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# Cross-section measurement for $^{114}$Cd(p, $\gamma$)$^{115m}$In reaction relevant to astrophysical p-process

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# Table of Contents

# Introduction

## Open questions

What is the origin of chemical elements ?
How were the heavy elements made?
Why stars are shining?

- E. M. Burbidge, G. R. Burbidge, W. A. Fowler, F. Hoyle and A. Cameron almost simultaneously summarized the existing knowledge of the burning processes of stars explaining the origin of the chemical elements.
- After their work, a new interdisciplinary branch of physics was born - Nuclear Astrophysics.
- The origin of almost all stable isotopes was explained assuming eight main synthesizing processes: Hydrogen burning phase, Helium burning phase (Triple $\alpha$-process), $\alpha$-process, e-process, s-process, r-process, **p-process** and x-process

# Introduction to *p*-process

- The nuclei burning stops at Iron (Fe) and most of the elements above iron peak are created via nucleosynthesis processes (s-process, r-process).
- The stable neutron-deficient nuclei with the mass number of $74 \leqslant A \leqslant 196$ (between $^{74}$Se and $^{196}$Hg) are the **p-nuclei**. The synthesis is called **p-process**.

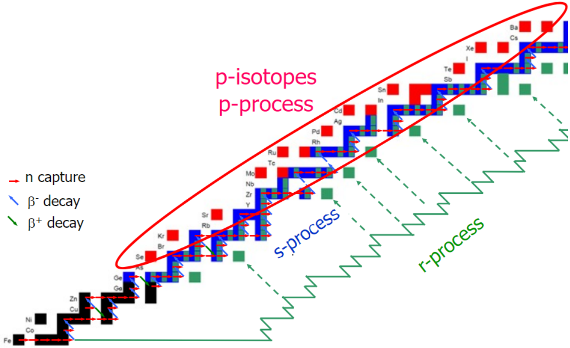


Figure: Schematic curve of atomic abundances relative to Si=$10^6$ vs atomic mass number.

# Introduction: *p*-process & *p*-nuclei

- mainly even-even nuclei
- 0.1 - 1 % abundance

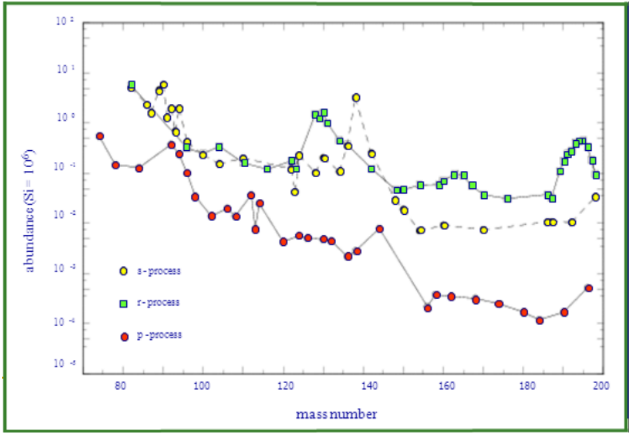


Figure: Schematic curve of atomic abundances relative to Si$=10^6$ vs atomic mass number.

# Introduction: *p*-process & *p*-nuclei

- The origin of *p* nuclei is challenging due to no direct evidence found in the stars and supernova remnants.
- Many assumptions are made for the *p* nuclei production
  - type II supernovae
  - neutrino winds of SN-II
  - type-Ia supernovae
  - neutron stars.
- The span of the *p*-process is roughly 2000 nuclei, forming around 20000 reaction networks.
- By considering these quests, it's a small contribution from our side to gain knowledge about the astrophysical *p* process reaction network.

# Experimental Methodology

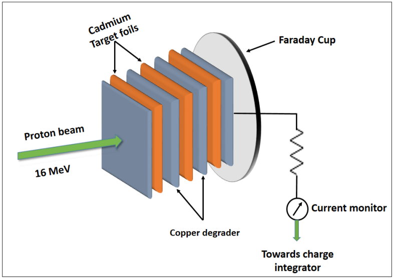


Figure: A schematic diagram of the stacked foil experiment.

