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Experimental investigation of radiative proton-capture reactions relevant to nucleosynthesis

A. Khaliel[1], T.J. Mertzimekis[1], A. Psaltis[1], I. Psyrra[1], A. Kanellakopoulos[1], V. Lagaki[1], V. Foteinou[2], M. Axiotis[2], S. Harissopulos[2]

[1] Department of Physics, Zografou Campus, GR-15784, University of Athens, Greece
[2] Tandem Accelerator Lab, NCSR "Demokritos", Ag. Paraskevi, 15310, Greece

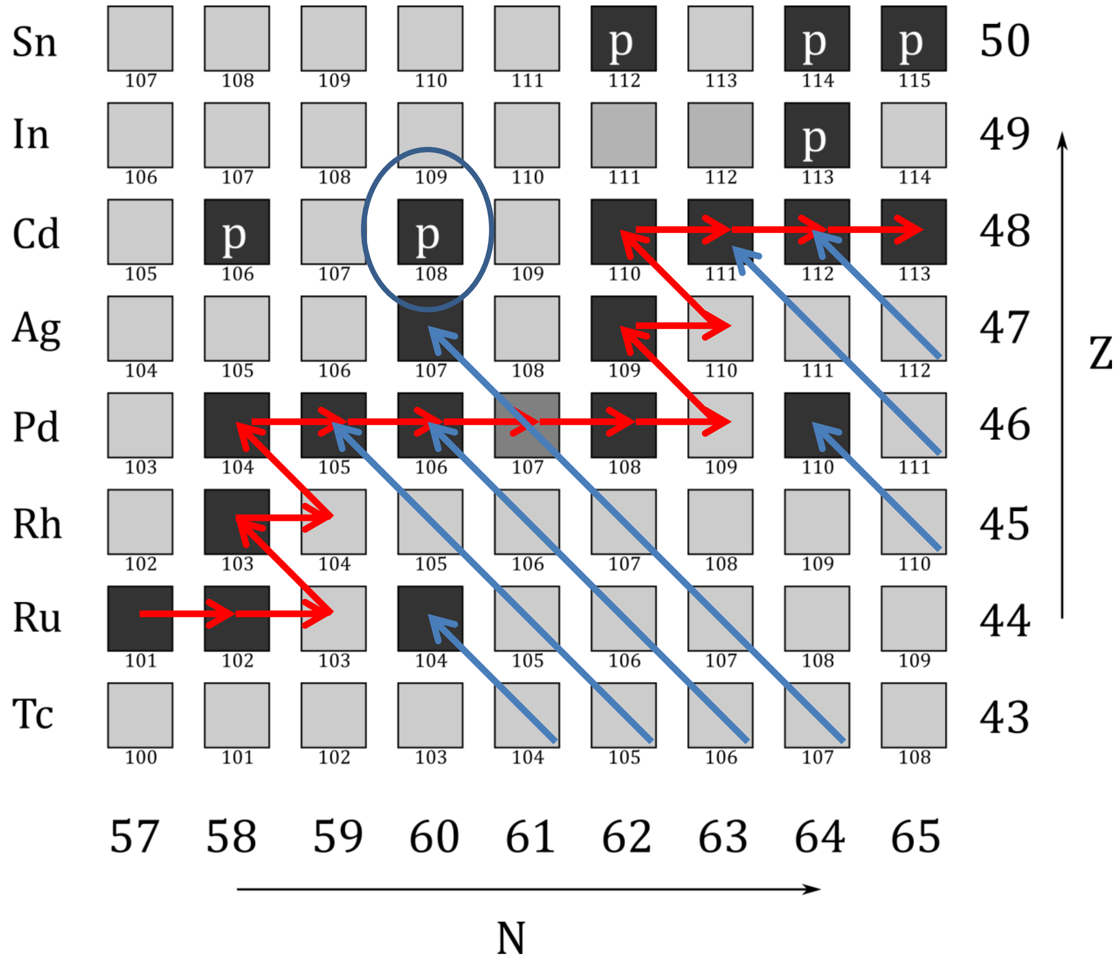
Contents

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**
  ($\rho_n = 10^8$ cm^{-3}, $t_n \sim 10^3$ y)
- ***r* process**
  ($\rho_n = 10^{20}$-10^{25} cm^{-3}, $t_n \sim 1$ s)
- The ***p nuclei*** cannot be synthesized via the above two processes

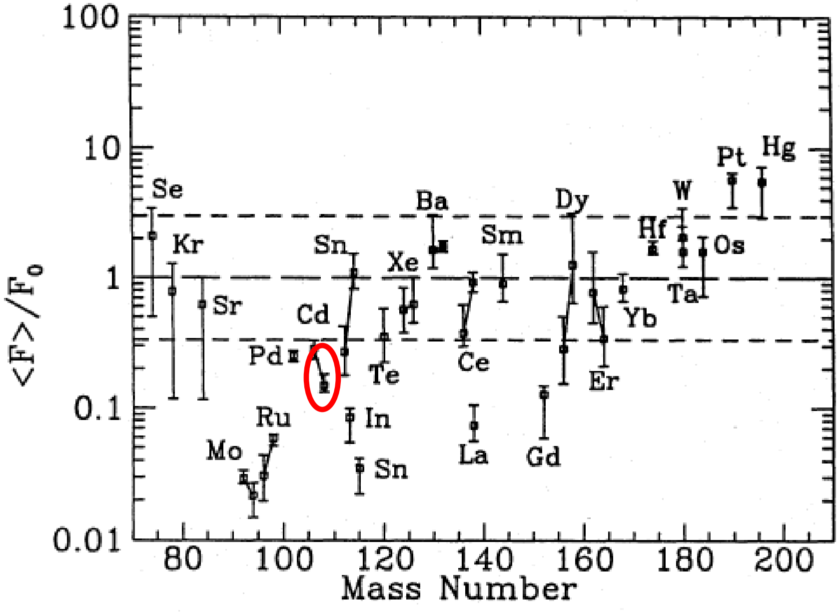


p process

- 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 (γ, n), (γ, p), (γ, α) photodisintegration reactions as well as capture reactions: (p,γ), (n,γ) , (a,γ), along with β^+ decays and electron captures

Why focus on the reactions $^{nat}Ag(p,\gamma)^{108,110}Cd$?

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



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

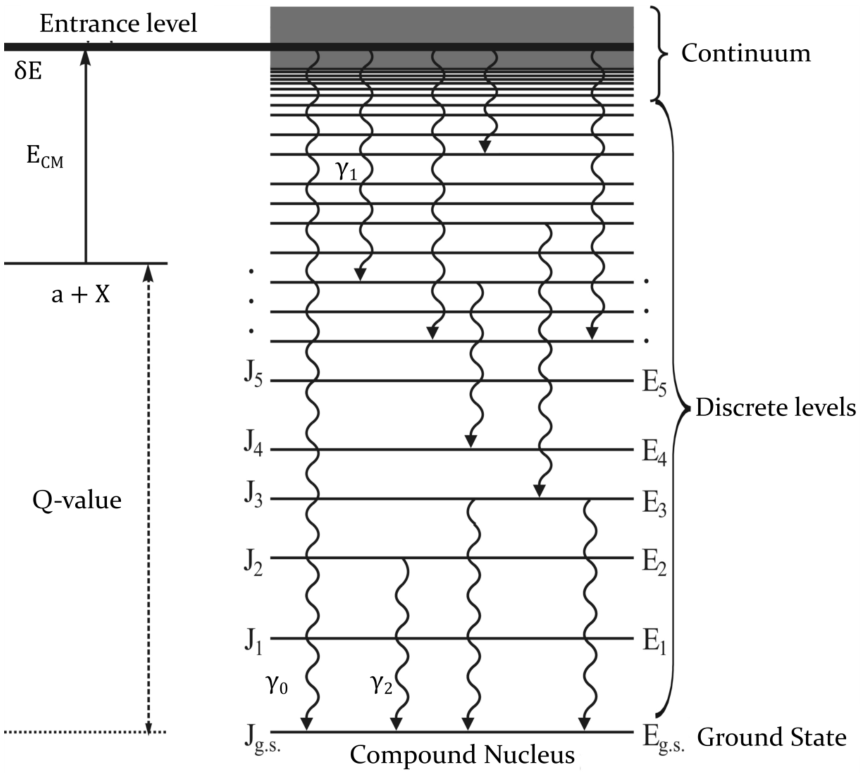
- Cross section measurements of proton capture reactions (p,γ) as well as of their inverse reactions (γ,p) are important for the study of the *p* process

The Hauser-Feshbach model

$$\underbrace{\mathrm{a} + \mathrm{X}}_{\alpha} \rightarrow \mathrm{C}^* \rightarrow \underbrace{\mathrm{C} + \gamma}_{\beta}$$

- 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,γ) reaction, the exit channel transmission coefficient is determined by the **γ-ray strength function**.



$$\sigma_{\alpha\beta} = \pi \lambda_\alpha^2 \frac{1}{(2i_\alpha + 1)(2I_\alpha + 1)} \sum_{J,\pi} (2J^\pi + 1) \frac{T^{J^\pi}(\alpha) T^{J^\pi}(\beta)}{\sum_e T^{J^\pi}(e)}$$

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:

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

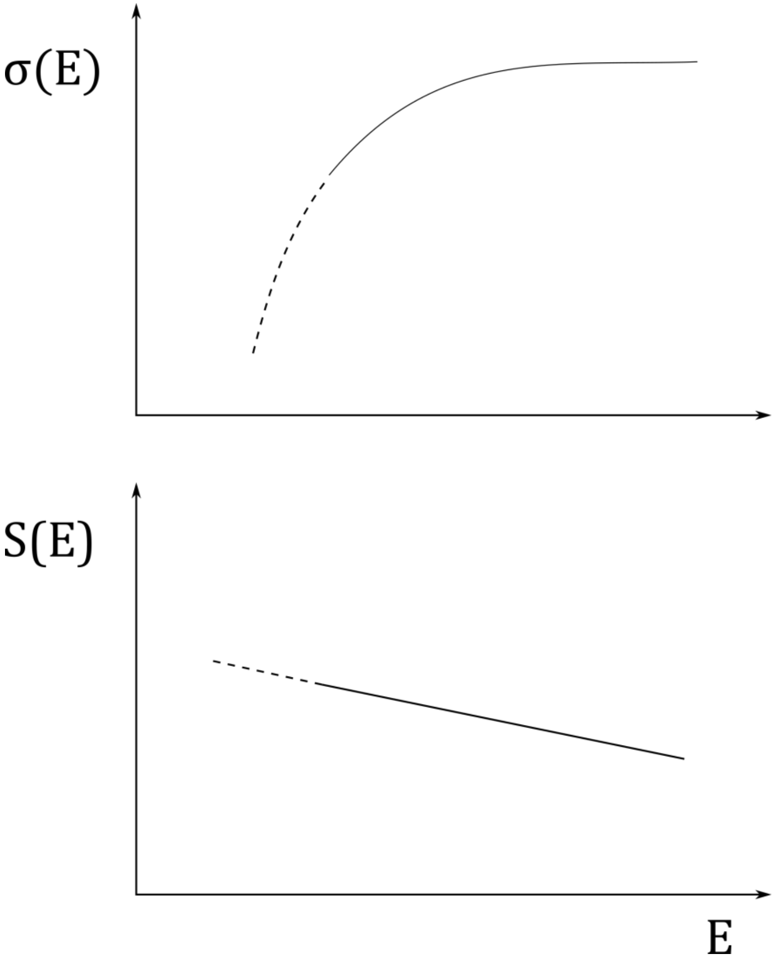
Also:

