Experimental investigation of radiative proton-capture reactions relevant to nucleosynthesis

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• Experimental Setup
• Data Analysis and Results
• Theoretical Modeling and Conclusions
Synthesis of heavy elements

• Charged-particle induced reactions become unlikely because of the large Coulomb barrier
• The bulk of heavy elements is synthesized via neutron capture reactions

Neutron-capture processes
• **s process**
  \( \rho_n = 10^8 \text{ cm}^{-3}, t_n \sim 10^3 \text{ y} \)
• **r process**
  \( \rho_n = 10^{20}-10^{25} \text{ cm}^{-3}, t_n \sim 1 \text{ s} \)
• The **p nuclei** cannot be synthesized via the above two processes
The $p$ process is every process capable of synthesizing a $p$ nucleus.

In general, the pre-existence of “seed” nuclei, previously made by the $s$ and $r$ processes is required.

The $p$ nuclei can then be synthesized by various combinations of $(\gamma, n)$, $(\gamma, p)$, $(\gamma, \alpha)$ photodisintegration reactions as well as capture reactions: $(p, \gamma)$, $(n, \gamma)$, $(a, \gamma)$, along with $\beta^+$ decays and electron captures.
**Why focus on the reactions \(^{nat}\text{Ag}(p,\gamma)^{108,110}\text{Cd} \)?**

- The study of \(^{108}\text{Cd} \) is of special astrophysical interest because it is characterized by a very small abundance, compared to those of most of the heavier elements.

- Cross section measurements of proton capture reactions \((p,\gamma)\) as well as of their inverse reactions \((\gamma,p)\) are important for the study of the \(p\) process.

All the normalized overproductions would be equal to unity, if the derived abundance patterns were solar.
The transmission coefficients are determined by solving the Schrödinger equation, after choosing an appropriate optical potential, which describes sufficiently the interaction of the reactants.

High excitation energies require knowledge of the nuclear level density of the compound nucleus. Especially for a \((p,\gamma)\) reaction, the exit channel transmission coefficient is determined by the \(\gamma\)-ray strength function.

\[
\sigma_{\alpha\beta} = \pi \lambda^2 \frac{1}{(2i_\alpha + 1)(2I_\alpha + 1)} \sum_{J,\pi} \frac{(2J^\pi + 1)}{\sum_e T^J_\pi (e)}
\]
The astrophysical $S$-factor $S(E)$

By solving the Schrödinger equation and taking the limit $E \ll E_c$:

$$\sigma(E) \propto \exp(-2\pi \eta)$$

where:

$$\eta = \frac{Z_a Z_X e^2}{\hbar \nu}$$

Also:

$$\sigma(E) \propto \pi \lambda^2 \propto \frac{1}{E}$$

The astrophysical $S$-factor is defined then as:

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

- The astrophysical $S$ factor varies smoothly with energy compared to the cross section
- Allows for extrapolation to energy ranges where the experimental measurements are extremely difficult
The Van de Graaff Tandem Accelerator at N.C.S.R. “Demokritos”

5.5 MV Tandem Accelerator
N.C.S.R. Demokritos.
$E_p \approx 300 \text{ keV} - 10 \text{ MeV}$. 
Detector Setup

Three HPGe detectors (100% rel. efficiency)

<table>
<thead>
<tr>
<th>Detector</th>
<th>Angle [deg]</th>
<th>Distance [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>165</td>
<td>20</td>
</tr>
<tr>
<td>L2</td>
<td>90</td>
<td>20</td>
</tr>
<tr>
<td>L3</td>
<td>0</td>
<td>30</td>
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</table>
**Gamow windows for the reactions $^{\text{nat}}\text{Ag}(p,\gamma)^{108,110}\text{Cd}$**