## Detail of Experiment

- The experiment was performed at 14-UD BARC-TIFR Pelletron facility, Mumbai-INDIA.
- A Cadmium foil was used as a target followed by the Copper degrador.
- The degradation in energy was calculated using SRIM code.
- Assuming reactions taking place in the middle of the target, the effective energy is given by

$$E_{eff} = E_p - \Delta E/2 \qquad (1)$$

# Activation Analysis

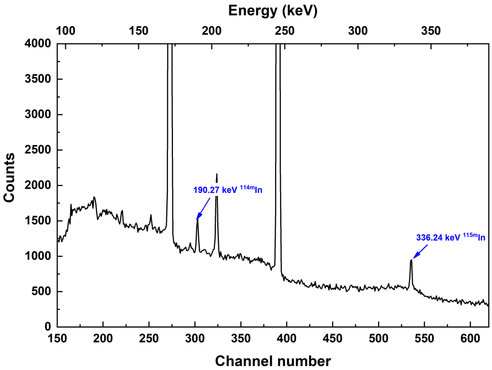


Figure: Typical $\gamma$-ray energy spectrum obtained from the interaction of p+$^{114}$Cd.

| reaction | Isotopic abundance (%) | Threshold energy (keV) | Half-life (hour) | Prominent $\gamma$-ray energy (keV) | branching intensity (%) |
|---|---|---|---|---|---|
| $^{114}$Cd(p, $\gamma$)$^{115m}$In | 28.73 | 0.0 | 4.486 (4) h | 336.24 (25) | 45.9 (1) |

# Activation Analysis

- The cross-section was measured for the $^{114}$Cd(p, $\gamma$)$^{115m}$In reaction at 4.86 MeV of proton energy using an activation equation.

$$\sigma_R = \frac{A_\gamma \lambda(\frac{t_c}{t_r}) e^{\lambda t_w}}{N \epsilon I_\gamma \phi (1 - e^{-\lambda t_i})(1 - e^{-\lambda t_c})} \tag{2}$$

where,
$\sigma_R$ = the reaction cross-section;
A$\gamma$ = number of detected $\gamma$-ray count;
$\lambda$ = decay constant of product nuclei (s$^{-1}$);
t$_c$ = counting time (s);
t$_r$ = real time (s);
t$_w$ = cooling time (s);
N = number of target atoms;
$\phi$ = Proton flux incident on the target (p cm$^{-2}$ s$^{-1}$);
I$_\gamma$ = branching intensity of $\gamma$-ray;
$\epsilon$ = efficiency of the detector for desired $\gamma$-ray.

# Data Analysis: Gamow window

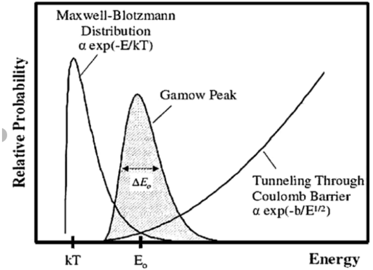


Figure: The Coulomb penetration probability folded with the Maxwell-Boltzmann velocity distribution forms the so-called Gamow peak.

## Gamow window calculation

- **The effective burning energy,**

$$E_0 = 0.12204(\mu {Z_1}^2 {Z_2}^2 {T_9}^2)^{\frac{1}{3}}$$

- **The effective width,**

$$\Delta = 0.23682(\mu {Z_1}^2 {Z_2}^2 {T_9}^5)^{\frac{1}{6}}$$

Here $E_0$ and $\Delta$ are in MeV, $T_9$ is the plasma temperature in GK.

- **Effective energy range**

$E_0 - (\Delta /2) \leqslant E \leqslant E_0 + (\Delta/2)$

# Data Analysis: S-factor Calculation

The nuclear reactions in stars will occur near the energies where the product of velocity distribution and the cross-section are at maximum.