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

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

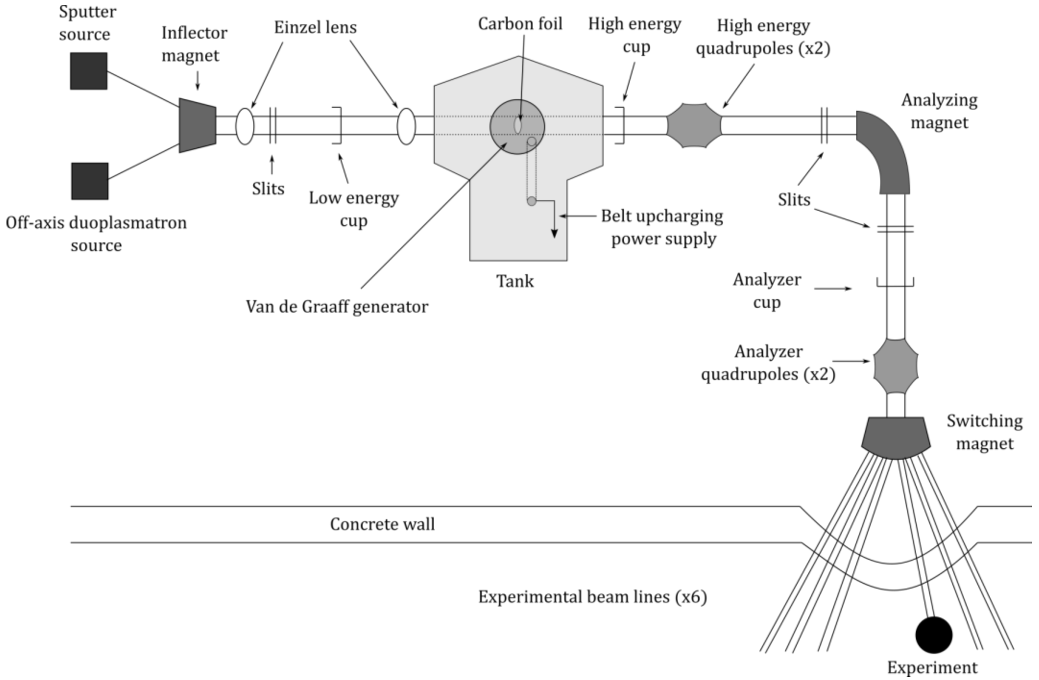
$$S(E) = E\sigma(E)\exp(2\pi\eta)$$

- 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"

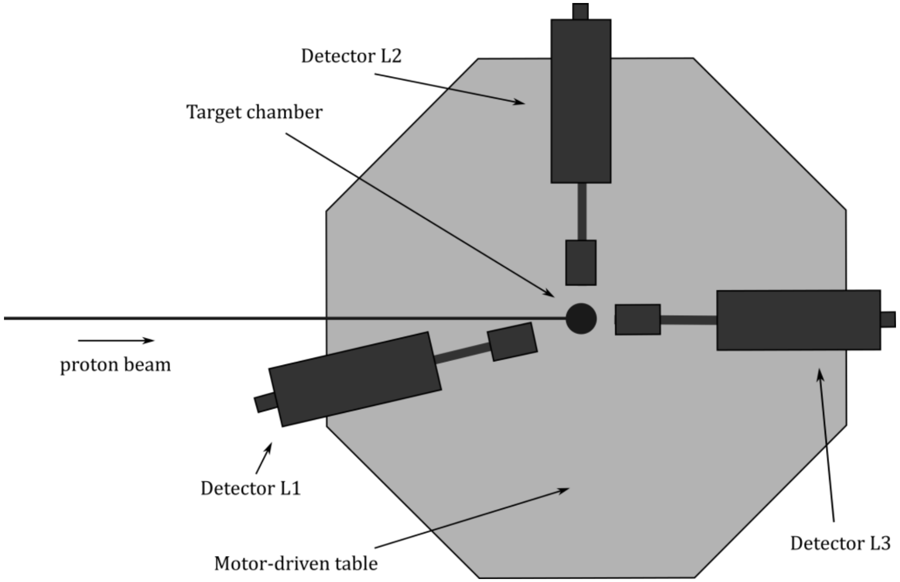
5.5 MV Tandem Accelerator
N.C.S.R. Demokritos.
$E_p \approx 300$ keV – 10 MeV.

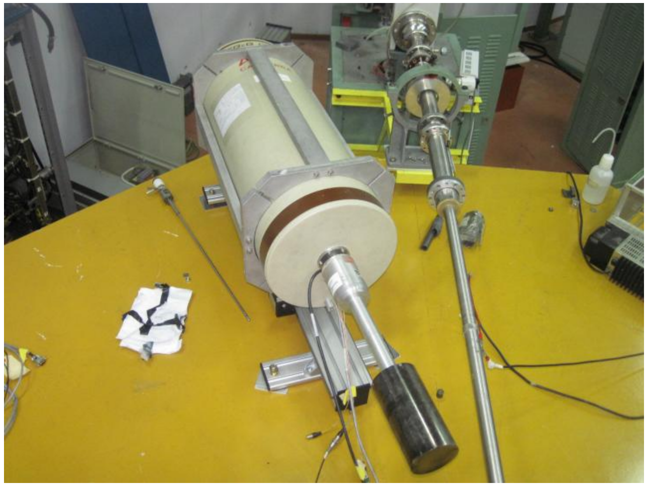


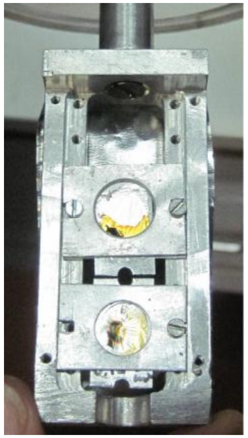
Detector Setup

Three HPGe detectors (100% rel. efficiency)

Detector	Angle [deg]	Distance [cm]
L1	165	20
L2	90	20
L3	0	30







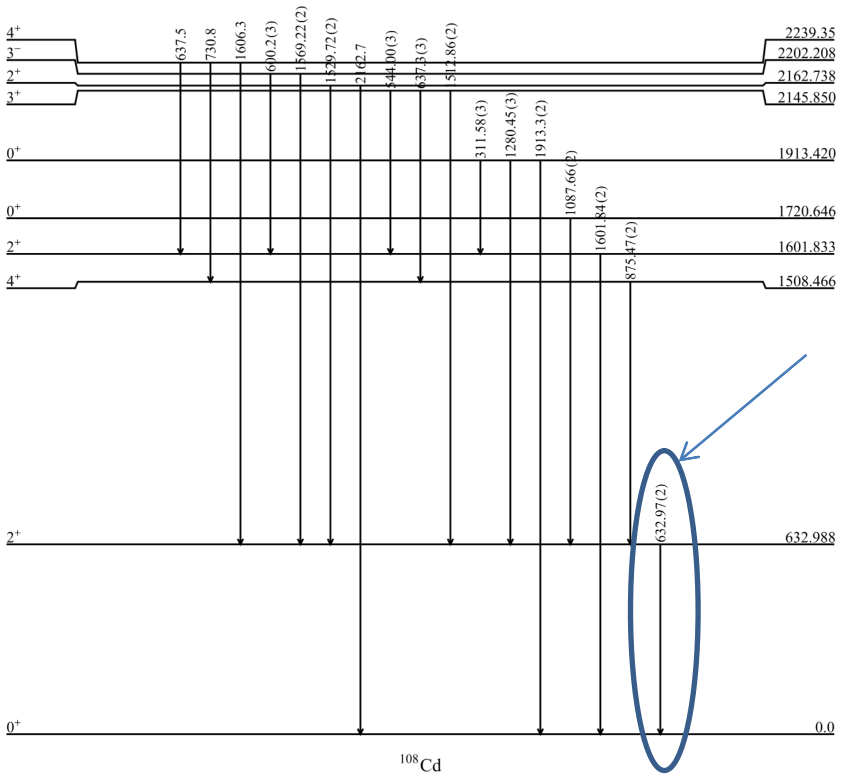
Gamow windows for the reactions $^{nat}Ag(p,\gamma)^{108,110}Cd$

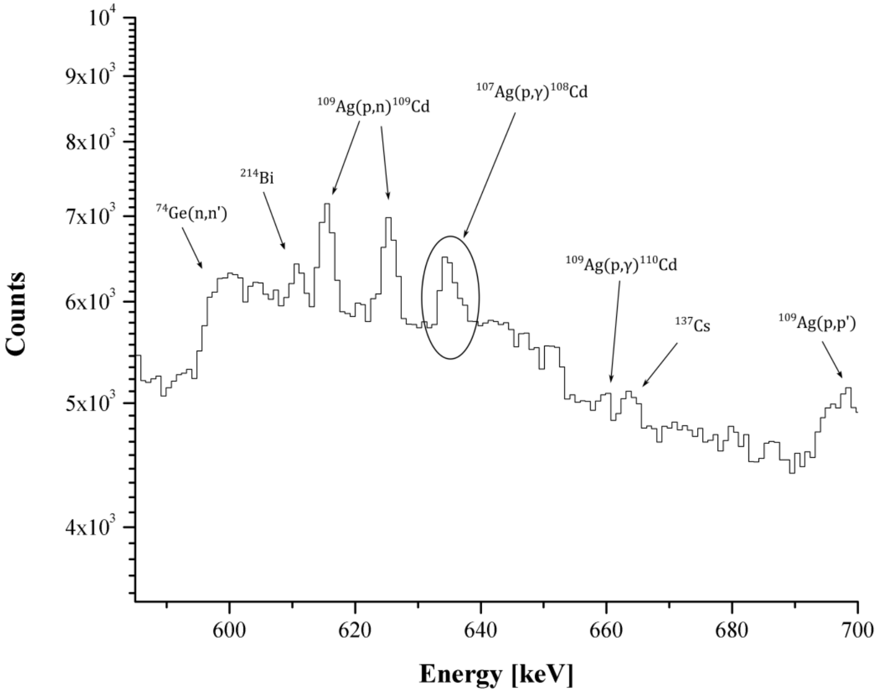
Beam energies studied: 2.2, 3.5, 4 MeV

Isotope	m_X [amu]	m_{aX} [amu]	T_9	E_0 [MeV]	Δ [MeV]	E^p_{min} (LAB) [MeV]	E^p_{max} (LAB) [MeV]
^{107}Ag	106.905093	0.998413	1.7	2.263	1.331	**1.613**	2.957
			3.3	3.522	2.313	2.388	**4.723**
^{109}Ag	108.904756	0.998584	1.7	2.265	1.331	**1.613**	2.956
			3.3	3.522	2.313	2.388	**4.722**

