of a beam of accelerated charged particles hitting a target, where the products of the reactions can be identified using a set of detectors placed around the target.

In particular, this experiment was carried out at the LAFN. The accelerated ^{16}O beam impinged the oxygen target and the products of this reaction were detected by a set of gamma and particle detectors. Two different experimental procedures were tested: the first was based on the gamma-particle coincidence method. Its advantage is the potential reduction of the background observed in the gamma radiation spectrum. The second used a single-gamma detection technique.

This chapter presents the details of these experiments, such as the equipment used, experimental methods, as well as the problems encountered and their possible solutions.

3.1 Equipment Used

3.1.1 Laboratory Overview

The LAFN is equipped with a tandem electrostatic accelerator, an ion source that produces a negatively charged ion beam, seven beamlines, a target laboratory and a technical team to give support on the experiments.

As illustrated in figure 3.1, the accelerator is installed inside a nine story building. The ion source and the first magnet (ME-20)[29], which is used to select the mass of the beam, are placed in the eighth floor. The accelerator tank is installed between the sixth and the third floor. On the ground floor a second magnet (ME-200) is used to select the beam energy. Passing the ME-200, a switching magnet is used to deliver the beam to a specific experimental beamline, which are located at the experimental hall on the ground floor. A set of steerings, quadrupole doublets and triplets, and faraday cups are mounted along the accelerator beamline to adjusting and controlling the beam optics.

SISTEMA DE MONTAGEM DO LABORATÓRIO PELLETRON LINHA DE FEIXE

Figure 3.1: Detailed scheme of the Pelletron Laboratory beamline (Author: J. C. Terassi).

Figure 3.2 shows a scheme of the experimental hall with its seven beamlines. In this experiment we used the 30A Gamma Ray Spectroscopy beamline.

Figure 3.2: Scheme of the Experimental Hall, showing the seven experimental beamlines available at the LAFN (Author: J. C. Terassi).

3.1.2 Ion Source

The negatively charged ion beam is produced by a 32 MC-SNICS (32 sample Multi-Cathode Source of Negative Ions by Cesium Sputtering)[30] provided by NEC[31]. In figure 3.3 we can see a scheme of the principle of operation of the MC-SNICS. Heating the cesium oven produces Cs vapor. This vapor flows to the enclosed area between the cooled cathode and the heated ionizer surface. Some of the cesium condenses on the surface of the cathode forming a thin neutral layer and some of the cesium is ionized by the hot surface of the ionizer being immediately boiled-away. These positively charged cesium ions leaving the ionizer are accelerated toward and focused onto the cathode, sputtering material from the cathode at impact. Some of the sputtered material gain an electron in passing through the neutral cesium layer accumulated on the surface of the cathode (due to the cesium's very low electronegativity). This negatively charged beam is accelerated and focused by different voltage levels, leaving the ion source with approximately 96 keV.

3.1.3 Pelletron Accelerator

This type of accelerator was developed by NEC[31] in the mid 1960s. It was installed at the Institute of Physics of the University of São Paulo in 1972, being the first Pelletron accelerator to operate in the world. In figure 3.4 we can see a scheme of the accelerator charging system. The charging chain is an improvement of the older Van de Graaff charging belts. In the tandem accelerators, the high positive voltage terminal is located at the center of the tank. The chain is made of metal pellets connected by insulating nylon links. As illustrated on the lower left side of the figure 3.4, the negatively-biased inductor electrode, which is not in contact with the chain, pushes electrons off the pellets while they are in contact with the grounded drive pulley. As the chain leaves the pulley, it retains a net positive charge, which is transferred to the high-voltage terminal. When it reaches the terminal, the chain passes through a negatively-biased suppressor electrode which prevents electrical discharges between the chain and the terminal pulley[32]. Leaving the field

Figure 3.3: *Operational scheme of the Multi-Cathode Source of Negative Ions by Cesium Sputtering [30].*

suppressor, the charge flows to the terminal. After that, the chain passes through a positively-biased inductor electrode, causing electrons to be attracted to the pellets, leaving the terminal positively charged. As the terminal pulley is connected to the terminal by an electrical conductor, the terminal loses its electrons to the chain. Thus, the terminal is positively charged when the chain is rising and when it is down. The pickoff pulleys bias are maintained by the extracted charges from the pellets.

On the right side of the figure 3.4 we have an expanded scheme of the acceleration tube. When the negatively charged ion beam reaches the tube they are attracted by the positively charged terminal and are therefore accelerated. In the center of the acceleration tube there is a ^{12}C stripper foil to remove electrons from the beam. After passing through the stripper foil, the beam becomes positively charged, being repulsed by the terminal, so the beam is accelerated again. After an upgrade of the accelerator, made in 2010, the distribution of the bias between the terminal and the grounded ends is done through resistors. This upgrade was important to improve the control of the electric potential within the accelerator. The terminal voltage has to remain constant over long periods of time during operation of the accelerator. This is done using corona points, that can be moved toward or away from the terminal, causing charge to flow from the terminal, and using a slit current feedback system, which is installed after the ME-200 magnet. The accelerator tube is enclosed in a high pressure vessel. Typically, the tank is filled with SF_6 insulating gas to prevent sparks, that would discharge the terminal completely. The maximum nominal operation voltage at the terminal is 8 MV.

Figure 3.4: On the left we have a scheme of the Pelletron Charging System [33], that was adapted from [34], and on the right a scheme of the acceleration tube.

3.1.4 Detectors

Plastic Phoswich Scintillators

Plastic scintillators are often used in nuclear physics experiments as they exhibit very short response times, with a decay time of a few nanoseconds, they can survive at very high counting rates, and they are inexpensive enough allowing the design of arrays to cover large solid angles.

In the first experiment we detected charged particles from the reaction using plastic phoswich scintillators. Phoswich means phosphor sandwich, made of two plastic scintillators optically coupled to each other as illustrated in figure 3.5. The system is composed of a first phosphor *A*, producing a fast pulse, and a second phosphor *B*, producing a slow pulse, both coupled to a photomultiplier. Phosphor *A* has a relatively small stopping power, so that the sharp time pulse produced is proportional to the charged particle entering the system (ΔE). In phosphor *B* the charged particle is completely absorbed, thus allowing the measurement of the remaining energy of this particle by the slower pulse (E). The interaction of charged particles with the two plastic scintillators gives rise to excitations and ionizations, so visible light is produced through the decay of the material that compose the scintillators. By photoelectric effect in the photocathode of the photomultiplier this radiation is absorbed and multiplied for pulse shape analysis [35].

Figure 3.5: Scheme of a basic combination of fast and slow phosphors with a photomultiplier [35].

In figure 3.6 we can see the current pulse from complete traversal (XX) of double phosphor as shown in figure 3.5. The signal from the photomultiplier consists then of a fast ΔE -signal superimposed on a slow E -signal. By integrating the charge on these two components of the signal, the two light outputs are measured. An outline of this procedure is shown in figure 3.7.

Figure 3.6: Current pulse from complete traversal (XX) of double phosphor [35].

Figure 3.7: Scheme of the procedure used to integrate the charge of the two light outputs [36].

Typically, two gates provided by the two plastic scintillators are used to integrate the charge. These gates cannot cover the entire pulse being analyzed, then a correction is needed. Usually, a modified gate is obtained by the sum of the original gate and the other gate multiplied by some factor, as illustrated in figure 3.7.

Reverse Electrode HPGe Detector

The Reverse Electrode detector is a semiconductor detector of hyperpure germanium (HPGe), where the p-type electrode (ion-implanted boron) is on the outside, and the n-type electrode (diffused-lithium) is on the inside. A scheme of this configuration is shown in figure 3.8.

This type of detector is a semiconductor diode of a P-I-N structure, in which the intrinsic or depleted region is sensitive to ionizing radiation. Under reverse bias, an electric field extends across the intrinsic or depleted region. When photons interact with the material within the depleted region, charged carriers (holes and electrons) are produced and are swept by the electric field to the P and N electrodes. This charge, which is proportional to the energy deposited in the detector by the incoming photon, is converted into a voltage pulse by an integral charge-sensitive preamplifier [37].

Because germanium has a relatively low band gap, these detectors must be cooled in order to reduce the thermal generation of charge carriers (thus reducing reverse leakage current) to an acceptable level. To cool the detectors we used liquid nitrogen which has a common temperature of 77 K. In figure 3.9 is shown the cross section of the cryostat used for the storage of the liquid nitrogen. This cryostat has a cold finger that is in thermal contact with the detector.

Figure 3.8: Scheme of the Reverse Electrode detector [37].

Figure 3.9: Cross section of the cryostat used for the storage of the liquid nitrogen [37].

Compton Suppressor

The vast majority of Compton scattered photons escape the detector resulting in the increase of background counts in the spectrum as illustrates figure 3.10. For this reason the use of a Compton Suppressor is important to improve the signal to background ratio in the spectrum. In the figure 3.11 is shown a scheme of the suppressor used in this experiment. It consists of 6 BGO (Bismuth Germanate) scintillation crystals optically isolated. Due to its great density and high atomic number, these scintillation detectors can absorb almost all the Compton radiation coming from the HPGe, producing visible light collected by photomultipliers. This signal is then used in anti-coincidence in time with the HPGe signal, vetoing the pulse from the detector that comes from Compton scattering.

Figure 3.10: *Illustration of the background generated by the Compton scattering of the gamma ray inside the detector.*

Figure 3.11: *Scheme of the Compton Suppressor used in this experiment.*

Silicon Detector

The silicon detector used in the second experiment was a surface barrier detector. It is a reverse-biased diode with parallel and planar electrodes. Figure 3.12 shows a simplified diagram of the detector manufacturing.

Figure 3.12: *Simplified diagram of surface barrier Si detector manufacturing [38].*

A semiconductor diode junction is formed after the metallization process of a silicon wafer. Even if the junction is unbiased it will function as a detector, but its performance will be very poor. If a particle enters the detector, the charges produced by Coulomb interaction will be readily lost as a result of trapping and recombination. Thus the contact potential formed spontaneously across the junction cannot generate a large enough electric field to make the charge carriers move very rapidly. For these reasons, a reverse bias is applied increasing the natural potential. This allows a relatively free flow of current in one direction while presenting a large resistance to its flow in the opposite direction [39].

3.2 Experimental Methods - First Experiment

3.2.1 Energy and Charge States

Due to the Coulomb barrier, the probability of fusing two heavy-ion nuclei depends strongly on the energy. For this reason, in a first and exploratory phase of this work, the $^{16}\text{O}+^{16}\text{O}$ fusion cross section was measured at 25, 21.6 and 20 MeV in the laboratory frame. The first two energies were chosen for being above the Coulomb barrier ($V_b \simeq 10.2$ MeV). As earlier mentioned, the accelerated negative beam loses electrons after passing through the carbon stripper foil located at the terminal inside the accelerator. The probability of forming a "positive" beam with a given charge state depends on the velocity of the incident beam. For the aforementioned energies, the voltage terminal of the accelerator was charged to 4.98, 4.30 and 3.98 MV, respectively, and the ^{16}O charge state was the +4.

Regarding the measurements at energies below the Coulomb barrier, it was important to verify the lower limit of the voltage on the terminal to which the control of the accelerator remains stable. At the occasion, the lowest voltage that we could apply on the terminal was 3.69 MV, giving $^{16}\text{O}^{+4}$ beam with energy of 18.6 MeV in the laboratory frame. In order to prevent corona discharges inside the tank, insulating SF_6 gas is commonly used in electrostatic accelerators. Typical operating pressure for our Pelletron accelerator is around 68–85 psi above the atmospheric pressure. In this particular experiment, the SF_6 gas pressure was 59.8 psi.

3.2.2 Target

The ^{16}O target was made from a tantalum anodized foil of thickness around 25 mg/cm^2 . It was produced at the University of Michigan by Michael Febraro. With this material we could produce three targets, that were subsequently glued on stainless steel frames. Figure 3.13 shows a picture of the target used in the experiment.

Figure 3.13: ^{16}O target used in the experiment.