**Beam energies studied:** 2.2, 3.5, 4 MeV

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$m_x$ [amu]</th>
<th>$m_{ax}$ [amu]</th>
<th>$T_9$</th>
<th>$E_0$ [MeV]</th>
<th>$\Delta$ [MeV]</th>
<th>$E_{p_{\text{min}}}^{p}$ (LAB) [MeV]</th>
<th>$E_{p_{\text{max}}}^{p}$ (LAB) [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{107}\text{Ag}$</td>
<td>106.905093</td>
<td>0.998413</td>
<td>1.7</td>
<td>2.263</td>
<td>1.331</td>
<td>1.613</td>
<td>2.957</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.3</td>
<td>3.522</td>
<td>2.313</td>
<td>2.388</td>
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<td>$^{109}\text{Ag}$</td>
<td>108.904756</td>
<td>0.998584</td>
<td>1.7</td>
<td>2.265</td>
<td>1.331</td>
<td>1.613</td>
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<td></td>
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</tbody>
</table>
The reaction $^{107}\text{Ag}(p,\gamma)^{108}\text{Cd}$

Level Scheme of $^{108}\text{Cd}$

Data Analysis and Results

University of Athens, 2016
The reaction $^{109}\text{Ag}(p,\gamma)^{110}\text{Cd}$

Level Scheme of $^{110}\text{Cd}$
Angular Distributions

$^{107}\text{Ag}(p,\gamma)^{108}\text{Cd}$

$^{109}\text{Ag}(p,\gamma)^{110}\text{Cd}$

$W(\theta) = A_0(1 + a_2P_2(\cos \theta) + a_4P_4(\cos \theta) + ...)$
Results

\[ {^{107}}Ag(p,\gamma){^{108}}Cd \]

\[ \sigma = \frac{A}{N_p N_A \xi} \sum_{i=1}^{N} (A_0)_i \]
**Theoretical nuclear models**

- The theoretical results were calculated with the TALYS 1.6 and EMPIRE (MALTA) codes.
- Input: Optical potentials, Nuclear Level Densities and γ-ray strength function models.

<table>
<thead>
<tr>
<th>Combination</th>
<th>Optical Potential Model</th>
<th>Nuclear Level Density Model</th>
<th>γ-ray strength function model</th>
</tr>
</thead>
<tbody>
<tr>
<td>TALYS 1</td>
<td>Koning-Delaroche</td>
<td>CTM</td>
<td>Kopecky-Uhl</td>
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<td>TALYS 2</td>
<td>Bauge-Delaroche-Girod</td>
<td>Demetriou-Goriely</td>
<td>Hartree-Fock-BCS</td>
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<td>TALYS 3</td>
<td>Bauge-Delaroche-Girod</td>
<td>Goriely-Hilaire</td>
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<td>TALYS 4</td>
<td>Bauge-Delaroche-Girod</td>
<td>Temperature Dependent HFB</td>
<td>Goriely’s Hybrid Model</td>
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<td>EMPIRE</td>
<td>Koning-Delaroche</td>
<td>EGSM</td>
<td>Plujko MLO1</td>
</tr>
</tbody>
</table>
Results

$^{107}\text{Ag}(p,\gamma)^{108}\text{Cd}$

$^{109}\text{Ag}(p,\gamma)^{110}\text{Cd}$

Graphs showing cross-section and S-factor variations with energy for $^{107}\text{Ag}(p,\gamma)^{108}\text{Cd}$ and $^{109}\text{Ag}(p,\gamma)^{110}\text{Cd}$ reactions.
• An attempt to measure cross sections and $S$-factors of the reactions $^{\text{nat}}\text{Ag}(p,\gamma)^{108,110}\text{Cd}$, was carried out for the first time at an astrophysically relevant energy range.

• Overall agreement between the data and the theoretical calculations seems satisfactory.

• Need for further investigation both in experimental (angular distributions) and theoretical (sensitivity analysis) level.
Acknowledgement

To the staff of the Tandem Accelerator Laboratory for the excellent cooperation both in scientific and technical level
Additional
Solar System Abundances

- Most of the solar system consists of H (71.1 %) and He (27.4 %)
- Minimum at $5 < A < 11$, corresponding to the elements Li, Be and B
- Maximum at $50 < A < 65$ (iron peak)
- Isotopic abundances with $A > 80$ are on average $10^{10}$ greater than H

Question:
How did the elements-isotopes form?