The reaction ^{107}Ag(p,γ)^{108}Cd

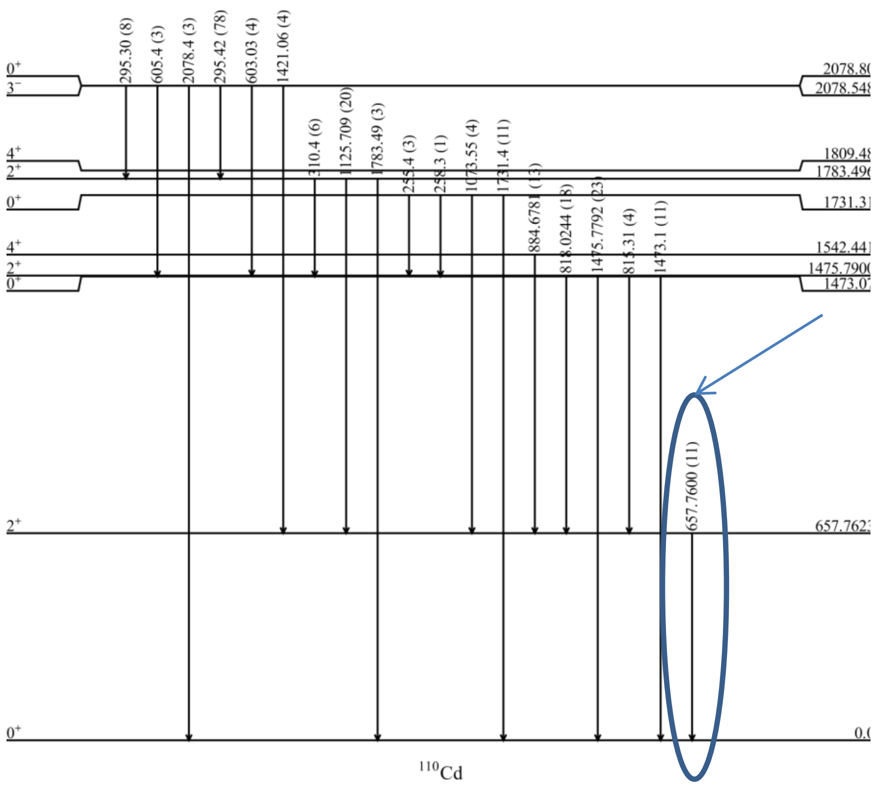
Level Scheme of ^{108}Cd

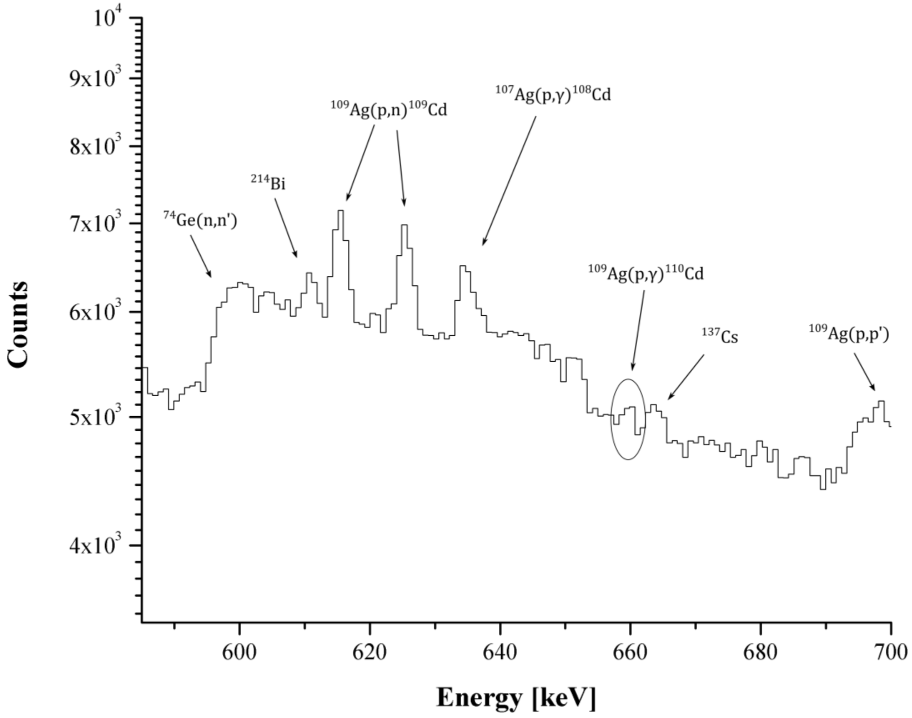




The reaction $^{109}Ag(p,\gamma)^{110}Cd$

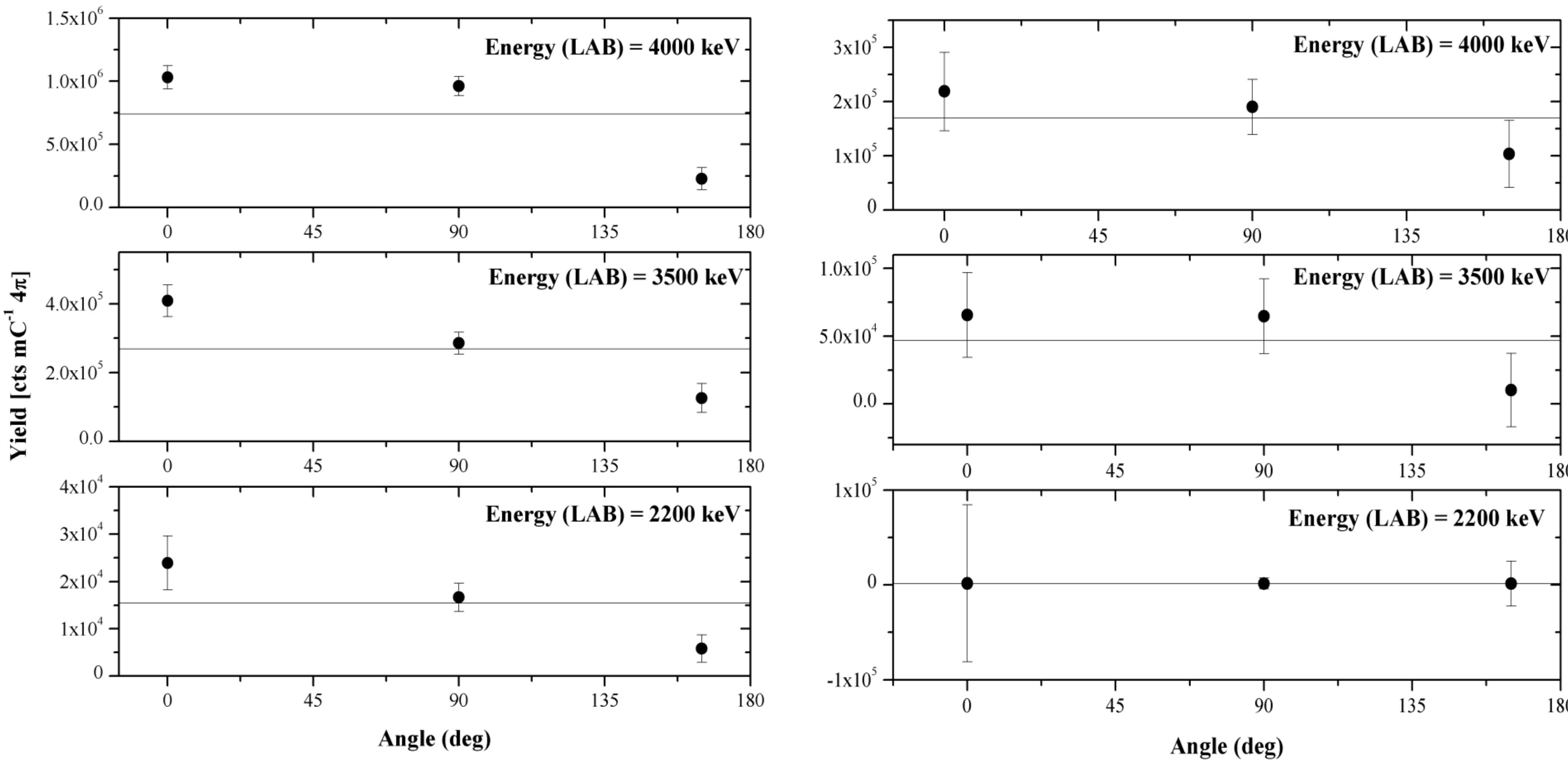
Level Scheme of ^{110}Cd





Angular Distributions

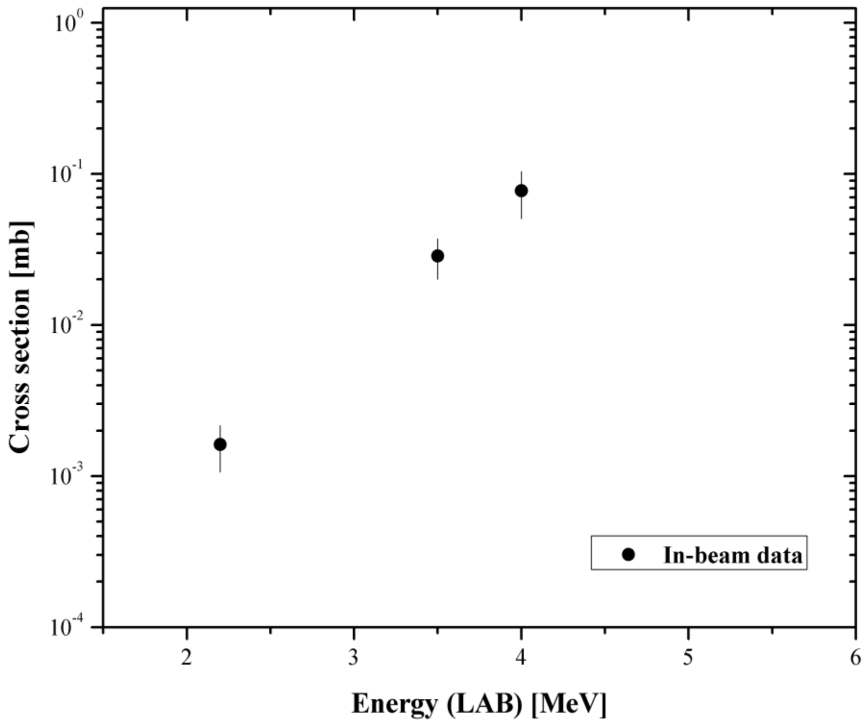
$^{107}Ag(p,\gamma)^{108}Cd$ $^{109}Ag(p,\gamma)^{110}Cd$