To determine the thickness of the ^{16}O target used in the experiment, we have measured its depth profile by a Rutherford backscattering method. This measurement was performed at the Laboratory of Materials and Ionic Beams of the University of *São Paulo* (LAMFI) [40], using an α -beam at 3.03 MeV. At this energy there is a resonance in the cross section for the Rutherford backscattering of alpha in oxygen. Using the software SIMNRA it was possible to fit the backscattering spectrum. Figure 3.14 shows the depth profile of the tantalum oxide obtained by this measurement. From the surface to around $7695 \times 10^{15} \text{ atoms/cm}^2$ there is about 2.57 oxygen atoms for each tantalum atom. Due to the large percentage of tantalum after this point, we consider that the limit of the ^{16}O target is around $7695 \times 10^{15} \text{ atoms/cm}^2$, which is equivalent ¹ to 0.807 mg/cm^2 . Therefore, by averaging the thickness weighted by the concentration percentage, we can estimate the length from the surface to the middle of the target as being around 0.33 mg/cm^2 ($3109 \times 10^{15} \text{ atoms/cm}^2$).

3.2.3 Detection System

The $^{16}\text{O} + ^{16}\text{O}$ reaction populates many levels in the residual nuclei. Our first goal was to measure the gamma and particle signals coming from the residual nuclei in temporal coincidence. For this purpose we used the Saci-Perere system (Ancillary System of plastic scintillators and Small Spectrometer with Rejection of Electromagnetic Radiation Scattering)[17, 18], which consists of four HPGe γ -detectors with Compton suppression and an array of charged particle detectors composed by eleven plastic phoswich scintillators with an almost 4π solid angle. A picture of the Saci-Perere system is shown in figures 3.15a and 3.15b. The left panel shows the HPGe γ -detectors with Compton suppression and the right panel shows the plastic scintillators arranged in different angles.

¹Atoms/cm² in mg/cm²: The atomic mass of ^{181}Ta is $180.94788(2)u$, where $1u=1.660538921(73)\times 10^{-27} \text{ kg}$. Thus, $m_{^{181}\text{Ta}}=300.470997(36)\times 10^{-27} \text{ kg}$. Similarly, we have $m_{^{16}\text{O}}=26.5676(5)\times 10^{-27} \text{ kg}$. Therefore, $m_{\text{Ta}_2\text{O}_5}=733.78\times 10^{-21} \text{ mg}$. Then, dividing the thickness, in atoms/cm², by seven (atoms in Ta_2O_5), and multiplying by $m_{\text{Ta}_2\text{O}_5}$ we have the thickness in mg/cm²

Figure 3.14: Depth profile resulting from the fit made in the backscattering spectrum by Cleber L. Rodrigues of LAMFI.

(a) HPGe γ -detectors with Compton suppression

(b) Eleven plastic scintillators

Figure 3.15: *Saci-Perere* system.

In this particular experiment we have used only two HPGe γ -detectors with Compton suppression (one at 37 degrees and other at 101 degrees) and nine plastic phoswich scintillators (five at 63 degrees and four at 117 degrees).

3.2.4 Acquisition Electronics - Coincidence Method

A detailed description of this method was previously given by V.A.B. Zagatto [41] and A.S. Freitas [42]. The compound nucleus formed during the collision of two oxygens is the ^{32}S , which subsequently evaporates a combination of neutrons and charged light particles. During this process,

different isotopes are produced in excited states, decaying afterwards by γ -rays to states at lower energies. To study the correlation between events originated from the same nucleus by measuring charged particles and γ -rays in coincidence, the electronic data acquisition must accept only signals that comes from γ -rays and charged particle detectors that are occurring simultaneously (*i.e.* in temporal coincidence). In the Appendix A.1, a description of each circuit composing the electronic data acquisition is given.

3.2.5 Acquisition Electronics - Single Detection Method

The tantalum anodized ^{16}O target was thick enough to stop a considerable portion of the charged particles produced during the $^{16}\text{O}+^{16}\text{O}$ fusion reaction. Then, using the same experimental setup, we have measured the $^{16}\text{O}+^{16}\text{O}$ fusion cross section without requiring the coincidence condition between γ 's and charged particle events. This procedure increased considerably the detection efficiency of our system. Besides, choosing the single detection method allowed the measurement of the $^{31}\text{S}+n$ channel. A description of the electronic scheme used in the single γ -rays detection method is presented at Appendix A.1, Circuit 1 and Circuit 2. To swap from the coincidence to the single detection method, the Quad Coincidence module in Circuit 6 (see Appendix A.1) were replaced by a LOG FI/FO in the electronics data acquisition.

3.2.6 Data Acquisition

The SPM-fx2 software controls the interaction between the CAMAC modules (ADCs, QDCs, and TDCs) and the acquisition computer. During the experiment, we could monitor the data acquisition using the DAMM software. The valid events were saved on the acquisition computer's hard disk, and could be analyzed subsequently.

3.3 Experimental Methods - Second Experiment

3.3.1 Energy and Charge States

For the beam energies of 25, 22 and 19 MeV, the charge state used was again the +4, and for the energies of 17 and 15 MeV the charge state used was the +3. In this experiment, the SF_6 gas pressure was reduced to 46.6 psi. The lowest voltage achieved was 3.71 MV, which is nearly the same value obtained during the first experiment, where the pressure inside the tank was 59.8 psi.

3.3.2 Target

Trying to overcome some difficulties found in the previous experiment, we have chosen a different composition for the oxygen target. For the second experiment, molybdenum oxide was evaporated in a gold backing foil. Using the Target Laboratory of LAFN, twelve targets were produced with an estimated thickness of around 0.5 mg/cm^2 of gold and 0.3 mg/cm^2 of molybdenum oxide. Three targets were used in the beginning of the experiment for tests, and a fourth target was chosen for the measurements. To reduce the peak broadening in the gamma spectrum due to the Doppler effect, we opted for a gold backing as thinner as possible. However, due to the relatively high temperatures necessary to evaporate the molybdenum oxide, there is a lower limit in which the integrity of the gold backing would remain preserved.

As in the previous experiment, the thickness of the target was measured at the LAMFI after the experiment in two different ways:

1. Using a He^{++} beam at 3.315 MeV, where there is a resonance in the cross section for the reaction $^4\text{He}(^{16}\text{O}, ^{16}\text{O})^4\text{He}$, a silicon detector placed at 170° , and an integrated charge of $10 \mu\text{C}$, the spectrum of figure 3.16 was obtained. The helium beam hit the target from the gold surface.

Figure 3.16: Alpha spectrum from the Rutherford backscattering method. The black dots are the data points and the red line is the fitting.

2. Using a H^+ beam at 1.738 MeV, where there is a resonance in the cross section for the reaction $^1H(^{12}C, ^{12}C)^1H$, a silicon detector placed at 170° , and an integrated charge of 10 μC , the spectrum of figure 3.17 was obtained. The hydrogen beam hit the target from the molybdenum oxide surface.

The fittings of both spectra were performed simultaneously using the SIMNRA software, by Tiago Fiorini da Silva from LAMFI [40]. In the spectrum of figure 3.16, the far right broad peak corresponds to gold (layer 3). The total counts in the peak and its FWHM determines the thickness of gold in the target. Next peak corresponds to molybdenum (layer 2). The small peak in the middle corresponds to the carbon of layer 2. The far left two peaks correspond to the oxygen in the target (layer 2). In the spectrum of figure 3.17, the first two peaks are from the carbon backing placed behind the target, used to facilitate the fitting and the charge integration. The second is observed due to the tail of the resonance at 1.738 keV. The third peak is from the carbon build up in the target. The fourth is from the oxygen of the target, and the fifth is an overlapping of the peak from gold and molybdenum of the target. Table 3.1 shows the thickness values obtained from the fitting procedures, and figure 3.18 shows a schematic illustration of the target.

Figure 3.17: Proton spectrum from the Rutherford backscattering method. The black dots are the data points and the red line is the fitting.

Table 3.1: Thickness values from the simultaneous fitting of the spectra of Figures 3.16 and 3.17.

Layer (#)	Thickness(10^{15} atm/cm 2)			
	Carbon	Oxygen	Molybdenum	Gold
1	426 ± 23	0	0	0
2	78 ± 10	1784 ± 43	645 ± 11	0
3	0	0	0	2167 ± 13
Layer (#)	Thickness(μ g/cm 2)			
	Carbon	Oxygen	Molybdenum	Gold
1	8.50 ± 0.46	0	0	0
2	1.56 ± 0.20	47.4 ± 1.1	102.7 ± 1.8	0
3	0	0	0	708.8 ± 4.3

Figure 3.18: Schematic illustration of the target.

3.3.3 Detection System

In this experiment we used a different configuration from the one used previously. Using the same beamline, we chose the antechamber of the Saci-Perere system to mount our setup. It consisted of two HPGe γ -detectors placed at 55° and 125° , distant 19 cm from the target. Both detectors presented an energy resolution of 2.3 keV. In general, the γ -emission have an angular distribution which is not isotropic in the laboratory reference frame. Actually, it has the form [43]

$$\sigma(\theta) = A_0 \left[1 + \sum_{k=1} a_{2k} P_{2k}(\cos\theta) \right], \quad (3.1)$$

where A_0 is a normalization constant and a_{2k} are the coefficient of the Legendre polynomials P_{2k} . In practice, it is rare to find multiple radiation of higher order than 2 among the relatively low-lying states. Consequently, placing the γ -detectors at 55° and 125° with respect to the beam direction, where $P_2(\theta) \simeq 0$, allows the hypothesis of isotropic angular distribution for the γ -decay to low-lying states.

A surface barrier detector was mounted at 130° with respect to the beam. Elastically scattered beam particles were measured with the surface barrier detector for further normalization. The setup is shown in figure 3.19.

Figure 3.19: Configuration of the detectors used in the second experiment.

3.3.4 Acquisition Electronics

The acquisition electronics for the single gamma detection is the same as described in subsection 3.2.5. For the silicon detector we used the MSI-8 modules manufactured by Mesytech [44], which is a compact 8 channel preamplifier shaper box with integrated timing filter amplifiers. The analogical signal from the silicon detector enters the MSI-8 by the preamplifier input, where after filtered and inverted becomes a logical pulse used as a gate signal for the original pulse that is extracted from the amplifier output. These two pulses go directly to the ADC.

Chapter 4

Data Reduction and Analysis

4.1 First Experiment

During the first experiment four beam energies were measured: 25, 21.6, 20 and 18.6 MeV. For each energy the beam current ranged from 10 to 50 nA with an average value of 29 nA for 25 MeV, 27 nA for 18.6 MeV, 29 nA for 20 MeV and 23 nA for 21.6 MeV. For 18.6 MeV we used two different detection methods (described in subsections 3.2.4 and 3.2.5). To monitor the incident beam on the target we used a charge integrator with $(10^{-10} \pm 0.1\%)$ Coulomb/pulse. Table 4.1 shows the number of counts in the integrator and the time of measurement for each beam energy.

Table 4.1: *Values of the time of measurement and counts in the integrator for the four measured energies.*

Beam Energy (MeV)	Integrator (counts)	Time (minutes)	Counts/minute
18.6 [*]	3146874	372	8459
18.6 ^{**}	11474590	1280	8965
20.0	13319886	1405	9480
21.6	2099762	190	11051
25.0	8244736	639	12903

^{*} Coincidence detection method

^{**} Single detection method

Several peaks were identified using the γ -ray energies reported at the nuclear data table of the Brookhaven National Laboratory [45]. At the Appendix B we show the spectra for the beam energies at 25 and 18.6 MeV and a table with the corresponding peaks identified. Each energy was measured in runs of about four hours. The energy calibration of the spectra was made with two peaks, 1460.8 keV from the beta decay of $^{40}\text{K} \rightarrow ^{40}\text{Ar}$, and 2614.5 keV from the beta decay of $^{208}\text{Tl} \rightarrow ^{208}\text{Pb}$. Both nuclei are present in the bricks used in the construction of the laboratory. The Compton radiation produced by these γ -rays are the main source of the background observed in the spectra at energies below 2615 keV.