Abundance evolution and reaction networks

\[
\frac{dN_i}{dt} = \left[ \sum_{i,j} N_j N_k \langle \sigma v \rangle_{jk \rightarrow i} + \sum_l \lambda_{\beta,l \rightarrow i} N_i + \sum_m \lambda_{\gamma,m \rightarrow i} N_m \right] - \left[ \sum_n N_n N_i \langle \sigma v \rangle_{ni} + \sum_o \lambda_{\beta,i \rightarrow o} N_i + \sum_p \lambda_{\gamma,i \rightarrow p} N_i \right]
\]

Cross section is a quantity that can be measured in the lab.

Cross section is:

\[
\langle \sigma v \rangle_{jk} = \left( \frac{8}{\pi m_{jk}} \right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty E^2 \sigma(E) e^{-E/kT} dE
\]
The most likely scenario is that the \( p \) process happens in the O/Ne shell of massive star either in its Supernova Type II (SNII) explosive or pre-explosive state.

Temperature and density:

\[ T \approx 1.7 - 3.3 \times 10^9 \text{ K}, \]
\[ \rho \approx 10^8 \text{ gr cm}^{-3}. \]

Other astrophysical sites: Supernovae Type Ia, Ib/Ic etc.
Nucleosynthetic Mechanisms

**B²FH and Cameron:**
- Elements are formed inside stars via various thermonuclear reactions
- Foundations of the theory of *stellar nucleosynthesis*


The p process network involves about **20,000** reactions, involving over **1,000** isotopes.

Solutions rely on theoretical calculations, using the statistical Hauser-Feshbach model.
Compound nucleus reactions

The reaction occurs in two stages:
• Formation of a compound nucleus of a relatively large lifetime.
• Subsequent decay of the compound nucleus, *independent* of the entrance channel.

\[ \sigma_{\alpha\beta} = \sigma_{\text{CN}}(\alpha) P_{\beta} \]
Gamow formalism

\[
\langle \sigma v \rangle_{ax} = \left( \frac{8}{\pi m_{ax}} \right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty S(E) \exp \left( -\frac{E}{kT} - \frac{b}{E^{1/2}} \right) dE
\]

For non-resonant reactions, the \( S \) factor is constant over a small energy interval:

\[
\langle \sigma v \rangle_{ax} = \left( \frac{8}{\pi m_{ax}} \right)^{1/2} \frac{1}{(kT)^{3/2}} S(E_0) \int_0^\infty \exp \left( -\frac{E}{kT} - \frac{b}{E^{1/2}} \right) dE
\]

The Gamow distribution can be approximated with a Gaussian:

\[
E_0 = \left( \frac{b kT}{2} \right)^{2/3} = 0.122(Z_a^2 Z_X^2 m_{ax} T_g^2)^{1/3} \text{ MeV}
\]

\[
\Delta = \frac{4}{3^{1/2}} (E_0 kT)^{1/2} = 0.237(Z_a^2 Z_X^2 m_{ax} T_g^5)^{1/6} \text{ MeV}
\]
A Stellar Timeline

1. First generation of stars begin to form after the Big Bang. These elements eventually form the first stars.

2. The core temperature in the stars heats up, forging carbon, nitrogen, oxygen and eventually iron.

3. Extreme high temperatures in the stars produce gamma rays. When the gamma rays turn into particles, the stars explode into pair-instability supernovas.

Three types of stars:

1. 10–100 solar masses: The volatile stars have short lives. When they blow up, light elements spew out while iron, a heavier element, is left behind.

2. 50–100 solar masses: The stars spin so fast that their cores' heavy elements mix with the upper layers. All of the elements explode out when the stars go supernova.

3. 140–260 solar masses: Iron is trapped in the black hole while the lighter elements escape.

Black holes develop:

Elements combine:

Second generation stars form:

A new generation of smaller but more stable stars is born. They last long enough to be detected today.