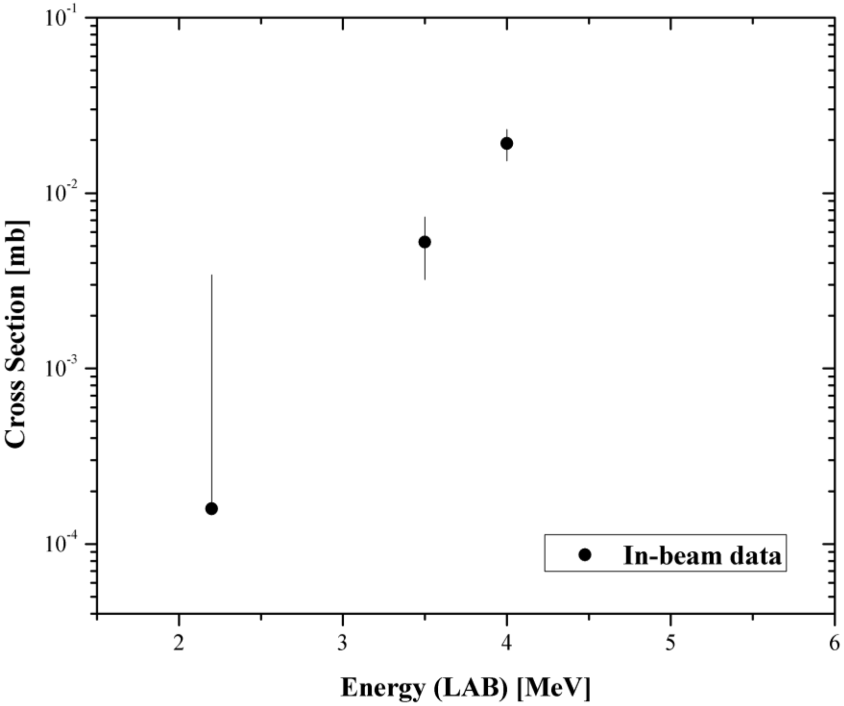
$$W(\theta) = A_0(1 + a_2 P_2(\cos\theta) + a_4 P_4(\cos\theta) + \ldots)$$

Results

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



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



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

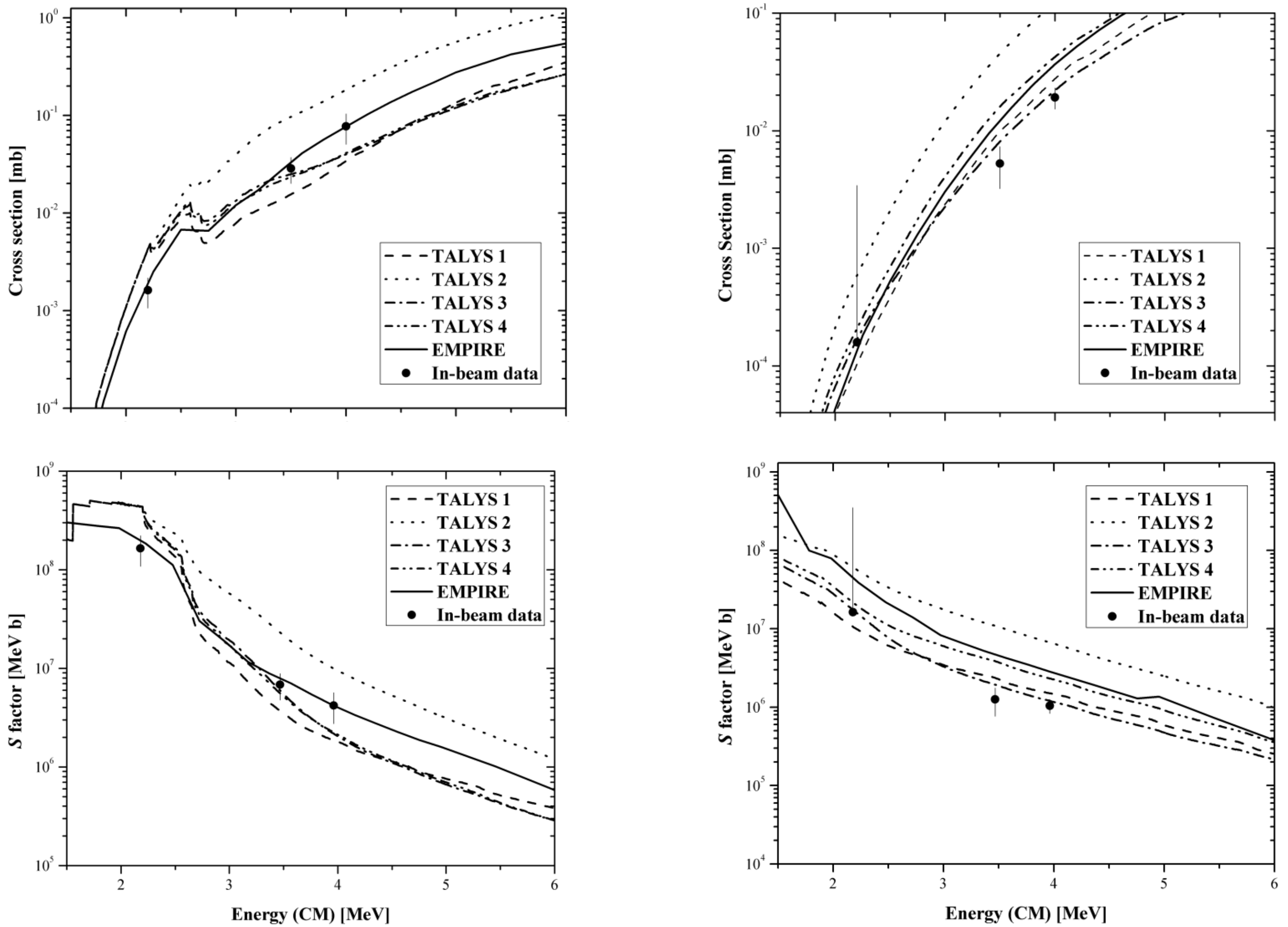
Theoretical nuclear models

- 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

Combination	Optical Potential Model	Nuclear Level Density Model	γ-ray strength function model
TALYS 1	Koning-Delaroche	CTM	Kopecky-Uhl
TALYS 2	Bauge-Delaroche-Girod	Demetriou-Goriely	Hartree-Fock-BCS
TALYS 3	Bauge-Delaroche-Girod	Goriely-Hilaire	Hartree-Fock-Bogolyubov
TALYS 4	Bauge-Delaroche-Girod	Temperature Dependent HFB	Goriely's Hybrid Model
EMPIRE	Koning-Delaroche	EGSM	Plujko MLO1

Results

$^{107}Ag(p,\gamma)^{108}Cd$ | $^{109}Ag(p,\gamma)^{110}Cd$



- An attempt to measure cross sections and *S*-factors of the reactions $^{nat}Ag(p,\gamma)^{108,\,110}Cd$, 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

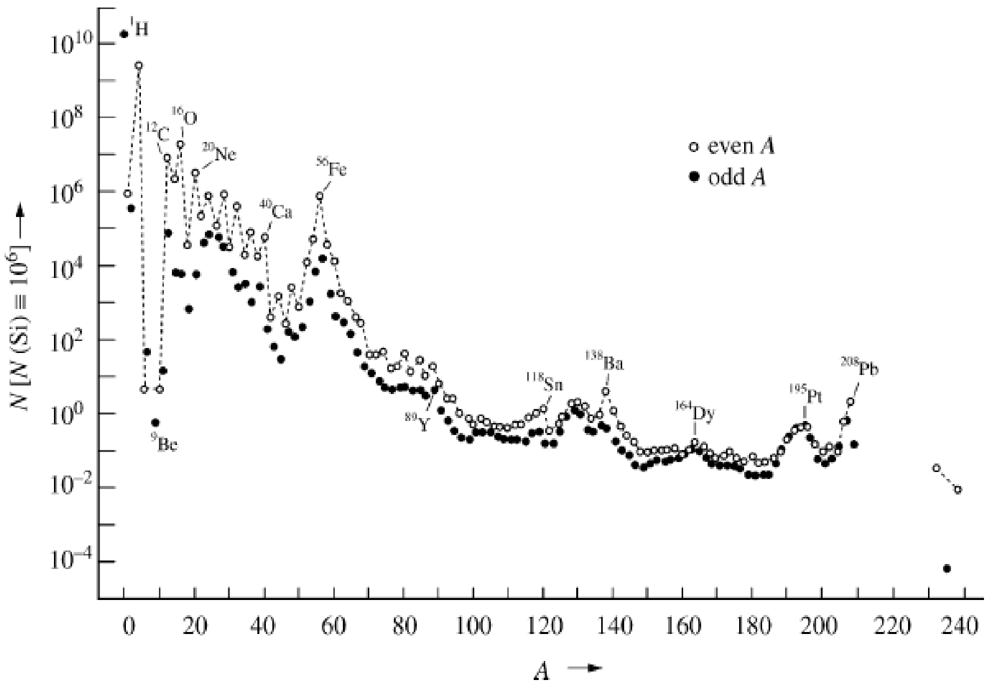
Acknowledgement

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

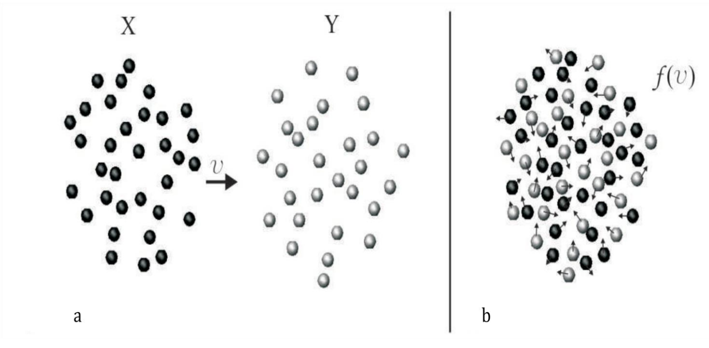


Palme H. and Beer H. (1993)

Question:
How did the elements-isotopes form?