After calibration and sum of the runs for each energy, we performed the integration of the peaks. The number of counts of each gamma peak from the $^{16}\text{O} + ^{16}\text{O}$ fusion reactions divided by the counts of the integrator turned out to be inconsistent. Integrating the peaks by each run separately, just confirmed the inconsistency. There are runs with a high number of counts in the integrator and no observable reaction channels. Other runs present few counts in the integrator but many counts corresponding to reaction channels. This can be mostly explained by technical issues found afterwards with the integrator. The Ortec charge integrator presented problems to accurating

measure current during a benchmark test performed at LAFN. Since the counts of the integrator were not reliable we could not normalize the data.

We also considered the possibility of using the peaks from Coulomb excitation of the tantalum present in the target, but there is tantalum in a few components along the 30A beamline, like the collimator located at the entrance of the scattering chamber. In face of this reality, we decided to discard these data and try a different setup.

4.2 Second Experiment

During the second experiment, five beam energies were measured: 15, 17, 19, 22 and 25 MeV. To avoid the previous problems with relative normalization, a silicon detector were placed at a backward angle to detect the oxygen backscattered, which gives an indirect measurement of the number of incident nuclei. Alternatively, a gold foil used as backing for the target, and the molybdenum present in the target, could be used to normalize the data, since they undergo Coulomb excitation. So, they can provide an indirect measurement of the number of incident nuclei, which can be calculated using the corresponding theoretical cross sections for the Coulomb excitation. In fact, the gammas from the Coulomb deexcitation of gold and molybdenum were used to normalize the data, since they could only be observed if the oxygen beam is impinging the target. In our experimental arrangement, we could have counts in the particle spectrum due to the scattering in the frame of the target. Thus, analysis of the gammas from the Coulomb excitation of gold and molybdenum provides a more reliable measurement of the real number of incident nuclei.

4.2.1 Processing of the Spectra

The calibration was done individually by each run with the two peaks mentioned in section 4.1, 1460.8 keV and 2614.5 keV. Before summing the runs for each energy, a test of quality of each spectra was done, and a few spectra with problems were discarded. Sum and calibration were done by the Module DAMM (Display, Analysis and Manipulation Module) of the VaxPak from Argonne National Laboratory of the U.S. Department of Energy [46].

The background spectrum was measured without beam for a period of about 36 hours during the experiment. The setup was not changed during the measurement, and was considered that the composition of the external background do not change during the experiment except by a linear growth. Since the longer half-life observed in an unstable nucleus formed by the $^{16}\text{O}+^{16}\text{O}$ reaction is 2.498 minutes (^{30}P) we considered that the background observed without beam is composed only by natural background. Figure 4.1 shows the background spectrum with the two peaks used for the calibration. It is in logarithm scale to illustrate the Compton background generated by the peaks used for the calibration.

By a systematic analysis using these two peaks we could subtracted the background of each spectrum. Table 4.2 shows the normalization factors used for the subtraction. The difference of yields between detectors C1 and C2 is due to a problem with the detector C2, since its cooling became inefficient due to issues with its internal vacuum. It returned to its normal operation after its internal vacuum had been redone. Figures 4.2 and 4.3 show the comparison between the 19 and 22 MeV spectrum with and without background.

Figure 4.1: Spectrum of the background observed during the experiment with detector C2.

Table 4.2: Normalization factors.

Energy (MeV)	Detector	Counts		Normalization Factor		
		1461 keV	2615 keV	$(E/BG)_{1461}^*$	$(E/BG)_{2615}^{**}$	Average
15	C1	24937	6973	0.5354	0.5585	0.5469
	C2	24957	7233	0.5477	0.5777	0.5627
17	C1	161699	45931	3.4715	3.6789	3.5752
	C2	81993	23413	1.7994	1.8700	1.8347
19	C1	94889	26783	2.0372	2.1452	2.0912
	C2	94151	27755	2.0662	2.2169	2.1415
22	C1	54174	16602	1.1631	1.3298	1.2464
	C2	22303	7638	0.4895	0.6101	0.5498
25	C1	42148	11773	0.9049	0.9430	0.9239
	C2	14409	5097	0.3162	0.4091	0.3617
BG	C1	46579	12485			
	C2	45567	12520			

* Yield of the beam spectrum divided by the yield of the background spectrum for $E_\gamma = 1461$ keV.

** Yield of the beam spectrum divided by the yield of the background spectrum for $E_\gamma = 2615$ keV.

As expected, background subtraction has a greater effect at energies below the Coulomb barrier, because the Compton background due to the $^{16}\text{O}+^{16}\text{O}$ reaction is smaller. The negative peaks observed in the subtracted spectra is due to differences between the shape of the subtracted peaks and small disagreements between calibrations. This effect can be better seen in the background subtracted spectrum at $E_{lab} = 15$ MeV of figure 4.4. At this beam energy we could not observe any

Figure 4.2: Spectra of detector C2 for the beam energy of 19 MeV with (black line) and without background (red line).

of the expected peaks of the $^{16}\text{O}+^{16}\text{O}$ reaction. Therefore, the spectrum at 15 MeV corresponds practically to a background spectrum. The events below the baseline at 1000 counts are due to statistical fluctuations of the background line and due to the effect of dead time of the electronics, that is more pronounced when beam is on the target.

4.2.2 Identification of the γ -ray Peaks

For the $^{16}\text{O}+^{16}\text{O}$ reaction, the most important exit channels at energies around the Coulomb barrier ($V_b = 10.2$ MeV) [13, 14, 15] are shown in figure 4.5, where the energy threshold values for each exit reaction channel is also presented. For every energetically allowed exit channel, all the possible gamma rays within the range of energy sensible to our experiment ($60 \leq E_\gamma \leq 4000$ keV) were investigated.

For most of the measured energies, the main gammas reported in the literature were observed in our experiment, and those from the Coulomb excitation of gold and molybdenum nuclei were also identified. The gammas from reactions involving ^{16}O are all Doppler shifted. As the detectors were placed in supplementary angles related to the beam (55° and 125°), a direct comparison between them allowed an easily identification of the peaks. They are almost symmetric with respect to the energy of the γ -ray emitted. Figure 4.6 shows a typical spectrum where the thin peaks at 1015 keV correspond to the unshifted peaks from the ^{27}Al deexcitation, and the two broad peaks in the left and in the right sides are the Doppler shifted peaks with observed with the detectors at the backward and forward angles, respectively.

For most of the residual nuclei formed in excited states, more than a single gamma ray were observed due to the deexcitation of different levels populated in the $^{16}\text{O}+^{16}\text{O}$ reaction. In our analysis, we have determined the cross section for each exit reaction channel integrating only the most intense γ -ray peak, and by using its corresponding branching factor calculated theoretically

Figure 4.3: Spectra of detector C2 for the beam energy 22 MeV with (black line) and without background (red line).

using the Hauser-Feshbach statistical model formalism [14]. The branching factor includes all the possible cascade that feeds the γ -ray analyzed and the contributions to the deexcitation of the residual nucleus from other γ -rays that decay to the ground state and their cascade. In summary, this factor provides the relative contribution of a specific γ -ray to the deexcitation of its emitting nucleus depending on the center-of-mass energy. Figure 4.7 shows the branching factors used, and table 4.3 shows the peaks used for the analysis. Some of them could not be identified due to peak overlappings. These cases will be discussed in subsection 4.2.4.

4.2.3 Carbon Contamination

To avoid carbon buildup on the target, it is necessary to ensure that ultra-high vacuum conditions are maintained in the vicinity of the target. In our experiment, the typical vacuum is around 10^{-7} Torr, which is probably not enough to completely avoid carbon buildup. As showed in subsection 3.3.2, a thin layer of carbon was found in the molybdenum oxide target and from table 3.1 we can infer that for each ^{12}C there are 3.5 atoms of ^{16}O . During the experiment, we could observe γ -rays coming from the reaction between ^{16}O and ^{12}C .

In our data analysis, we have compared two different runs where the $^{16}\text{O}+^{16}\text{O}$ reaction was measured at 25 MeV at the beginning and at the end of our experiment. As presented in table 4.4, the ^{26}Al (417 keV) and ^{23}Na (440 keV) are open channels for the $^{16}\text{O}+^{12}\text{C}$ at 25 MeV but not for $^{16}\text{O}+^{16}\text{O}$. Comparing the black and red lines in figure 4.8, it is possible to observe a clear signature of carbon buildup on the target along the experiment. As each run was measured during different intervals of time, we used the γ -ray yields coming from the ^{100}Mo (535.6 keV) to normalize the spectra.

Figure 4.4: Spectra of detector C1 for the beam energy 15 MeV without background, shifted in counts by a factor 1000.

Table 4.4: Threshold for the exit channels ^{26}Al and ^{23}Na [45].

Reaction	Threshold (MeV)
$^{16}\text{O} + ^{16}\text{O} \rightarrow ^{26}\text{Al} + \text{d} + \alpha$	25.65
$^{16}\text{O} + ^{16}\text{O} \rightarrow ^{23}\text{Na} + \text{p} + 2\alpha$	24.17
$^{16}\text{O} + ^{12}\text{C} \rightarrow ^{26}\text{Al} + \text{d}$	13.21
$^{16}\text{O} + ^{12}\text{C} \rightarrow ^{23}\text{Na} + \text{p} + \alpha$	11.48

4.2.4 Integration of the Peaks

All the spectra obtained during the experiment were analyzed with the module DAMM. Peaks lying in a region where the background was easily identified were integrated using a constant energy window along the spectra corresponding to each bombarding energy. Depending on the shape of the background below the peak it was necessary to perform a fit using an asymmetric Gaussian in the case of thin peaks, which are usually the case of unshifted peaks¹, and two or more asymmetric Gaussians for broad peaks, as are typically the Doppler peaks². In some cases it was necessary to use a quadratic background rather than a linear background, but all these considerations and the number of Gaussians fitted were kept constant for the same peak over the different spectra obtained for each bombarding energy.

As mentioned before, no-beam spectra were acquired, and after normalization were subtracted from the in-beam spectra in order to improve the signal to background ratio. For the analysis

¹Unshifted Peak: Peak from γ -rays without Doppler shift.

²Doppler peak: Peak from γ -rays with Doppler shift.

Figure 4.5: Q -value diagram for the $^{16}\text{O}+^{16}\text{O}$ reaction showing the energy in the center of mass frame required to open each exit channel [14].

we always used the background subtracted spectra, despite periodically comparison of the results obtained with the original spectra shows very good agreement apart from some peaks lying in a region containing strong background contamination.

Gamma rays were observed for seven exit channel, ^{31}S , ^{31}P , ^{30}P , ^{30}Si , ^{28}Si , ^{27}Al and ^{24}Mg . In addition, γ -rays from the Coulomb excitation of gold and molybdenum were also observed in the spectrum. At $E_{\text{lab}} = 17$ MeV, only four γ -rays coming from the fusion reactions were observed at around 1014, 1369, 2212 and 2235 keV. The first two were partially Doppler shifted and the last two were completely Doppler shifted. The peaks at 1014 and 2212 keV were attributed to ^{27}Al , and the peak at 1369 keV to ^{24}Mg . Comparing the results reported by references [14] and [48] we observed that at $E_{\text{lab}} = 17$ MeV the cross section for the ^{24}Mg channel from $^{16}\text{O}+^{12}\text{C}$ is 848 times higher than from $^{16}\text{O}+^{16}\text{O}$ reaction, and the cross section for the ^{27}Al channel is 121 higher. Thus, due to their low observed intensity, they were attributed to the $^{16}\text{O}+^{12}\text{C}$ reaction. The γ -ray at 2235 keV corresponds to ^{30}Si . Table 4.5 shows details of these γ -rays. In the following, we discuss the procedure for obtaining the partial cross sections for each exit channel.

Figure 4.6: Typical Doppler shift observed in the spectra obtained with detectors C1 and C2 for the beam energy of 19 MeV.