Key for elements:

- He: Helium
- H: Hydrogen
- Li: Lithium
- N: Nitrogen
- O: Oxygen
- Fe: Iron
- C: Carbon

University of Athens, 2016
The reaction $^{107}\text{Ag}(p,\gamma)^{108}\text{Cd}$

- Measurement of the photopeak corresponding to the transition: $2^+ \rightarrow 0^+$, for every angle: $0^\circ, 90^\circ, 165^\circ$

- Determination of the angular distribution of the reaction

- Determination of the cross section and $S$ factor
The reaction $^{109}\text{Ag}(p,\gamma)^{110}\text{Cd}$

- Measurement of the photon peak that corresponds to the transition: $2^+ \rightarrow 0^+$, for the angles: $0^\circ, 90^\circ, 165^\circ$.
- Determination of the angular distribution for each energy bin.
- Calculation of the active cross section and the astrophysical factor.
Reaction rate

- For a reaction \( a + X \rightarrow b + Y \) in a stellar environment:
- Represents the number of reactions per unit time per unit volume.
- Cross section appears explicitly, and is calculated via the Hauser-Feshbach statistical model.

\[
\langle \sigma v \rangle_{aX} = \left( \frac{8}{\pi m_{aX}} \right)^{1/2} \frac{1}{(kT)^{3/2}} \int_{0}^{\infty} E \sigma(E) e^{-E/kT} dE
\]
Evaluation of the cross section and S-factor

\[ \sigma \equiv \frac{(N_R/t) [N_a/(tD)] N_X}{[N_p N_A \xi]} \]

\[ \sigma = \frac{A}{N_p N_A \xi} \sum_{i=1}^{N} (A_0)_i \]

\[ S(E) = E\sigma(E) \exp \left( 0.9895 z_p z_t \sqrt{\frac{m_{aX}}{E}} \right) \]

\[ S(E) = E\sigma(E) \exp \left( 0.9934 z_t \sqrt{\frac{m_X}{(m_X + 1.007825)E}} \right) \]

\[ Y(E_i^\gamma, E_j^p, \theta_k) = \frac{N(E_i^\gamma, E_j^p, \theta_k) \omega(E_j^p, \theta_k)}{\epsilon_{abs} Q(E_j^p)} \]

\[ W(\theta) = A_0 (1 + a_2 P_2(\cos \theta) + a_4 P_4(\cos \theta) + \ldots) \]

\[ \sigma = 2.6565 \times 10^{-10} \frac{A}{\xi} \sum_{i=1}^{N} (A_0)_i \text{ [barns]} \]
Typical reaction spectrum at beam energy of 4 MeV, and angle of 90°.
Πυρηνοσυνθετικοί Μηχανισμοί

B²FH και Cameron:
- Τα στοιχεία δημιουργούνται στους αστέρες μέσω διαφόρων θερμοπυρηνικών αντιδράσεων.
- Θεμελίωση της θεωρίας της αστρικής πυρηνοσύνθεσης.

Σύνθεση ελαφρύτερων πυρήνων
- Καύση Υδρογόνου
- Καύση Ηλίου
- l-διεργασία: σύνθεση των ελαφρών πυρήνων D-Li-Be-B
- Καύση Άνθρακα, Οξυγόνου και Νέου: 16<A<28
- Καύση Πυριτίου: 28<A<60

Σύνθεση βαρύτερων πυρήνων
- s διεργασία
- r διεργασία
- p διεργασία


Πανεπιστήμιο Αθηνών, 2016
Σύνθετος πυρήνας για αντιδράσεις \((p,\gamma)\)

\[
E^* = E_{CM} + Q - \frac{\Delta E}{2}
\]

Σχηματισμός του σύνθετου πυρήνα σε υψηλές ενέργειες διέγερσης. – Συνεχές.
Μετρήσεις In-beam

- Βομβαρδισμός του στόχου σε ενέργειες 2.2, 3.5 και 4 MeV.
- Μέτρηση των ακτινών γ που τροφοδοτούν τη βασική στάθμη του σύνθετου πυρήνα.
- Διόρθωση ως προς την απολυτή ανιχνευτική ικανότητα και ως προς τη γωνιακή κατανομή.
- Υπολογισμός της ενεργού διατομής και του αστροφυσικού παράγοντα.

$\sigma = \frac{A}{N_p N_A \xi} \sum_{i=1}^{N} (A_0)_i$

$W(\theta) = A_0 + a_2 P_2(\cos \theta) + a_4 P_4(\cos \theta) + ...$

$S(E) = E \sigma(E) \exp \left( 0.9895 Z_a Z_X \sqrt{\frac{m_{\infty}}{E}} \right)$
Target of $^{\text{nat}}$Ag:
51.8\% of $^{107}$Ag,
48.2\% of $^{109}$Ag

The target’s thickness was determined with the Rutherford Backscattering Technique, and was found very close to its nominal value.