## S-factor

- The astrophysical S-factor was calculated using the equation below,

$$S(E) = \frac{\sigma(E)E}{e^{-2\pi\eta}} \tag{3}$$

$\eta$= Sommerfeld parameter = ($Z_1$ $Z_2$ $e^2$ $/\hbar\ \nu$)
$\nu$ = magnitude of the incident particles' relative velocity.
The exponent can be approximated in numerical units by

$$2\pi\eta = 31.29 Z_1 Z_2 \sqrt{\frac{\mu}{E_{c.m.}}} \tag{4}$$

where, $E_{c.m.}$ is in [keV] and the reduced mass $\mu$ in [amu].

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# TALYS-1.95 Calculation

- The measured cross-section data were compared with theoretical predictions of TAYS-1.95.
- The results from 96 combinations are used for the cross-section comparison.

| **Optical model potential** | **Nuclear level density** | $\gamma$ **strength function** |
|---|---|---|
| Koning-Delaroche (KD) | Constant-temperature model (CTM) | Kopecky-Uhl |
| Bauge-Delaroche-Girod (BDG) | Back-shifted Fermi gas model (BSFG) | Brink and Axel |
| | Generalized superfluid model (GSM) | Hartree-Fock BCS (HFBCS) |
| | Goriely of Goriely et al. | Hartree-Fock-Bogolyubov (HFB) |
| | Tables of Goriely et al. | Goriely hybrid model |
| | T -dependent HFB, Gogny force (TDHFB) | Goriely TDHFB |
| | | T -dependent relativistic mean field (RMF) |
| | | Gogny D1M HFB + quasi-random-phase approximation (QRPA) |

- **Combination of TALYS models for $^{114}$Cd(p, $\gamma$)$^{115m}$In reaction**
  - **TALYS-1 :** BDG (JLM) OMP + BA $\gamma$ -SF + BSFG NLD
  - **TALYS-2 :** BDG (JLM) OMP + BA $\gamma$ -SF + GSM NLD
  - **TALYS-3 :** KD OMP + KU $\gamma$ -SF + GSM NLD

# Results & Discussion

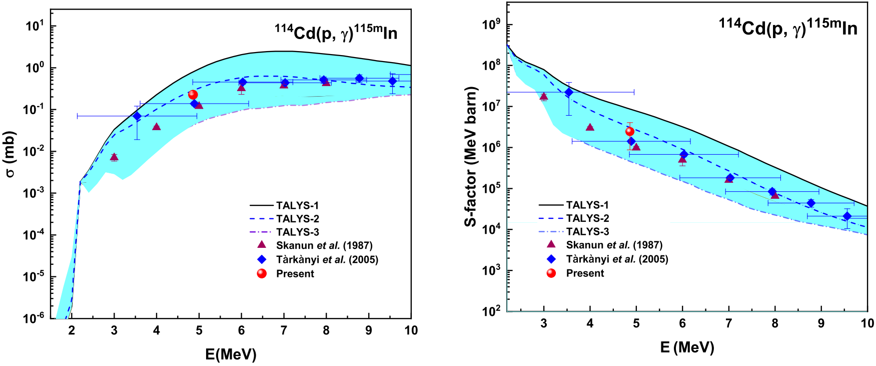


Figure: Comparison of the cross sections for the $^{114}$Cd(p, $\gamma$)$^{115m}$In reaction with three different HF calculations using the TALYS-1, TALYS-2, and TALYS-3 combinations and with the data retrieved from the EXFOR. The corresponding astrophysical S-factors are plotted in the right panel.

# Conclusion

- The reaction cross sections and astrophysical S factor of $^{114}Cd$(p, $\gamma$)$^{115m}$In reaction has been calculated in the astrophysical interest.
- The measured cross section value is 0.227 $\pm$ 0.054 and S factor value is 2.4542 $\times 10^6$ MeV barn for 4.86$\pm$2.40 MeV of proton energy.
- The work will enhance the nuclear data library of proton-induced nuclear reactions and it is a small contribution to the astrophysical *p*-process.
- Both experimental and theoretical studies are required to acquire firm insight into the driving mechanisms behind the *p*-process nucleosynthesis and restrict the parameters of the theoretical models in an energy region where there is a scarcity of experimental data, even for stable nuclei, still persists.

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*Thank you for paying attention !!!*