Table 4.5: Gamma rays integrated for the calculation of the partial cross sections.

Channel	Unshifted peak (keV)	Doppler peak (keV)	
		Backward Angle	Forward Angle
$^{31}\text{S}+\text{n}$	1249	1232	1265
$^{31}\text{P}+\text{p}$	1266	1248	1283
$^{30}\text{P}+\text{d}$	709	696	719
$^{30}\text{Si}+2\text{p}$	2235	2206	2266
$^{28}\text{Si}+2\alpha$	1779	1759	1802
$^{27}\text{Al}+\text{p}+\alpha$	1015	997	1028
$^{24}\text{Mg}+2\alpha$	1369	1351	1387

Relative Efficiency

Each gamma detector has its relative efficiency, that indicates the relative probability of detecting a γ -ray depending on its energy. As done by V.A.B. Zagatto [41], with a radioactive source of ^{152}Eu , we measured the relative efficiency of both gamma detectors. Figure 4.9 shows the fitting of the measured relative efficiencies, obtained by dividing the integrated peaks of each γ -ray by its proportional intensity [45]. The equation used to fit the data is [47]:

$$\epsilon_{\gamma} = \exp [A + B(x) + C(x)^2 + D(x)^3 + E'(x)^4 + F(x)^5] , \text{ with } x = \ln(E_{\gamma}) , \quad (4.1)$$

where ϵ_{γ} is the relative efficiency and E_{γ} is the γ -ray energy. The parameters obtained for the fitting are presented in table 4.6. To illustrate the method, figure 4.10 shows the γ -ray spectrum

Figure 4.7: Branching factor curves calculated theoretically using the Hauser-Feshbach statistical model formalism [14].

observed for the ^{152}Eu radioactive source.

Table 4.6: Parameters obtained for the fitting of the relative efficiency data.

Parameter	Detector C1	Detector C2
A	-46.3972	0.515257
B	27.7603	2.067090
C	-2.99218	0.180125
D	-0.448556	-0.030578
E'	0.105992	-0.009118
F	-0.005495	0.000962

In the determination of the relative efficiencies, we have calculated the corresponding energies using the relation

$$E_{\gamma} = \frac{Y_{\gamma(dps)}^{ch} E_{\gamma}^{(dps)} + Y_{\gamma(unp)}^{ch} E_{\gamma}^{(unp)}}{2 Y_{\gamma(tot)}^{ch}}, \quad (4.2)$$

for the cases in which the γ -ray peaks were partially Doppler shifted (dps). In equation 4.2, $Y_{\gamma(dps)}^{ch}$ is the yield of the Doppler peak, $Y_{\gamma(unp)}^{ch}$ is the yield of the unshifted peak (unp), and $Y_{\gamma(tot)}^{ch}$ is the total (tot) yield of a particular channel (ch) formed in the fusion reaction. Then, for the case in which the γ -ray peaks were completely Doppler shifted, we have assumed the corresponding energy as the centroid position of these peaks.

^{31}S and ^{31}P Channels

The γ -rays at 1249 keV and 1266 keV from ^{31}S and ^{31}P were fitted together because their tails are overlap. Both peaks apparently are completely Doppler shifted. In the background spectrum

Figure 4.8: Part of the spectra from detector C1 observed at 25 MeV bombarding energy at the beginning (black line) and end (red line) of the experiment.

observed with the detector placed at a backward angle there is a peak at 1238 keV, which lies in the same region as the ^{31}S Doppler peak. This could cause an increase in the yield for ^{31}S , resulting in a larger partial cross section for the backward angle as compared to the detector located at a forward angle. We considered that this peak was completely subtracted by the method adopted (see subsection 4.2.1), because this effect was not observed within the statistical errors of the experiment.

The peak at 1266 keV attributed to ^{31}P has a contribution from other nuclei formed in the $^{16}\text{O}+^{16}\text{O}$ reaction. To deduct these contributions it is necessary to infer their number of counts. Below we discuss each of these contributions:

1. ^{31}S is an unstable nucleus, with half life of 2.572 seconds, that decays 100% by emitting a β^+ particle and forming ^{31}P with a 1.09% probability of emitting a γ -ray at 1266 keV. Thus, 1.09% of the ^{31}S produced will lead to a γ -ray at 1266 keV. Then, this contribution can be calculated by the relation below:

$$Y_{1266}^{31\text{S}} = \left(\frac{1.09 \epsilon_{1266}}{100 \epsilon_{1249}} \right) Y_{1249}^{31\text{S}} ; \quad (4.3)$$

2. The state at 1973 keV of ^{30}P decays 41.5% to the ground state and 58.5% to the 709 keV state emitting a γ -ray at 1265 keV. By the relation below we calculated the yield of the γ -ray at 1265 keV:

$$Y_{1265}^{30\text{P}} = \left(\frac{100 \epsilon_{1265}}{70.9 \epsilon_{1973}} \right) Y_{1973}^{30\text{P}} ; \quad (4.4)$$

where 70.9 is the relative contribution of the 1973 keV $\rightarrow$ 0 keV decay to the decay of the 1973 keV state, and 100 the relative contribution of the 1973 keV $\rightarrow$ 709 keV decay.

Figure 4.9: Curves obtained from the fitting of the relative efficiency measured with the ^{152}Eu radioactive source.

3. The state at 3498 keV of ^{30}Si decays 49.5% to the ground state and 50.5% to the 2235 keV state emitting a γ -ray at 1263 keV. By the relation below we calculated the yield of the γ -ray at 1263 keV:

$$Y_{1263}^{30Si} = \left(\frac{100 \epsilon_{1263}}{98 \epsilon_{3498}} \right) Y_{3498}^{30Si} ; \quad (4.5)$$

4. Thus, the yield attributed to the ^{31}P channel is given by the relation:

$$Y_{1266}^{31P} = Y_{tot} - Y_{1266}^{31S} - Y_{1265}^{30P} - Y_{1263}^{30Si} . \quad (4.6)$$

^{30}P Channel

Channel ^{30}P was obtained from the γ -ray at 709 keV. The peak observed at a forward angle is completely Doppler shifted, and the peak observed at a backward angle is 93% Doppler shifted. Five intense cascade γ -rays were observed, but they will be considered later on using their branching factors.

^{30}Si Channel

The peak at 2235 keV was attributed to the deexcitation of ^{30}Si . However, this peak has other contributions from the beta decay of ^{30}P which produces ^{30}Si , and from the deexcitation of ^{31}S and ^{31}P . There are also two peaks that lie in the same region, at 2212 keV from ^{27}Al and at 2204 keV observed in the background spectra. Below we discuss all these contributions:

1. Both peaks at 2212 and 2235 keV apparently are completely Doppler shifted. The life-time of their initial states are respectively 26.6 and 215 fs. If a nucleus takes more time to decay, it will lose more energy, resulting in a smaller Doppler shift. This effect can be seen in the figure 4.11, where the 2212 and 2235 keV peaks were obtained with the backward detector at 22 MeV. For the forward detector, the distance between the centroids of the Doppler peaks decreases, causing an overlapping of them. Figure 4.12 shows this effect.

The contribution of the 2212 keV yield to the 2235 keV yield observed with the forward detector was subtracted assuming that the ratio between the yields remains constant in both detectors, resulting in the relation

$$Y_{2235}^{C2} = \frac{Y_{(2212+2235)}^{C2} Y_{2235}^{C1}}{Y_{2235}^{C1} + Y_{2212}^{C1}} ; \quad (4.7)$$

Figure 4.10: Spectrum of the ^{152}Eu radioactive source observed at a backward angle (55°).

2. The peak at 2204 keV observed in the background spectrum was successfully subtracted of the spectra observed at $E_{lab} = 19, 22$ and 25 MeV, but at $E_{lab} = 17$ MeV difficulties were encountered. Figure 4.13 shows the spectra obtained with the backward and forward detectors with no background subtraction at $E_{lab} = 17$ MeV. Three peaks were used to fit the spectrum of the backward detector in the range of 2150 to 2300 keV.
3. ^{30}P is an unstable nucleus, with half life of 2.498 minutes, that decays 100% by emitting a β^+ particle and forming ^{30}Si with 0.059 % chance of emitting a γ -ray at 2235 keV. Thus, 0.059% of the ^{30}Si produced will emit a γ -ray at 2235 keV. Then, this contribution can be calculated by the relation below:

$$Y_{2235}^{30\text{P}} = \left(\frac{0.059 \epsilon_{2235}}{100 \epsilon_{709}} \right) Y_{709}^{30\text{P}} ; \quad (4.8)$$

4. The state at 2234 keV of ^{31}S decays 99.7% to the ground state emitting a γ -ray at 2234 keV. Reference [13] gives the branching factor for the γ -ray at 2234 related to the ^{31}S channel, which is constant (0.213) between the energy range of $E_{cm} = 7 - 14$ MeV. By the relation below we calculated its contribution:

$$Y_{2234}^{31\text{S}} = \left(\frac{0.213 \epsilon_{2234}}{\beta_{1249}^{31\text{S}} \epsilon_{1249}} \right) Y_{1249}^{31\text{S}} , \quad (4.9)$$

where $\beta_{1249}^{31\text{S}}$ is the branching factor for the γ -ray at 1249 keV related to the ^{31}S channel;

5. The state at 2234 keV of ^{31}P decays 97.34% to the ground state emitting a γ -ray at 2234 keV. Again, the branching factor of 2234 keV related to the ^{31}P channel given by reference [13] was used, it is constant (0.321) between the energy range of $E_{cm} = 7 - 14$ MeV. By the

Figure 4.11: Spectrum obtained with the backward (*C1*) detector at 22 MeV.

relation below we calculated its contribution:

$$Y_{2234}^{31P} = \left(\frac{0.321}{\beta_{1266}^{31P}} \frac{\epsilon_{2234}}{\epsilon_{1266}} \right) Y_{1266}^{31P} ; \quad (4.10)$$

6. Thus, the yield attributed to the ^{30}Si channel is given by the relation:

$$Y_{2235}^{30Si} = Y_{tot} - Y_{2235}^{30P} - Y_{2234}^{31S} - Y_{2234}^{31P} . \quad (4.11)$$

^{28}Si Channel

The peak at 1779 keV is attributed to the deexcitation of ^{28}Si , where the major part of the peak is Doppler shifted. Lying in the same region of the spectra, there is a peak at 1808 keV that is also Doppler shifted. This peak comes from the contribution of ^{26}Mg formed in the reaction with ^{12}C , which is a contamination in our target. In the spectra of the detector placed at a backward angle we observed that the unshifted peak of 1779 keV is overlapped with the Doppler peak of 1808 keV. Conversely, in the spectra of the detector placed at a forward angle we observed the Doppler peak of 1779 keV overlapped with the unshifted peak of 1808 keV. Turning the situation even more complex, there is a peak lying at 1764 keV in the spectra obtained with the backward detector, which comes from the natural background radiation. Due to all these reasons we had no other alternative but to adopt the partial cross section for this particular channel from the literature [14]. Knowing the ^{28}Si partial cross section for the energies of interest, it is possible to determine the yield of the ^{28}Si from the relation:

$$Y_{1779}^{28Si} = \left(\frac{\epsilon_{1779}}{\epsilon_{1266}} \frac{\beta_{1779}^{28Si}}{\beta_{1266}^{28Si}} \frac{\sigma^{28Si}}{\sigma^{31P}} \right) Y_{E_{1266}}^{ch} , \quad (4.12)$$

where we used the partial cross section and yield of the ^{31}P , which have been previously determined from our experiment. Integrating the entire region where the peaks of $^{28}\text{Si}(E_{\gamma} = 1779 \text{ keV})$ and

Figure 4.12: Spectrum obtained with the forward (C2) detector at 22 MeV.