Abundance evolution and reaction networks

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



$$\langle\sigma\upsilon\rangle_{jk} = \left(\frac{8}{\pi m_{jk}}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty E\sigma(E) e^{-E/kT} dE$$

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

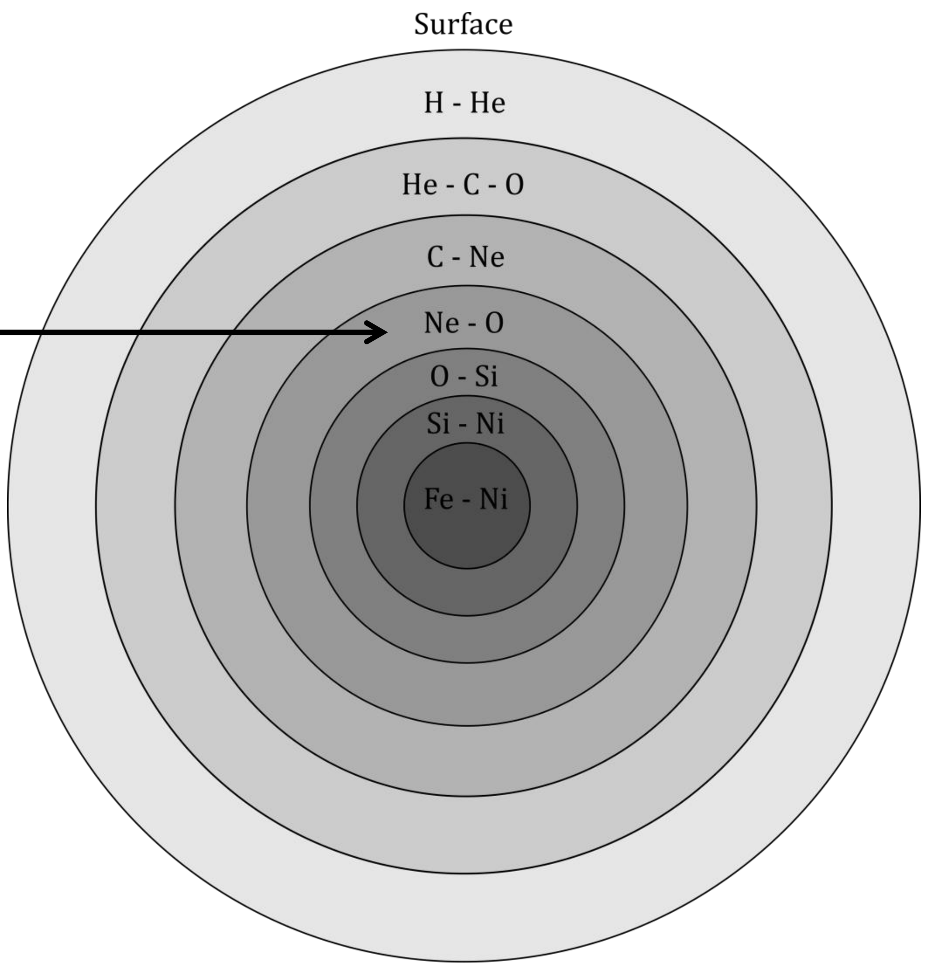
Astrophysical Sites

- 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:

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

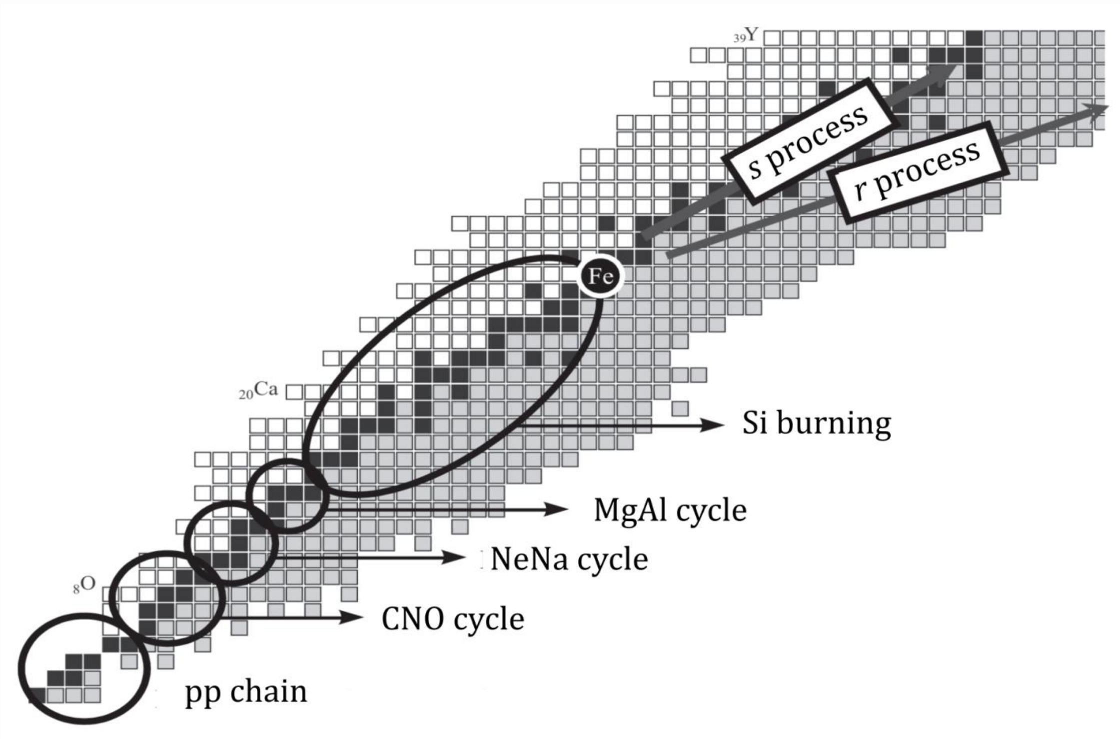
- Other astrophysical sites: Supernovae Type Ia, Ib/Ic etc.



Nucleosynthetic Mechanisms

B²FH and Cameron:

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



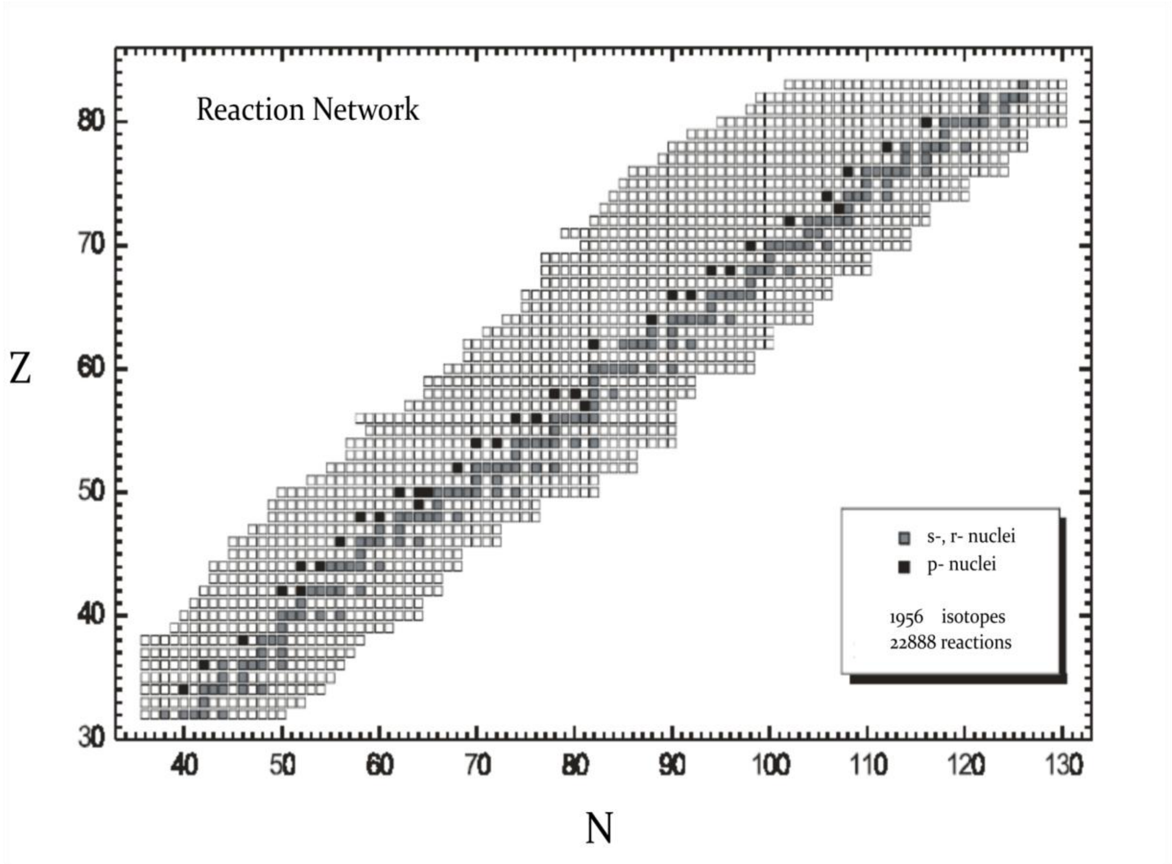
E. Margaret Burbidge, G. R. Burbidge, William A. Fowler, and F. Hoyle. Synthesis of the elements in stars. *Rev. Mod. Phys.*, 29:547, 1957.

A. G. W. Cameron. Nuclear reactions in stars and nucleogenesis. *Pub. Astron. Soc. Pac.*, 69:201, 1957.

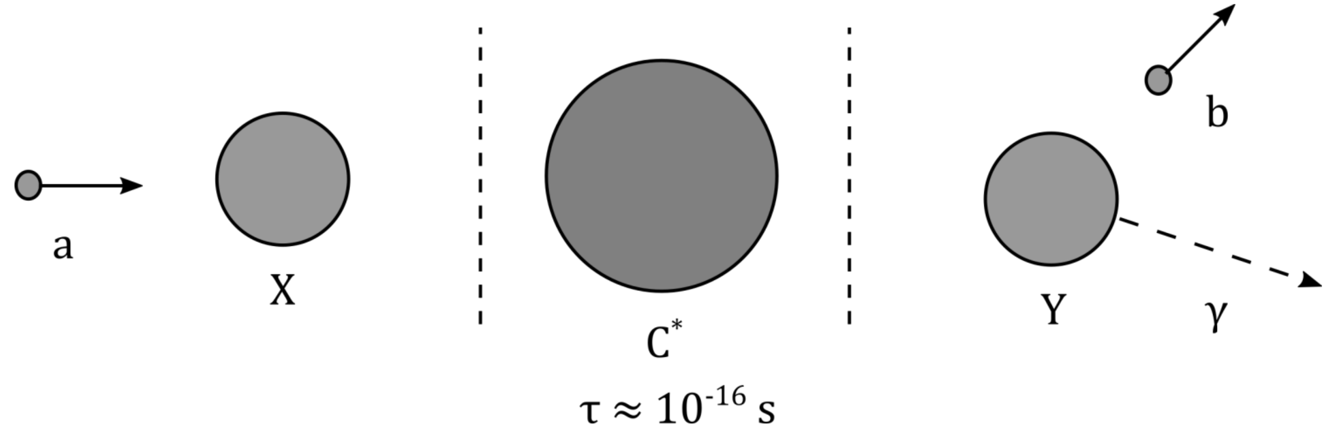
Reaction network for the p process

- The p process network invovles 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