- Backing: Au, Ta.

\[
x = 0.437 \text{ nm}
\]
\[
\xi = \rho x = 458 \text{ \(\mu\)g cm}^{-2}
\]
\[
\xi_{\text{nom}} = 420 \text{ \(\mu\)g cm}^{-2}
\]
Absolute detector efficiencies

- Determination of the absolute efficiency at an angle:

\[ \epsilon_{abs}(E_i^\gamma, \theta_k) = \frac{N(E_i^\gamma, \theta_k)}{R \times P_i \times t_L} \]

- Fitting a Debertin function of the form:

\[ \epsilon_{abs}(E, \theta_k) = A \ln E + B \frac{\ln E}{E} + C \frac{(\ln E)^2}{E} + D \frac{(\ln E)^4}{E} + F \frac{(\ln E)^5}{E} \]
• Introduction
• Introduction

• Experimental Setup
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• Data Analysis and Results
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• Theoretical Modeling and Conclusions
**Abundances of p nuclei**

<table>
<thead>
<tr>
<th>P nucleus</th>
<th>(%)</th>
<th>P nucleus</th>
<th>(%)</th>
<th>P nucleus</th>
<th>(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{74}$Se</td>
<td>0.89</td>
<td>$^{114}$Sn</td>
<td>0.659</td>
<td>$^{156}$Dy</td>
<td>0.056</td>
</tr>
<tr>
<td>$^{78}$Kr</td>
<td>0.362</td>
<td>$^{115}$Sn</td>
<td>0.339</td>
<td>$^{158}$Dy</td>
<td>0.095</td>
</tr>
<tr>
<td>$^{84}$Sr</td>
<td>0.5580</td>
<td>$^{120}$Te</td>
<td>0.096</td>
<td>$^{162}$Er</td>
<td>0.139</td>
</tr>
<tr>
<td>$^{92}$Mo</td>
<td>14.525</td>
<td>$^{124}$Xe</td>
<td>0.129</td>
<td>$^{164}$Er</td>
<td>1.61</td>
</tr>
<tr>
<td>$^{94}$Mo</td>
<td>9.151</td>
<td>$^{126}$Xe</td>
<td>0.112</td>
<td>$^{168}$Yb</td>
<td>0.12</td>
</tr>
<tr>
<td>$^{96}$Ru</td>
<td>5.542</td>
<td>$^{130}$Ba</td>
<td>0.106</td>
<td>$^{174}$Hf</td>
<td>0.162</td>
</tr>
<tr>
<td>$^{98}$Ru</td>
<td>1.869</td>
<td>$^{132}$Ba</td>
<td>0.101</td>
<td>$^{180}$Ta</td>
<td>0.0123</td>
</tr>
<tr>
<td>$^{102}$Pd</td>
<td>1.02</td>
<td>$^{138}$La</td>
<td>0.091</td>
<td>$^{180}$W</td>
<td>0.120</td>
</tr>
<tr>
<td>$^{106}$Cd</td>
<td>1.25</td>
<td>$^{136}$Ce</td>
<td>0.186</td>
<td>$^{184}$Os</td>
<td>0.020</td>
</tr>
<tr>
<td>$^{108}$Cd</td>
<td>0.89</td>
<td>$^{138}$Ce</td>
<td>0.250</td>
<td>$^{190}$Pt</td>
<td>0.014</td>
</tr>
<tr>
<td>$^{113}$In</td>
<td>4.288</td>
<td>$^{144}$Sm</td>
<td>3.073</td>
<td>$^{196}$Hg</td>
<td>0.15</td>
</tr>
<tr>
<td>$^{112}$Sn</td>
<td>0.971</td>
<td>$^{152}$Gd</td>
<td>0.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

All the normalized overproductions would be equal to unity, if the derived abundance patterns were solar.

The p nuclei are characterized by their small contribution to the corresponding elemental abundance.