$^{26}\text{Mg}(E_\gamma = 1808 \text{ keV})$ were observed, we can infer the yield for the ^{26}Mg through the relation:

$$Y_{1808}^{26\text{Mg}} = Y_{(1779+1808)}^{28\text{Si}, 26\text{Mg}} - Y_{1779}^{28\text{Si}}, \quad (4.13)$$

where $Y_{(1779+1808)}^{28\text{Si}, 26\text{Mg}}$ is the yield of the integrated region. The ^{26}Mg yield will be used in the determination of the ^{24}Mg and ^{27}Al yields associated with the $^{16}\text{O}+^{12}\text{C}$ reaction.

^{27}Al and ^{24}Mg Channels

The peaks at 1015 and 1369 keV were attributed to ^{27}Al and ^{24}Mg respectively. Their yields are 60(3)% at the Doppler peak and 40(3) % at the unshifted peak. These residual nuclei can come either from $^{16}\text{O}+^{16}\text{O}$ or from $^{16}\text{O}+^{12}\text{C}$. Reference [48] brings the latest measurement of the partial cross sections for the $^{16}\text{O}+^{12}\text{C}$ fusion reactions.

In order to obtain the partial cross sections for the ^{24}Mg and ^{27}Al , which are related to the $^{16}\text{O}+^{16}\text{O}$, we have to remove the contribution of these channels coming from the $^{16}\text{O}+^{12}\text{C}$. For this purpose, we have used the experimental cross sections for ^{24}Mg , ^{26}Mg and ^{27}Al from [48], and the ^{26}Mg yield determined as explained in the last subsection,

$$Y_{1015}^{27\text{Al}(12\text{C})} = \left(\frac{\epsilon_{1015} \beta_{1015}^{27\text{Al}(12\text{C})} \sigma_{27\text{Al}(12\text{C})}}{\epsilon_{1808} \beta_{1808}^{26\text{Mg}(12\text{C})} \sigma_{26\text{Mg}(12\text{C})}} \right) Y_{1808}^{26\text{Mg}(12\text{C})}, \quad (4.14)$$

$$Y_{1369}^{24\text{Mg}(12\text{C})} = \left(\frac{\epsilon_{1369} \beta_{1369}^{24\text{Mg}(12\text{C})} \sigma_{24\text{Mg}(12\text{C})}}{\epsilon_{1808} \beta_{1808}^{26\text{Mg}(12\text{C})} \sigma_{26\text{Mg}(12\text{C})}} \right) Y_{1808}^{26\text{Mg}(12\text{C})}, \quad (4.15)$$

where the branching factors ($\beta_{1015}^{27\text{Al}(12\text{C})}$, $\beta_{1369}^{24\text{Mg}(12\text{C})}$ and $\beta_{1808}^{26\text{Mg}(12\text{C})}$) were also extracted from [48]. Then, the remaining yields for ^{24}Mg and ^{27}Al can be associated to the respective cross section

Figure 4.13: Spectra obtained with the backward (blue line) and the forward (red line) detectors at $E_{lab} = 17$ MeV. The head-head arrows show the expected Doppler peaks position.

coming from the $^{16}\text{O}+^{16}\text{O}$ reaction.

4.2.5 Relative Normalization

Due to the Coulomb excitation of gold and molybdenum presented in the target, γ -rays from the decay of the excited states of these nuclei were observed, and two of them were chosen to perform the partial normalization of the data, 536 keV from ^{100}Mo and 279 keV from ^{197}Au . The energy state at 279 keV from ^{197}Au decays 98.5% to the ground state, thus a correction was made considering the remaining contribution part. As we can calculate the Coulomb excitation cross sections for these nuclei, these information can be used to normalize the partial fusion reaction cross sections among the measured beam energies. By the relation below we calculated the relative normalization (rn) for the yield:

$$Y_{\gamma}^{ch,rn} = \frac{\epsilon_{\gamma}^{CE} \sigma_{\gamma}^{CE}}{Y_{\gamma}^{CE}} Y_{\gamma}^{ch}, \quad (4.16)$$

where ϵ_{γ}^{CE} is the relative efficiency of detecting the γ -ray from the Coulomb excitation used as a reference, σ_{γ}^{CE} is the calculated Coulomb excitation cross section for the reference γ -ray (see Appendix C), and Y_{γ}^{CE} is the yield of the reference γ -ray.

At $E_{lab} = 17$ MeV the γ -ray at 536 keV has a great contribution from the background. Figure 4.14 shows a comparison between the 279 and 536 keV peaks observed at $E_{lab} = 17$ and 25 MeV for the forward detector. As the ^{197}Au peak remains almost the same in both spectra at $E_{lab} = 17$ and 25 MeV, the ^{100}Mo peak has its right tail Doppler shifted for the spectrum at $E_{lab} = 25$ MeV, while a background peak around 532 keV can be observed at $E_{lab} = 17$ MeV. Despite of that, the agreement between the fusion cross section data obtained with both ^{100}Mo and ^{197}Au is completely satisfactory, as it is shown in subsection 4.2.9.

Figure 4.14: Spectra with no background subtraction obtained at $E_{lab} = 17$ and 25 MeV.

4.2.6 Partial Fusion Cross Section

The partial fusion cross section can be derived from the relation:

$$\sigma^{ch} = \frac{Y_{\gamma}^{ch}}{N_i N_t \beta_{\gamma}^{ch} \epsilon_{\gamma}^{abs}} , \quad (4.17)$$

where N_i is the number of incident nuclei, N_t is the number of atoms per unit of area of the target, and ϵ_{γ}^{abs} is the absolute efficiency. The branching factors were extracted from reference [14]. The calculation of the Coulomb excitation cross section can be used to infer the number of incident nuclei (N_i) by the relation:

$$N_i = \zeta \left(\frac{Y_{\gamma}^{CE}}{\epsilon_{\gamma}^{CE} \sigma_{\gamma}^{CE}} \right) , \quad (4.18)$$

where ζ is a constant. N_t was measured and is presented in table 3.1. The absolute efficiency of the detectors could not be measured due to the lack of a calibrated radioactive gamma source. Thus, as explained in subsection 4.2.4, we have measured the relative efficiency, which carries the γ -ray energy dependency. Therefore, the absolute efficiency can be written as:

$$\epsilon_{\gamma}^{abs} = \xi \epsilon_{\gamma} , \quad (4.19)$$

where ξ is a constant and ϵ_{γ} is the relative efficiency. Substituting equations 4.16, 4.18 and 4.19 in equation 4.17 we obtain:

$$\sigma^{ch} = \Gamma \frac{Y_{\gamma}^{ch, rn}}{\beta_{\gamma}^{ch} \epsilon_{\gamma}} , \quad (4.20)$$

where $\Gamma = 1/(\xi \zeta N_t)$ is a constant obtained by normalization.

4.2.7 CC calculation

The coupled channel calculations were made using the zero point motion (ZPM) model [28], that couples the complete sets of inelastic states related to the quadrupole 2^+ and the octopole 3^- vibrational bands. The effect of the couplings is to replace the Coulomb barrier height, which is coupled to an harmonic oscillator, by a set of barriers, hence simulating different orientations of the colliding nuclei during the reaction, where the total transmission coefficient is given by a weighted average of the transmission for each effective barrier. As the oxygen nucleus is roughly spherical, the difference between the cross sections calculated using the BPM and the ZPM model is not very pronounced. Figure 4.15 shows the cross sections obtained from the BPM and ZPM model calculations.

Figure 4.15: Cross sections obtained from the BPM and ZPM model calculations.

4.2.8 Energy Loss in the Target

To determine the effective bombarding energy of the ^{16}O beam, a correction due to the thickness of the target must be considered. As explained in subsection 4.2.3 a carbon buildup in the target was observed, but unfortunately we could not determine its rate. For this reason, two effective bombarding energies were calculated, considering the complete amount of carbon fixed in the target by buildup (layer 1) and considering only the pre-existing carbon in the target. The bombarding energy (E_0) has been corrected by assuming an exponential decrease of the fusion cross section from σ_1 at E_0 to σ_2 at $E_0 - \Delta$, where Δ is the total energy loss in the target:

$$E_{eff} = \frac{1}{\alpha} \ln \left\{ \frac{[e^{\alpha E_0} - e^{\alpha(E_0 - \Delta)}]}{\alpha \Delta} \right\}, \quad (4.21)$$

where α is obtained by fitting the ZPM results using the relation $\sigma(E) = \sigma_0 e^{\alpha E}$. Table 4.7 presents the parameters obtained for the fittings. The effective bombarding energies correspond to the average of the effective energies given at table 4.7: 8.27, 9.27, 10.77 and 12.27.

Table 4.7: *Effective energy calculation.*

With carbon					
E_0	α	σ_0	Δ	$E_{eff,lab}$	$E_{eff,cm}$
16.912	1.503	1.78×10^{-11}	0.934	16.499	8.25
18.915	1.143	1.02×10^{-8}	0.920	18.495	9.25
21.919	0.449	0.011	0.880	21.493	10.75
24.923	0.174	5.715	0.842	24.507	12.25
Without carbon					
17	1.503	1.78×10^{-11}	0.948	16.581	8.29
19	1.143	1.02×10^{-8}	0.933	18.575	9.29
22	0.449	0.011	0.893	21.568	10.78
25	0.174	5.715	0.854	24.578	12.29

4.2.9 Total Fusion Cross Section

The total fusion cross section was calculated by the relation:

$$\sigma_{tot} = \sum_i \sigma^i = \Gamma \sum_i \frac{Y_{\gamma}^{i,rn}}{\beta_{\gamma}^i \epsilon_{\gamma}} ; i = channel. \quad (4.22)$$

The Γ value was obtained by normalizing the experimental cross section measured at the highest energy at $E_{cm} = 12.27$ MeV to the cross section obtained using the ZPM model. Table 4.8 shows the Γ values obtained for ^{197}Au and ^{100}Mo normalization for detectors C1 and C2.

Table 4.8: Γ values.

Detector	Relative Normalization	
	^{197}Au (279 keV)	^{100}Mo (536 keV)
C1	11.92	5.342×10^{-2}
C2	11.00	4.251×10^{-2}

As explained in subsection 4.2.4, at $E_{cm} = 8.27$ MeV only the γ -ray at 2235 keV from ^{30}Si was observed. To obtain the total fusion cross section, a correction considering the contributions of the $^{31}\text{S}(n)$, $^{31}\text{P}(p)$, $^{30}\text{P}(np)$, $^{28}\text{Si}(\alpha)$, $^{27}\text{Al}(\alpha p)$ and $^{24}\text{Mg}(2\alpha)$ channels was made. To understand the ^{30}Si contribution with respect to the total fusion cross section, the ratio between its partial fusion cross section and the total fusion cross section reported in [13, 14, 15] is shown in figure 4.16. At $E_{cm} = 8.27$ MeV the contribution of the ^{30}Si channel varies from 37% to 52%, with an average value of 43.7%. Thus, to obtain the total fusion cross section at this energy, the partial cross section from ^{30}Si was divided by 0.437.

After normalization, an average of the cross sections obtained for detectors C1 and C2 was made. Figure 4.17 shows the cross sections obtained for each Γ -value of table 4.8 (left) and the final cross section obtained from the average of these cross sections (right). Figure 4.18 shows the averaged total fusion cross sections compared with data from references [12, 13, 14, 15, 24], and with the cross sections from BPM and ZPM predictions. Table 4.9 shows the averaged total fusion cross sections values. Considering the dispersion of the data points, our results are in good agreement with the literature.

Figure 4.16: *Partial cross sections obtained for each exit channel analyzed.*

Table 4.9: *Averaged total fusion cross section.*

Energy	σ_{total} (mb)
8.27	1.65 ± 0.37
9.27	21.1 ± 1.4
10.77	152 ± 7
12.27	408.9 ± 25

4.2.10 Astrophysical S(E) Factor

The penetration probability through the effective barrier is a rapidly varying function of the energy. At low energies, typical for astrophysical conditions, fusion cross sections are expressed in terms of the astrophysical S-factor

$$S(E) = E \sigma(E) \exp(2\pi\eta) , \quad (4.23)$$

$$\eta = \frac{e^2 Z_1 Z_2}{\hbar} \left(\frac{\mu}{2E} \right)^{1/2} , \quad (4.24)$$

where η is the Sommerfeld parameter, e is the elementary charge, Z_1 and Z_2 are the charge numbers of the nuclei, and μ is the reduced mass of the system. This parametrization was introduced [49, 50] as it removes from the fusion cross section the strong nonnuclear dependence associated with the Coulomb barrier penetration.