$$\boxed{\sigma_{\alpha\beta} = \sigma_{\rm CN}(\alpha) P_\beta}$$

Gamow formalism

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

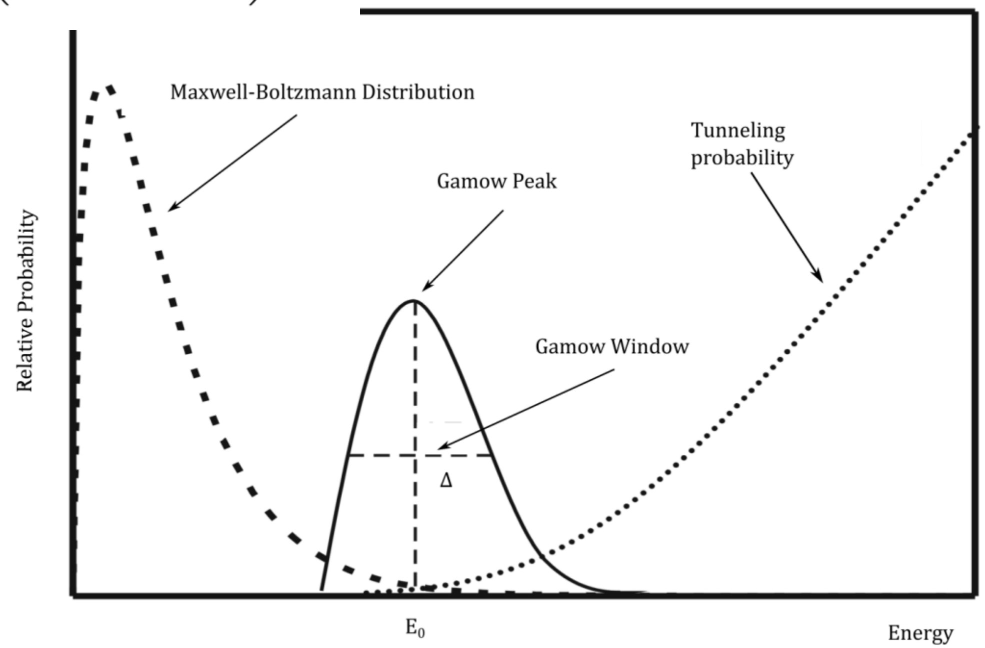
For non-resonant reactions, the *S* factor is constant over a small energy interval:

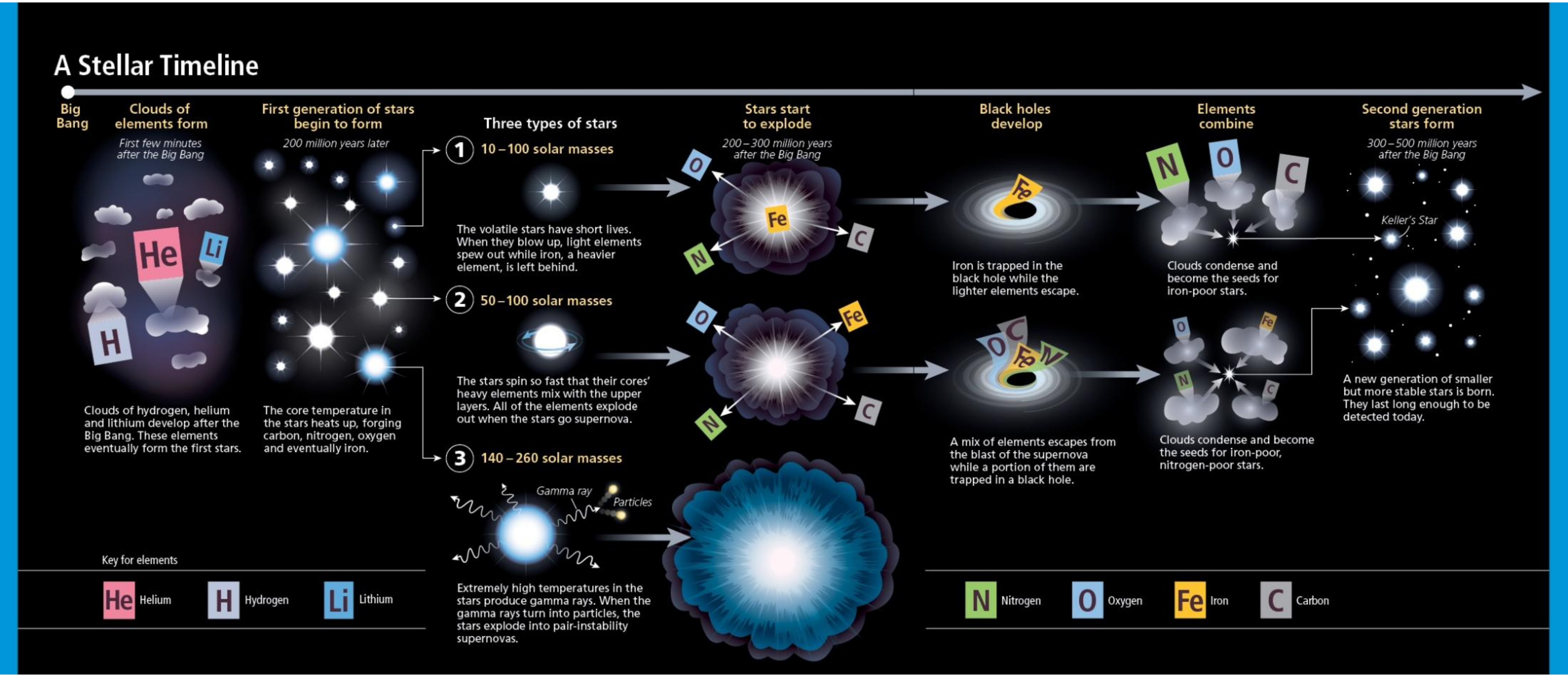
$$\langle \sigma v \rangle_{\mathrm{aX}} = \left(\frac{8}{\pi m_{\mathrm{aX}}}\right)^{1/2} \frac{1}{(kT)^{3/2}} S(E_0) \int_0^\infty \exp\left(-\frac{E}{kT} - \frac{b}{E^{1/2}}\right) dE$$

The Gamow distribution can be approximated with a Gaussian:

$$E_0 = \left(\frac{bkT}{2}\right)^{2/3} = 0.122(Z_{\mathrm{a}}^2 Z_{\mathrm{X}}^2 m_{\mathrm{aX}} T_9^2)^{1/3} \text{ MeV}$$

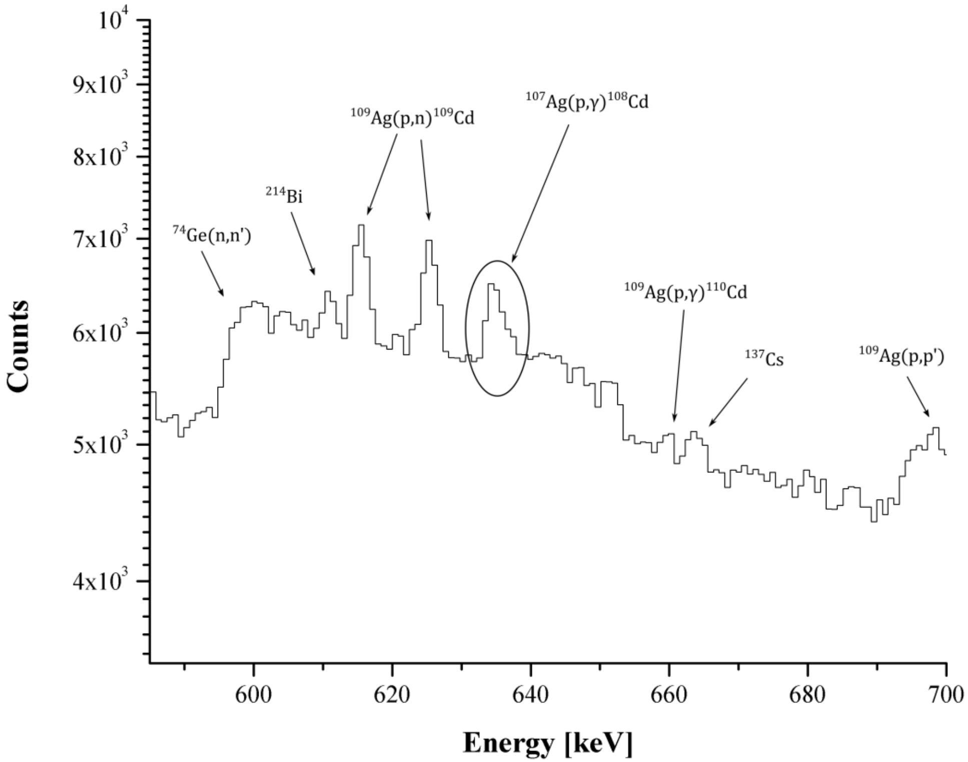
$$\Delta = \frac{4}{3^{1/2}}(E_0 kT)^{1/2} = 0.237(Z_{\mathrm{a}}^2 Z_{\mathrm{X}}^2 m_{\mathrm{aX}} T_9^5)^{1/6} \text{ MeV}$$




A Stellar Timeline
Big Bang
Clouds of elements form
First few minutes after the Big Bang
First generation of stars begin to form
200 million years later
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
Gamma ray
Particles
Extremely high temperatures in the stars produce gamma rays. When the gamma rays turn into particles, the stars explode into pair-instability supernovas.
Stars start to explode
200 – 300 million years after the Big Bang
Black holes develop
Iron is trapped in the black hole while the lighter elements escape.
A mix of elements escapes from the blast of the supernova while a portion of them are trapped in a black hole.
Elements combine
Clouds condense and become the seeds for iron-poor stars.
Clouds condense and become the seeds for iron-poor, nitrogen-poor stars.
Second generation stars form
300 – 500 million years after the Big Bang
Keller's Star
A new generation of smaller but more stable stars is born. They last long enough to be detected today.
Clouds of hydrogen, helium and lithium develop after the Big Bang. These elements eventually form the first stars.
The core temperature in the stars heats up, forging carbon, nitrogen, oxygen and eventually iron.
Key for elements
He Helium
H Hydrogen
Li Lithium
N Nitrogen
O Oxygen
Fe Iron
C Carbon

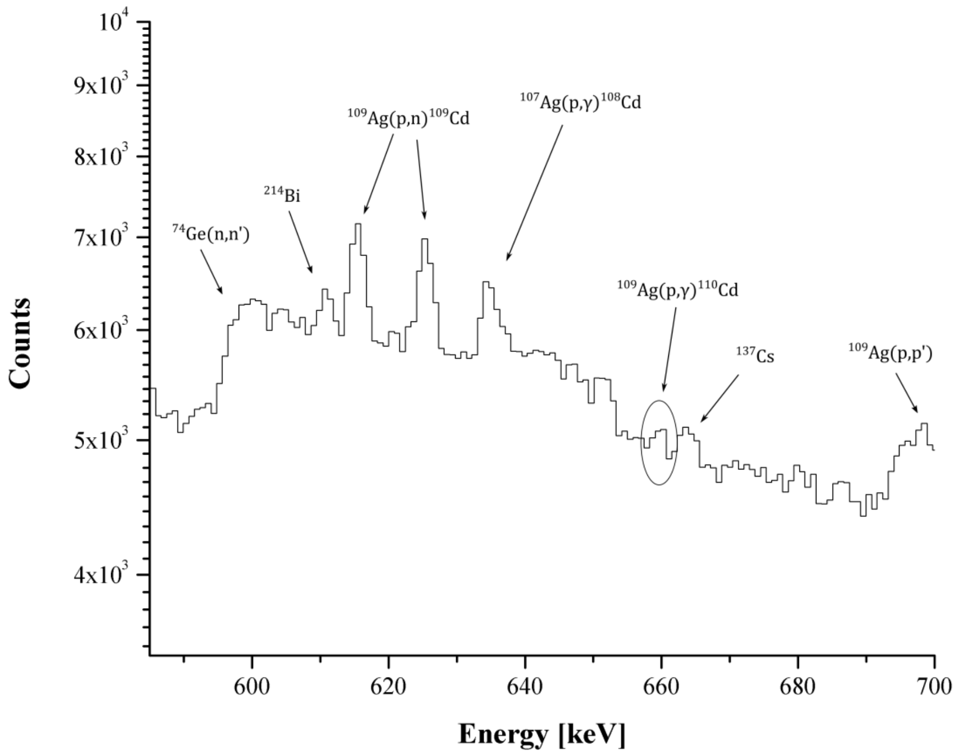
The reaction $^{107}Ag(p,\gamma)^{108}Cd$