Figure 4.17: (Left) Total fusion cross sections obtained from normalization with ^{197}Au (279 keV) (salmon and brown dots) and with ^{100}Mo (536 keV) (orange and black dots). (Right) Total fusion cross sections obtained from the average of the four sets of cross sections obtained. Just for a reference, the results from reference [14] (grey dots) are shown.

In the case where the projectile is the same as the target

$$\eta = \frac{31.29Z^2}{2\pi} \left(\frac{m}{2E} \right)^{1/2}, \quad (4.25)$$

where m is the mass of the nucleus in atomic mass units [51]. Substituting equation 4.25 in 4.23 we obtain

$$S(E) = E \sigma(E) \exp \left(31.29Z^2 \left(\frac{m}{2E} \right)^{1/2} \right). \quad (4.26)$$

With equation 4.26 we calculated the astrophysical S-factor, which is shown in figure 4.19. The solid square points shown in the figure are the astrophysical S-factors obtained with the averaged total fusion cross sections. The agreement of the data with the ZPM calculation is satisfactory at the entire region in which the fusion cross sections were measured. As can be seen, an increase of the effective number of coupled channels would result in a better accordance with the data. The general agreement with the data available at the literature can also be seen in the figure. Unfortunately we could not measure fusion cross sections at energies around 7.0 MeV where a clear disagreement between the existing data points is limiting the extrapolation of the S-factor towards low energies.

Table 4.10 shows the averaged total fusion cross sections values.

Table 4.10: S-factor obtained with the averaged total fusion cross section.

Energy	S-factor (MeV-b)
8.27	$(1.47 \pm 0.33) \times 10^{25}$
9.27	$(6.7 \pm 0.5) \times 10^{24}$
10.77	$(8.0 \pm 0.4) \times 10^{23}$
12.27	$(7.8 \pm 0.5) \times 10^{22}$

4.2.11 Partial Fusion Cross Section - Normalization

Using the Γ values from table 4.8 and the equation 4.20, the partial cross sections could be calculated. Figure 4.20 and table 4.11 show the averaged partial fusion cross sections obtained. Considering the dispersion of the available data points, the present results are in reasonable agreement with the literature.

Figure 4.18: Averaged total fusion cross sections compared with references [12, 13, 14, 15, 24], and theoretical predictions from ZPM model (solid line) and BPM model (dashed line).

Table 4.11: Averaged partial fusion cross sections presented in (mb).

Channel	E_{cm} (MeV)			
	8.27	9.27	10.77	12.27
$^{31}\text{S} + \text{n}$ (1249 keV)		0.7(1)	3.8(3)	5.0(4)
$^{31}\text{P} + \text{p}$ (1266 keV)		2.1(3)	10(1)	30(3)
$^{30}\text{P} + \text{np}$ (709 keV)		3.6(1)	32.7(3)	82(1)
$^{30}\text{Si} + 2\text{p}$ (2235 keV)	0.7(3)	6.7(3)	40.7(4)	88(1)
$^{27}\text{Al} + \alpha\text{p}$ (1014 keV)		6(2)	51(3)	167(32)
$^{24}\text{Mg} + 2\alpha$ (1369 keV)		1.2(6)	12(1)	35(6)

Figure 4.19: Astrophysical S -factors obtained with the averaged total fusion cross sections compared with references [12, 13, 14, 15, 24], and theoretical predictions from ZPM model (solid line) and BPM model (dashed line).

Table 4.3: *Gamma peaks used for the analysis.*

Energy (keV)	Transition	Half-life (ps)	Nucleus
2615	2615 $\rightarrow$ 0	16.7	^{208}Pb
77	77 $\rightarrow$ 0	1910	^{197}Au
191	269 $\rightarrow$ 77	15.4	^{197}Au
269	269 $\rightarrow$ 0	15.4	^{197}Au
279	279 $\rightarrow$ 0	18.6	^{197}Au
548	548 $\rightarrow$ 0	4.61	^{197}Au
536	536 $\rightarrow$ 0	12.6	^{100}Mo
1461	1461 $\rightarrow$ 0	1.12	^{40}Ar
1249	1249 $\rightarrow$ 0	0.5	$^{31}\text{S}^*$
2234	2234 $\rightarrow$ 0	0.222	^{31}S
1266	1266 $\rightarrow$ 0	0.523	$^{31}\text{P}^*$
2234	2234 $\rightarrow$ 0	0.269	^{31}P
2235	2235 $\rightarrow$ 0	0.215	$^{30}\text{Si}^*$
1263	3498 $\rightarrow$ 2235	0.058	^{30}Si
3498	3498 $\rightarrow$ 0	0.058	^{30}Si
1534	3769 $\rightarrow$ 2235	0.058	^{30}Si
677	677 $\rightarrow$ 0	0.096	^{30}P
709	709 $\rightarrow$ 0	45	$^{30}\text{P}^*$
746	1454 $\rightarrow$ 709	4.5	^{30}P
1265	1973 $\rightarrow$ 709	1.9	^{30}P
1973	1973 $\rightarrow$ 0	1.9	^{30}P
1830	2539 $\rightarrow$ 709	0.151	^{30}P
2539	2539 $\rightarrow$ 0	0.151	^{30}P
2015	2724 $\rightarrow$ 709	0.112	^{30}P
2724	2724 $\rightarrow$ 0	0.112	^{30}P
1779	1779 $\rightarrow$ 0	0.475	$^{28}\text{Si}^*$
957	957 $\rightarrow$ 0	1.2	^{27}Si
2163	2163 $\rightarrow$ 0	0.044	^{27}Si
1690	2648 $\rightarrow$ 957	0.017	^{27}Si
1015	1015 $\rightarrow$ 0	1.49	$^{27}\text{Al}^*$
2212	2212 $\rightarrow$ 0	0.0266	^{27}Al
1720	2735 $\rightarrow$ 1015	0.0089	^{27}Al
417	417 $\rightarrow$ 0	1250	^{26}Al
1809	1809 $\rightarrow$ 0	0.476	^{26}Mg
1369	1369 $\rightarrow$ 0	1.33	$^{24}\text{Mg}^*$
440	440 $\rightarrow$ 0	1.24	^{23}Na

*Gamma rays used for the calculation of the partial fusion cross sections.

Figure 4.20: Partial cross sections obtained for each exit channel analyzed.

Chapter 5

Conclusions and Outlook

5.1 Conclusions

The fusion cross section data for $^{16}\text{O}+^{16}\text{O}$ were obtained using the γ -ray spectroscopy technique. The measurements were performed in the center-of-mass energy range from 8.27 MeV to 12.27 MeV. For most of the measured energies, the partial fusion cross sections for each possible residual nucleus formed in the reaction were experimentally determined, apart from the ^{28}Si channel for which the results were taken from the literature [14].

The relative normalizations made with $^{197}\text{Au}(279\text{ keV})$ and $^{100}\text{Mo}(536\text{ keV})$ agree very well with each other. The partial fusion cross sections obtained are also in good agreement with the available data from the literature. The experimental fusion cross sections, represented in terms of the astrophysical S-factor, are in good agreement with the theoretical results obtained with the ZPM model, which predicts an extrapolated S-factor value of 2.8×10^{25} MeV-barn at the 6.6 MeV Gamow peak energy. Although problems with carbon contamination, natural background and low beam intensity affected our experiment, we consider that these issues were partially overcome, and the results were satisfactory.

5.2 Outlook

In order to avoid some difficulties faced in our experiment, important improvements need to be done in case a new measurement is planned in the future. A discussion about that is presented in subsections 5.2.1, 5.2.2 and 5.2.3.

5.2.1 Carbon Contamination

As discussed in subsection 4.2.3, it was detected a buildup of carbon in the target. We attributed this contamination to the vacuum pressure level (around 10^{-7} Torr) of the 30A beamline. The initial pumping of the beamline is performed by a mechanical vacuum pump, which uses oil for its operation. During operation it can contaminate the beamline with carbon. An ultra-vacuum is necessary to ensure that the amount of carbon in the beamline becomes negligible.

In table 3.1 of subsection 3.3.2 we can see that 15% of the amount of carbon found in the target is in the second layer. This indicates that part of the carbon contaminating the target has probably been introduced during the target manufacturing. Again we attributed this contamination to the vacuum pressure level (around 10^{-6} Torr) used in the evaporation chamber, where the target was manufactured. As stated above, a cleaner pumping system needs to be developed, so that the carbon contamination can be avoided.

Four channels were affected by the carbon contamination, being two directly and two indirectly:

1. The first directly channel affected is the $^{27}\text{Al}(\alpha p)$, where the residual nucleus ^{27}Al can be

formed by two reactions, $^{16}\text{O}+^{16}\text{O} \rightarrow ^{27}\text{Al}+\text{p}\alpha$ and $^{16}\text{O}+^{12}\text{C} \rightarrow ^{27}\text{Al}+\text{p}$, being most probable in the second for the energies of our experiment;

2. The second directly channel affected is the $^{24}\text{Mg}(2\alpha)$ where the ^{24}Mg also can be formed by two reactions, $^{16}\text{O}+^{16}\text{O} \rightarrow ^{24}\text{Mg}+2\alpha$ and $^{16}\text{O}+^{12}\text{C} \rightarrow ^{24}\text{Mg}+\alpha$, being most probable in the second for the energies of our experiment;
3. The first indirectly channel affected is the $^{28}\text{Si}(\alpha)$. Its γ -ray analyzed at 1779 keV is Doppler shifted and lies down in the same region as the γ -ray at 1808 keV from ^{26}Mg , which is formed by the reaction $^{16}\text{O}+^{12}\text{C} \rightarrow ^{26}\text{Mg}+2\text{p}$;
4. The second indirectly channel affected is the $^{30}\text{Si}(2\text{p})$. Its γ -ray analyzed at 2235 keV is Doppler shifted and its tail lies down in the same region as the γ -ray at 2212 keV from ^{27}Al , which is formed by the reaction $^{16}\text{O}+^{12}\text{C} \rightarrow ^{27}\text{Al}+\text{p}$.

5.2.2 Natural Background

Several γ -rays were identified as coming from the bricks of the experimental hall. However, two of them were identified as the main cause of the background generated, the γ -rays at 1461 keV from ^{40}Ar and at 2615 keV from ^{208}Pb . Although we have Compton suppressors for both detectors with efficiency around 95%, the effect of the other 5% becomes relevant for this kind of experiment where very small cross sections are measured. One possible solution to this problem is to make a shield with aged lead. A rough calculation indicates that around 3 cm of lead can stop 99% of the incident γ -rays with energy at 1461 keV and 2615 keV. Other γ -rays from natural background that lies in the same region of some reaction peaks can be avoided with an appropriate shielding. During the experiment an attempt to shield the detectors with some lead bricks was made, but the bricks were insufficient and no noticeable reduction of the background was observed.

5.2.3 Low Beam Intensity

As explained in sections 3.2 and 3.3, difficulties were faced to reduce the terminal voltage, so reducing the energy of the ^{16}O beam. The reduction was necessary because the most probable charge state for the terminal voltage ranging between 3.0 to 4.5 MV is the 4^+ . Even with the reduction of the SF_6 pressure inside the tank we had to select the 3^+ charge state to measure the cross sections at 15 and 17 MeV since the lowest limit for the terminal voltage that allowed the control of the accelerator was around 3.8 MV. This caused a further reduction of the beam intensity, making the situation even more difficult. The possible solution is to propose this measurement in other accelerator that would deliver high beam intensities around cents of nano-amperes. If these conditions are met, a cooling system for the target should be developed.

Appendix A

Acquisition Electronics

A.1 Coincidence Method

A detailed description of this method was previously given by V.A.B. Zagatto [41] and A.S. Freitas [42]. The compound nucleus formed during the collision of two oxygens is the ^{32}S , which subsequently evaporates a combination of neutrons and charged light particles. During this process, different isotopes are produced in excited states, decaying afterwards by γ -rays to the ground state. The central idea of this experiment is to study the correlation between events originated from the same nucleus by measuring charged particles and γ -rays in coincidence. For this purpose, the data acquisition accepts only electronic signals from γ -rays and charged particle detectors occurring "simultaneously" (*i.e.* in temporal coincidence). In the following, a description of each circuit composing the electronic data acquisition is given.

Circuit 1: Energy circuit of the γ -ray detectors

The energy pulse from the γ -detector pass through an internal pre-Amplifier and an external Amplifier to integrate, amplify, filter and improve the electrical characteristics of the pulse. Then pass through an ADC module (Analogic to Digital Converter) where the pulse is transformed in a digital number of twelve bits, proportional to its height and to the γ -energy measured.

Circuit 2: Time circuit of the γ -ray detectors

An analogical pulse is generated by the detector when a γ -ray is detected. After filtered and amplified by a TFA module (Timing and Filter Amplifier), the pulse pass through a CFD module (Constant Fraction Discriminator), becoming a logical pulse. The arrival time of this pulse is determined by its leading edge. Finally, the pulse pass through a GG module (Gate and Delay Generator) that generates a logical pulse (gate) with adjustable width and delay.

Circuit 3: Compton suppression circuit

The Compton suppressor provides a time signal which pass through the same treatment as the γ -ray time signal (see Circuit 2). This circuit verifies the coincidence between a time signal of the γ -ray detector and the Compton detector. These two pulses pass through a 4-Fold Logic Input, which performs the AND function. If the γ -ray pulse arrives to this module in coincidence with the Compton signal, it is vetoed with no further processing. On the other hand, if there is no such coincidence, the pulse is duplicated and continues to Circuit 6.

Circuit 4: Energy circuit of the phoswich detectors

The analogical pulse of the phoswich detector first passes through a LIN FI/FO module (Linear Fan In / Fan Out) that duplicates the original pulse. One of the pulses goes to Circuit 5 and the

other is delayed so that the time pulse of the phoswich detector can be processed. After being delayed, this analogical pulse goes to the CAMAC QDCA (Charge Analogic to Digital Converter) and to the CAMAC QDCW (Charge ADC with Wide Gates). The QDCA converts the fast pulse charge in a digital number, by integrating it into the defined time interval, and the QDCW converts the slow pulse by the same process. The time intervals(gates) are defined in Circuit 5.

Circuit 5: Time circuit of the phoswich detectors

As aforementioned, one of the pulses generated in the LIN FI/FO module in the Circuit 4 is used to measure the particle energy. The other analogical pulse, pass through a TFD module (Timing Discriminator), and is converted into a logical pulse that determines the arrival time of the original pulse. All the pulses coming from the particle detectors are equally treated, and are grouped in the LOG FI/FO module (Logic Fan In / Fan Out), which performs the logical operation OR, thus indicating when a particle is detected in either detector.

Subsequently, the pulses pass through a Quad Coincidence module, that performs the coincidence between any output of the LOG FI/FO and a veto pulse coming from the Circuit 7, which will be generated in case the QDCs are busy. If they are busy, this module will not allow the output pulses. If not, five pulses are generated. Two of them are a fast gate and a slow gate. The fast gate goes to the QDCA and the slow gate, after passing through a GG module to adjust its delay and width, goes to the QDCW.

Circuit 6: γ -particle coincidence circuit

This circuit performs the γ -particle coincidence, and for that uses the two pulses from Circuit 3 which are related to each γ -ray detector. One pulse enters a Quad 4 Fold Logic Unit module and two logical pulses are generated indicating a γ event. One of these pulses goes to Circuit 7 flagging that the data acquisition system is busy. The other logical pulse goes to a Quad Coincidence module, where the temporal coincidence condition between a γ and a charged particle event will be verified. If the condition is fulfilled, four logical pulses are generated in the Quad Coincidence module. Two of these pulses will enter the ADC module referred in Circuit 1 allowing the full analog to digital conversion of γ events. The third pulse acts as the common start for the TDC module (Time to Digital Converter), while the fourth pulse goes to Circuit 7. The other pulse coming from Circuit 3 is delayed passing through a GG module and will provide the stop signal for the same TDC. The TDC converts the time interval between the common start and the stop logical pulse into a digital number of eleven bits.

Circuit 7: Veto circuit and cleaning of the modules

In our experiment, the counting rate can be much higher than the conversion rate of the modules (ADC and QDCs). In the electronics, Circuit 7 is used to guarantee that any valid event will be fully converted into data by the acquisition system.

In case a γ and a charged particle fulfill the coincidence condition, two pulse coming from Circuit 6 are sent to Circuit 7. The first pulse enters to a busy circuit, where another two pulses are generated. One is sent back to Circuit 6 and acts as a veto flagging to the electronics that the acquisition system is busy, while the other is sent to a LOG FI/FO module. Two pulses coming from Circuit 5, being one of them delayed by a GG module, are also sent to the LOG FI/FO module. The output of this module is sent back to Circuit 5, indicating that a valid event is being converted. This operation will prevent the acquisition of new particle events during the conversion process. In Circuit 7, a Quad Coincidence module takes two pulses coming from Circuits 5 and 6. Those will be used to clear the QDC modules after the full conversion is achieved.

Appendix B

Spectra of the First Experiment

The figures below show the spectra for the beam energies of 18.6 MeV in the single and coincidence detection methods, and of 25 MeV in the single detection method.

Figure B.1: *Spectrum obtained for a beam energy of 18.6 MeV with the single detection method, for an energy range of 660 to 1420 keV.*

Figure B.2: Spectrum obtained for a beam energy of 18.6 MeV with the single detection method, for an energy range of 1480 to 2460 keV.

Figure B.3: Spectrum obtained for a beam energy of 18.6 MeV with the coincidence detection method, for an energy range of 640 to 1400 keV.

Figure B.4: Spectrum obtained for a beam energy of 18.6 MeV with the coincidence detection method, for an energy range of 1740 to 2300 keV.

Figure B.5: Spectrum obtained for a beam energy of 25 MeV with the single detection method, for an energy range of 580 to 1800 keV.

Figure B.6: Spectrum obtained for a beam energy of 25 MeV with the single detection method, for an energy range of 1760 to 2860 keV.

Table B.1 shows the peaks identified in the spectrum for the beam energy of 25 MeV.

Table B.1: *Peaks identified in the spectrum for the beam energy of 25 MeV.*

Energy (keV)	Transition	Half-life (ps)	Nucleus
136	136 $\rightarrow$ 0	39.5	¹⁸¹ Ta
165	302 $\rightarrow$ 136	16	¹⁸¹ Ta
302	302 $\rightarrow$ 0	16	¹⁸¹ Ta
415	717 $\rightarrow$ 302	3	¹⁸¹ Ta
440	440 $\rightarrow$ 0	1.24	²³ Na
566	2539 $\rightarrow$ 1973	0.151	³⁰ P
583	3198 $\rightarrow$ 2615	16.7	²⁰⁸ Pb
709	709 $\rightarrow$ 0	45	³⁰ P
746	1454 $\rightarrow$ 709	4.5	³⁰ P
781	781 $\rightarrow$ 0	35	²⁷ Si
844	844 $\rightarrow$ 0	35	²⁷ Al
957	957 $\rightarrow$ 0	1.2	²⁷ Si
968	2234 $\rightarrow$ 1266	0.269	³¹ P
1015	1015 $\rightarrow$ 0	1.49	²⁷ Al
1249	1249 $\rightarrow$ 0	0.5	³¹ S
1265	1973 $\rightarrow$ 709	1.9	³⁰ P
1266	1266 $\rightarrow$ 0	0.523	³¹ P
1369	1369 $\rightarrow$ 0	1.33	²⁴ Mg
1454	1454 $\rightarrow$ 0	4.5	³⁰ P
1461	1461 $\rightarrow$ 0	1.12	⁴⁰ Ar
1634	1634 $\rightarrow$ 0	0.73	²⁰ Ne
1779	1779 $\rightarrow$ 0	0.475	²⁸ Si
1809	1809 $\rightarrow$ 0	0.476	²⁶ Mg
1973	1973 $\rightarrow$ 0	1.9	³⁰ P
2028	2028 $\rightarrow$ 0	0.306	²⁹ Si
2131	2839 $\rightarrow$ 709	0.573	³⁰ P
2164	2164 $\rightarrow$ 0	0.044	²⁷ Si
2212	2212 $\rightarrow$ 0	0.0266	²⁷ Al
2234	2234 $\rightarrow$ 0	0.222	³¹ S
2234	2234 $\rightarrow$ 0	0.269	³¹ P
2235	2235 $\rightarrow$ 0	0.215	³⁰ Si
2539	2539 $\rightarrow$ 0	0.151	³⁰ P
2615	2615 $\rightarrow$ 0	16.7	²⁰⁸ Pb
2839	2839 $\rightarrow$ 0	0.573	³⁰ P

Appendix C

Fresco Inputs

C.1 Input for ^{100}Mo

16O+100Mo - Coupling the 1 inel. state

NAMELIST

&FRESCO

hcm=0.02 rmatch=200.

jtmax=100. absend=.0000

thmin=0. thmax=180. thinc=0.1

iblock=2

pade=1

chans=1 smats=4 xstabl=1

elab(1:3)=15 25 0 nlab(1:3)= 20 0 0

/

&PARTITION

Namep='16O' Massp=16. Zp=8.

Namet='100Mo' Masst=100. Zt=42. qval=0. pwf=F nex=2 /

&STATES Jp=0. Bandp=+1 Ep=0. Cpot=1 Jt=0. Bandt=+1 Et=0. /

&STATES Copyp=1 Cpot=1 Jt=2. Bandt=+1 Et=0.536 /

&partition /

&POT

kp=1 type=0 shape=0 at=100. ap=16. rc=0.95 ac=0.5

/

&POT

kp=1 type=13 shape=11 p2=71.8 /

&STEP ib=1 ia=2 k=2 Str=71.8 /

&STEP ib=2 ia=1 k=2 Str=71.8 /

&step /

&POT

kp=1 type=1 shape=9 p1=0.0 p2=0.0 p3=0.0 /

&pot / &OVERLAP / &COUPLING /

C.2 Input for ^{197}Au

16O+197Au

NAMELIST

&FRESCO hcm=0.0200 rmatch=200.000 jtmin=0.0

```

jtmax=100.0 absend=-0.0000
thmin=0.00 thmax=180.00 thinc=0.100
iblock=5
pade=1
chans=1 smats=4 xstabl=1
elab(1:3)=24.56 24.56 0 nlab(1:3)= 1 0 0 /

&PARTITION namep='16O' massp=16.00 zp=8
  namet='197Au' masst=197.000 zt=79. qval=0.00 pwf=F nex=5 /
&STATES jp=0.0 bandp=1 ep=0.0 jt=1.5 bandt=1 et=0.00 cpot=1 fexch=F /
&STATES jp=0.0 copyyp=1 bandp=1 ep=0.0 jt=0.5 bandt=1 et=0.0773 cpot=1 fexch=F /
&STATES jp=0.0 copyyp=1 bandp=1 ep=0.0 jt=1.5 bandt=1 et=0.269 cpot=1 fexch=F /
&STATES jp=0.0 copyyp=1 bandp=1 ep=0.0 jt=2.5 bandt=1 et=0.279 cpot=1 fexch=F /
&STATES jp=0.0 copyyp=1 bandp=1 ep=0.0 jt=3.5 bandt=1 et=0.547 cpot=1 fexch=F /
&partition /

&POT kp=1 type=0 ap=16.0000 at=197.0000 rc=0.95 ac=0.5 /
&POT
kp=1 type=11 shape=11 p2=72.1 /
&STEP ib=1 ia=2 k=2 Str=72.1 /
&STEP ib=2 ia=1 k=2 Str=72.1 /
&STEP ib=2 ia=3 k=2 Str=40.7 /
&STEP ib=3 ia=2 k=2 Str=40.7 /
&STEP ib=1 ia=2 k=2 Str=112.2 /
&STEP ib=2 ia=1 k=2 Str=112.2 /
&STEP ib=1 ia=5 k=2 Str=133.7 /
&STEP ib=5 ia=1 k=2 Str=133.7 /
&step /
&POT kp=1 type=1 shape=9 p1=0.0d0 p2=0. p3=0.0 /
&POT kp=1 type=1 shape=9 p1=0.d0 p2=0.0d0 p3=0.d0 /
&pot /

&overlap /

&coupling /