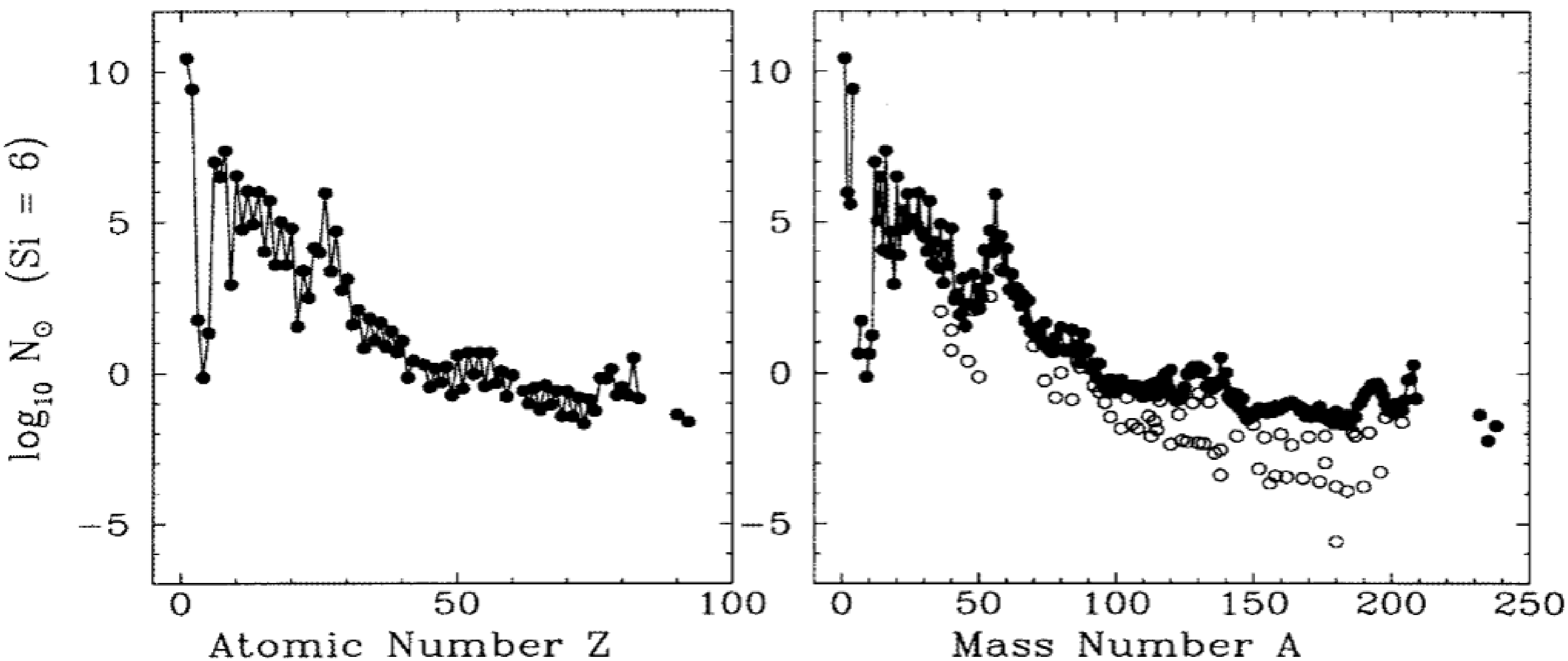
- Measurement of the photopeak corresponding to the transition: $2^+ \rightarrow 0^+$, for every angle: 0°, 90°, 165°
- Determination of the angular distribution of the reaction
- Determination of the cross section and *S* factor



The reaction ^{109}Ag(p,γ)^{110}Cd

- Μέτρηση της φωτοκορυφής που αντιστοιχεί στη μετάπτωση: $2^{+} \rightarrow 0^{+}$, για τις γωνίες: 0°, 90 °, 165 °.
- Προσδιορισμός της γωνιακής κατανομής της για κάθε ενέργεια δέσμης.
- Υπολογισμός της ενεργού διατομής και του αστροφυσικού παράγοντα.



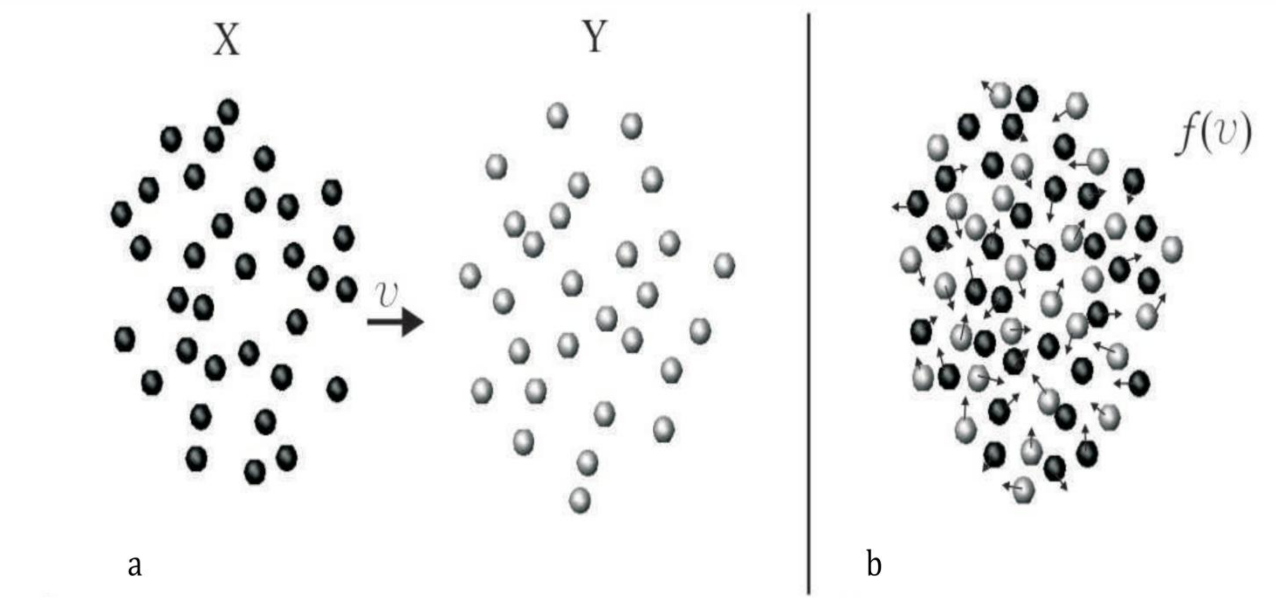


log$_{10}$ N$_\odot$ (Si = 6)
10
5
0
−5
0
50
100
Atomic Number Z
10
5
0
−5
0
50
100
150
200
250
Mass Number A

Reaction rate

- For a reaction a + X → 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.

$$\langle \sigma \upsilon \rangle_{aX} = \left(\frac{8}{\pi m_{aX}} \right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty E \sigma(E) e^{-E/kT} dE$$



Evaluation of the cross section and S-factor

$$\sigma \equiv \frac{(\mathcal{N}_R/t)}{[\mathcal{N}_{\mathrm{a}}/(tD)]\mathcal{N}_{\mathrm{X}}}$$

$$S(E) = E\sigma(E)\exp\left(0.9895 Z_p Z_t \sqrt{\frac{m_{\mathrm{aX}}}{E}}\right)$$

$$\downarrow$$

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

$$S(E) = E\sigma(E)\exp\left(0.9934 Z_t \sqrt{\frac{m_{\mathrm{X}}}{(m_{\mathrm{X}}+1.007825)E}}\right)$$

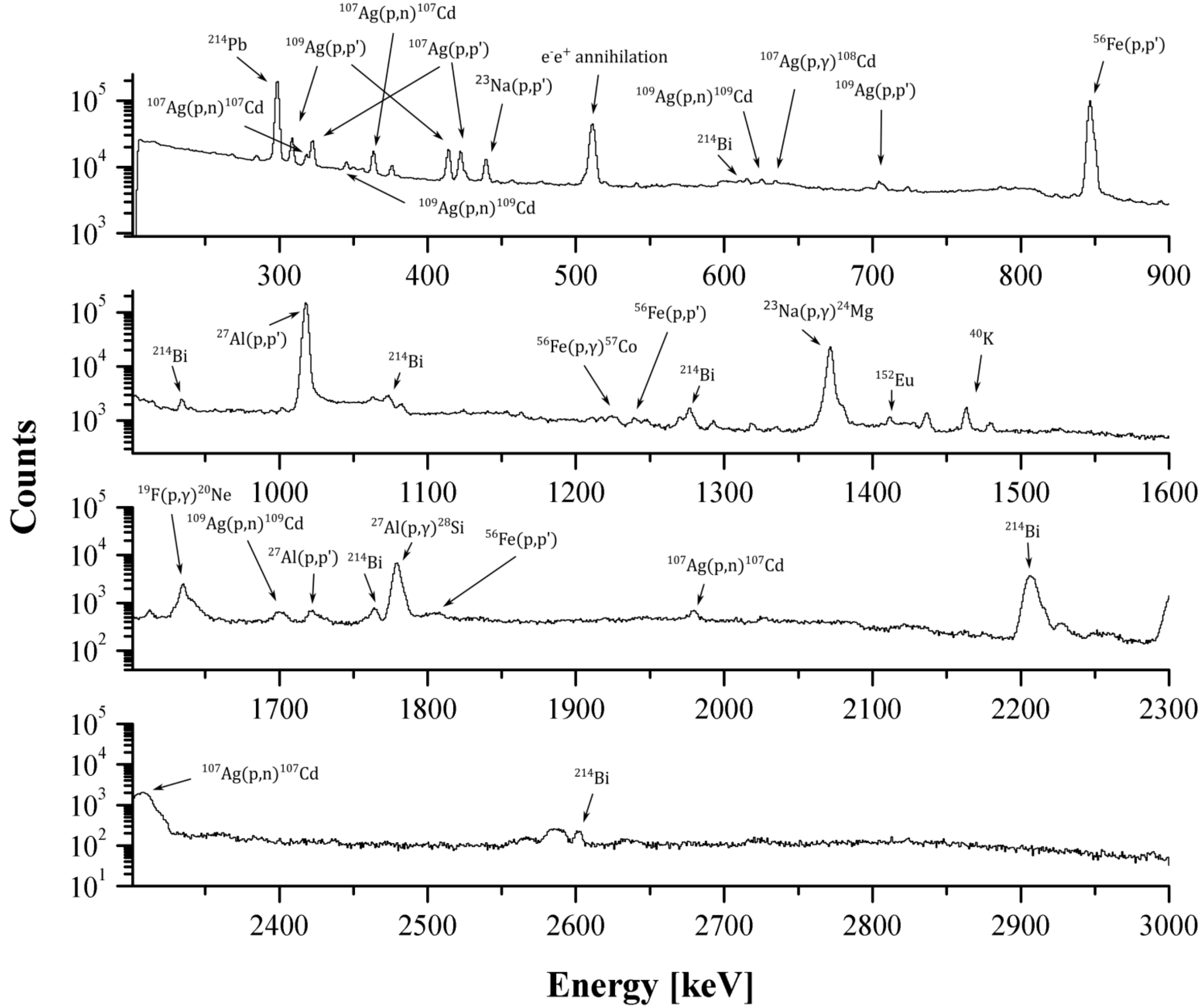
$$Y(E_i^{\gamma}, E_j^{p}, \theta_k) = \frac{N(E_i^{\gamma}, E_j^{p}, \theta_k)\omega(E_j^{p}, \theta_k)}{\epsilon_{abs} Q(E_j^{p})}$$