```

Bibliography

- [1] Claus E. Rolfs and William S. Rodney. *Cauldrons in the Cosmos*. The University of Chicago Press, 1988. xv, 1, 2
- [2] Eric G. Adelberger et al. Solar fusion cross sections. *Reviews of Modern Physics*, 70:1265, 1998. 2
- [3] F. Käppeler, F.-K. Thielemann, and M. Wiescher. Current quests in nuclear astrophysics and experimental approaches. *Annual Reviews Nuclear Particle Science*, 48:175, 1998. 2
- [4] L.R. Gasques, A.V. Afanasjev, E.F. Aguilera, M. Beard, L.C. Chamon, P. Ring, M. Wiescher, and D.G. Yakovlev. Nuclear fusion in dense matter: Reaction rate and carbon burning. *Physical Review C*, 72:025806, 2005. 2
- [5] D.G. Yakovlev, L.R. Gasques, A.V. Afanasjev, M. Beard, and M. Wiescher. Fusion reactions in multicomponent dense matter. *Physical Review C*, 74:035803, 2006. 2
- [6] C. A. Barnes, S. Trentalange, and S.-C. Wu. *Treatise on Heavy-Ion Science*, volume 6. Springer US, 1985. 2
- [7] Thomas A. Weaver and S.E. Woosley. Nucleosynthesis in massive stars and the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction rate. *Physics Reports*, 227:65, 1993. 2
- [8] S.E. Woosley, Alexander Heger, T. Rauscher, and R.D. Hoffman. Nuclear data needs for the study of nucleosynthesis in massive stars. *Nuclear Physics A*, 718:3c, 2003. 2
- [9] E.F. Aguilera et al. New γ -ray measurements for $^{12}\text{C}+^{12}\text{C}$ sub-Coulomb fusion: Toward data unification. *Physical Review C*, 73:064601, 2006. 2
- [10] T. Spillane et al. $^{12}\text{C}+^{12}\text{C}$ Fusion Reactions near the Gamow Energy. *Physical Review Letters*, 98:122501, 2007. 2
- [11] D.G. Kovar et al. Systematics of carbon- oxygen-induced fusion on nuclei with $12 \leq A \leq 19$. *Physical Review C*, 20:1305, 1979. 2
- [12] G. Hülke, C. Rolfs, and H.P. Trautvetter. Comparison of the Fusion Reactions $^{12}\text{C}+^{20}\text{Ne}$ and $^{16}\text{O}+^{16}\text{O}$ near the Coulomb Barrier. *Z. Physik A - Atoms and Nuclei*, 297:161, 1980. xiv, 2, 44, 47, 48
- [13] A. Kuronen, J. Keinonen, and P. Tikkanen. Cross section of $^{16}\text{O}+^{16}\text{O}$ near the Coulomb barrier. *Physical Review C*, 35:591, 1987. xiv, 2, 30, 38, 44, 47, 48
- [14] J. Thomas, Y.T. Chen, S. Hinds, D. Meredith, and M. Olson. Sub-barrier fusion of the oxygen isotopes: A more complete picture. *Physical Review C*, 33:1679, 1986. xiv, 2, 30, 31, 33, 35, 39, 42, 44, 46, 47, 48, 51
- [15] S.-C. Wu and C.A. Barnes. Fusion and elastic scattering cross sections for the $^{16}\text{O}+^{16}\text{O}$ reactions near the Coulomb barrier. *Nuclear Physics A*, 422:373, 1984. xiv, 2, 30, 44, 47, 48

- [16] A. Diaz-Torres, L.R. Gasques, and M. Wiescher. Effects of nuclear molecular configurations on the astrophysical S-factor for $^{16}\text{O}+^{16}\text{O}$. *Physics Letters B*, 652:255, 2007. 3
- [17] Juan Antonio Alcántara-Núñez. Ancillary system of phoswich scintillators with a 4π detection geometry. Master's thesis, Institute of Physics, University of São Paulo, Brazil, 1999. 3, 21
- [18] J.A. Alcántara-Núñez, J.R.B. Oliveira, E.W. Cybulska, N.H. Medina, M.N. Rao, R.V. Ribas, M.A. Rizzuto, W.A. Seale, F. Falla-Sotelo, F.R. Espinoza-Qui nones, and C. Tenreiro. Saci - a 4π plastic phoswich array ancillary detector system of a γ -ray spectrometer. *Nuclear instruments and Methods in Physics Research*, A497:429, 2003. 3, 21
- [19] R.M. Devries and M.R. Clover. Coulomb potentials in heavy-ion interactions. *Nuclear Physics A*, 243:528, 1975. 5
- [20] L.C. Chamon et al. Coulomb and nuclear potentials between deformed nuclei. *Physical Review C*, 70:014604, 2004. 5, 10
- [21] L.C. Chamon, B.V. Carlson, and L.R. Gasques. Toward a global description of the nucleus-nucleus interaction. *Physical Review C*, 66:014610, 2002. 5, 6, 10
- [22] A. Scalia. Heavy-Ion Elastic Scattering and Its Connections with Fusion and Absorption Processes. *Lettere Al Nuovo Cimento*, 37:129, 1983. 6
- [23] Niels Bohr. Neutron Capture and Nuclear Constitution. *Nature*, 137:344, 1936. 6
- [24] H. Spinka and H. Winkler. Experimental determination of the total reaction cross section of the stellar nuclear reaction $^{16}\text{O}+^{16}\text{O}$. *Nuclear Physics A*, 233:456, 1974. xiv, 6, 44, 47, 48
- [25] E. Kemble. A Contribution to the Theory of the B. W. K. Method. *Physical Review*, 48:549, 1935. 9
- [26] D.L. Hill and J.A. Wheeler. Nuclear Constitution and the interpretation of Fission Phenomena. *Physical Review*, 89:1102, 1953. 9
- [27] L.D. Landau and E.M. Lifshitz. *Quantum Mechanics*, volume 3. Pergamon, Oxford, 1965. 9
- [28] G.P.A. Nobre, L.C. Chamon, L.R. Gasques, B.V. Carlson, and I.J. Thompson. Consistent analysis of fusion data without adjustable parameters for a wide variety of heavy-ion systems. *Physical Review C*, 75:044606, 2007. 10, 43
- [29] Oscar Sala and George Spalek. The nuclear structure facility at the university of São Paulo. *Nuclear Instruments and Methods*, 122:213, 1974. 11
- [30] National Eletrostatics Corporation. Negative ion beam sources. URL <http://www.pelletron.com/negion.htm>, April 2007. Accessed: 2014-08-12. xiii, 13, 14
- [31] NEC. National eletrostatics corporation. URL <http://www.pelletron.com>, November 2009. Accessed: 2014-08-12. 13
- [32] Djalma Rosa Mendes Junior. *Study of the $^8\text{Li}(p,\alpha)^5\text{He}$ reaction with radioactive beam of ^8Li* . PhD thesis, Institute of Physics, University of São Paulo, Brazil, 2009. 13
- [33] Erich Leistenschneider. Proton-Induced Reactions on ^8Li at Low Energies and Spectroscopy of ^9Be at High Excitation Energies. Master's thesis, Institute of Physics, University of São Paulo, Brazil, April 2014. xiii, 15
- [34] National Eletrostatics Corp. Charging system. URL <http://www.pelletron.com/charging.htm>, December 2001. Accessed: 2014-08-12. xiii, 15

- [35] D. H. Wilkinson. The phoswich - a multiple phosphor. *The Review of Scientific Instruments*, 23:414, 1952. xiii, 16
- [36] Fredrik Lidén and Arne Johnson. Ericus - a plastic phoswich detector array for on-line identification of evaporated protons and α -particles following hi-fusion reactions. *Nuclear instruments and Methods in Physics Research*, A273:240, 1988. xiii, 17
- [37] Camberra Industries. *Germanium Detectors*, 2003. User's Manual - 9231358B. xiii, 17, 18
- [38] ORTEC. *Introduction to Charged-Particle Detectors*. xiii, 20
- [39] Glenn F. Knoll. *Radiation Detection and Measurement*. John Wiley Sons, Inc., third edition. 20
- [40] LAMFI. Multiuse chamber. URL <http://www2.if.usp.br/~lamfi/multiuso.htm>. Accessed: 2014-08-16. 21, 24
- [41] Vinicius Antonio Bocaline Zagatto. Implementation and analysis of measurements of reactions through γ -particle coincidences. Master's thesis, Institute of Physics, University of São Paulo, Brazil, 2011. 22, 34, 53
- [42] André de Souza Freitas. Study of the ${}^9\text{Be}+{}^{120}\text{Sn}$ reaction withusing the γ -particle coincidence technique. Master's thesis, Institute of Physics, University of São Paulo, Brazil, 2013. 22, 53
- [43] W.D. Hamilton. *The Electromagnetic Interaction in Nuclear Spectroscopy*. North-Holland, Amsterdam, 1985. 26
- [44] Mesytec. *MSI-8 - 8 channel preamplifier + shaper + timing filter amplifier*. Datasheet V2.0. 26
- [45] Brookhaven National Laboratory. National nuclear data center. URL <http://www.nndc.bnl.gov>. Accessed: 2014-11-02. xv, 27, 32, 34
- [46] Argonne National Laboratory. Display, analysis and manipulation module - damm. URL <http://www.phy.anl.gov/gammasphere/>. Accessed: 2014-11-04. 28
- [47] Z. Kis and B. Fazekas et al. Comparison of efficiency functions for Ge gamma-ray detectors in a wide energy range. *Nuclear Instruments and Methods in Physics Research A*, 418:374, 1998. 34
- [48] P. R. Christensen, Z. E. Switkowski, and R. A. Dayras. Sub-barrier fusion measurements for ${}^{12}\text{C}+{}^{16}\text{O}$. *Nuclear Physics A*, 280:189, 1977. 33, 40
- [49] C. A. Barnes. *Essays in Nuclear Astrophysics*. Cambridge University, 1982. Edited by C. A. Barnes, D. D. Clayton, and D. N. Schramm. 45
- [50] D. D. Clayton. *Principles of Stellar Evolution and Nucleosynthesis*. University of Chicago, 1983. 45
- [51] G. Audi, A. H. Wapstra, and C. Thibault. The AME2003 atomic mass evaluation - (II). Tables, graphs and references. *Nuclear Physics A*, 729:337, 2003. 46
- [52] F.M.Mann. volume Report No. HEDL-TME. Hanford Engineering and Development Laboratory, 1978. (unpublished).

Index

Background

- Contribution, 30
- Normalization Factor, 28
- of Reaction, 29
- Spectra, 28
- Subtraction, 28

Branching Factor, 31

Coincidence Method, 53

Compton Suppression, 18

Cross Section

- Coulomb Excitation, 65
- Fusion, 65

Doppler Peak, 32

Electronics, 53

Fresco Input, 61

Gamma-ray Detector, 17

Ion Source, 13

Pelletron

- Accelerator, 13
- Charging System, 13
- Laboratory, 11

Plastic Phoswich Scintillators, 16

Q-value

- diagram for $^{16}\text{O}+^{16}\text{O}$, 30

Relative Efficiency, 34

Silicon Detector, 19

Star Evolution, 1

Stop Peak, 32

Surface Barrier Detector, 20

Target

- Contamination of the, 51
- Molybdenum, 23
- Tantalum, 21