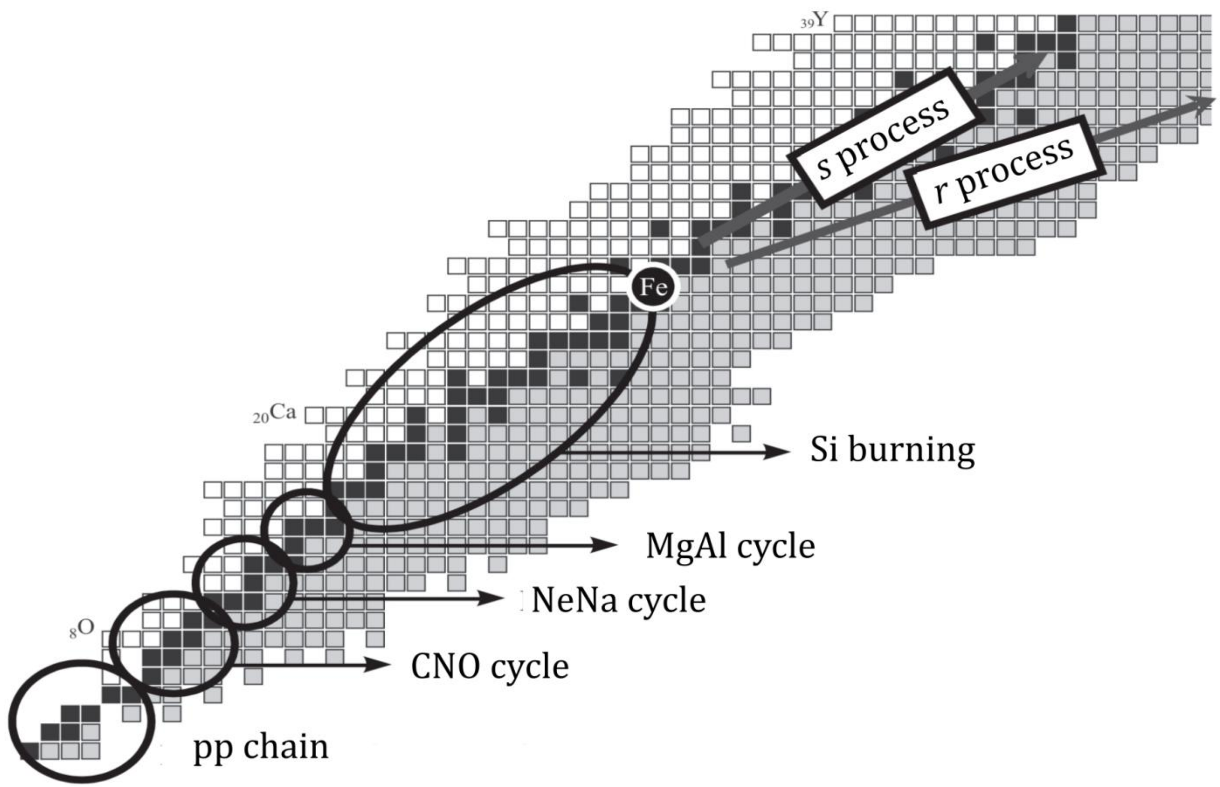
$$W(\theta) = A_0(1 + a_2 P_2(\cos\theta) + a_4 P_4(\cos\theta) + \dots)$$

$$\sigma = 2.6565 \times 10^{-10}\frac{A}{\xi}\sum_{i=1}^{N}(A_0)_i \quad \text{[barns]}$$

Spectra and angular distributions

Typical reaction spectrum at beam energy of 4 MeV, and angle of 90°.





39Y
s process
r process
Fe
20Ca
Si burning
MgAl cycle
NeNa cycle
8O
CNO cycle
pp chain

Πυρηνοσυνθετικοί Μηχανισμοί

B^{2}FH και Cameron:
• Τα στοιχεία δημιουργούνται στους αστέρες μέσω διαφόρων θερμοπυρηνικών αντιδράσεων.
• Θεμελίωση της θεωρίας της αστρικής πυρηνοσύνθεσης.

E. Margaret Burbidge, G. R. Burbidge, William A. Fowler, and F. Hoyle. Synthesis of the elements in stars. *Rev. Mod. Phys.*, 29:547, 1957.
A. G. W. Cameron. Nuclear reactions in stars and nucleogenesis. *Pub. Astron. Soc. Pac.*, 69:201, 1957.

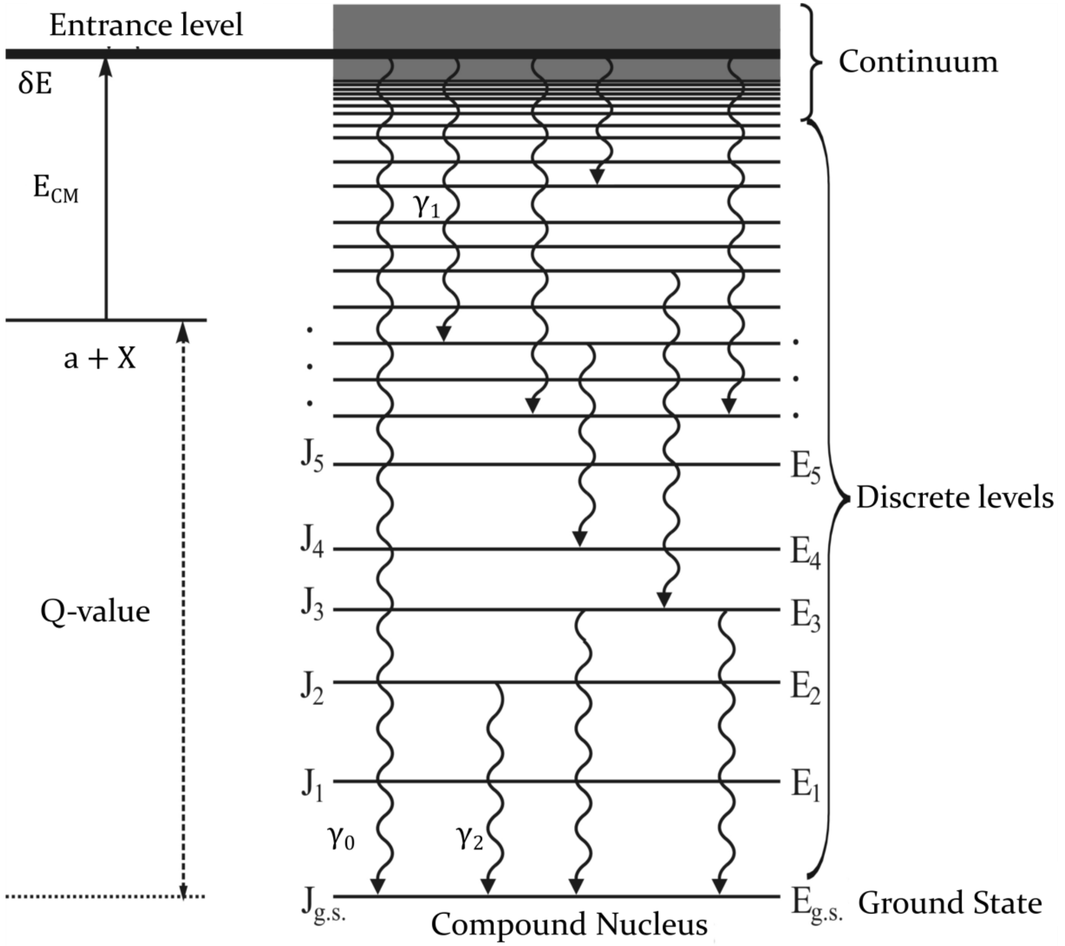
Σύνθεση ελαφρύτερων πυρήνων

- 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

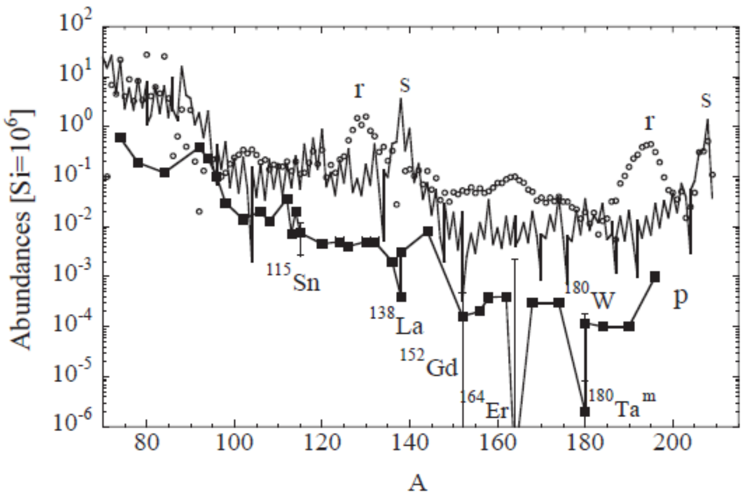
- *s* διεργασία
- *r* διεργασία
- *p* διεργασία

Σύνθετος πυρήνας για αντιδράσεις (p,γ)



Σχηματισμός του σύνθετου πυρήνα σε υψηλές ενέργειες διέγερσης. – Συνεχές.

$$E^* = E_{CM} + Q - \Delta E / 2$$



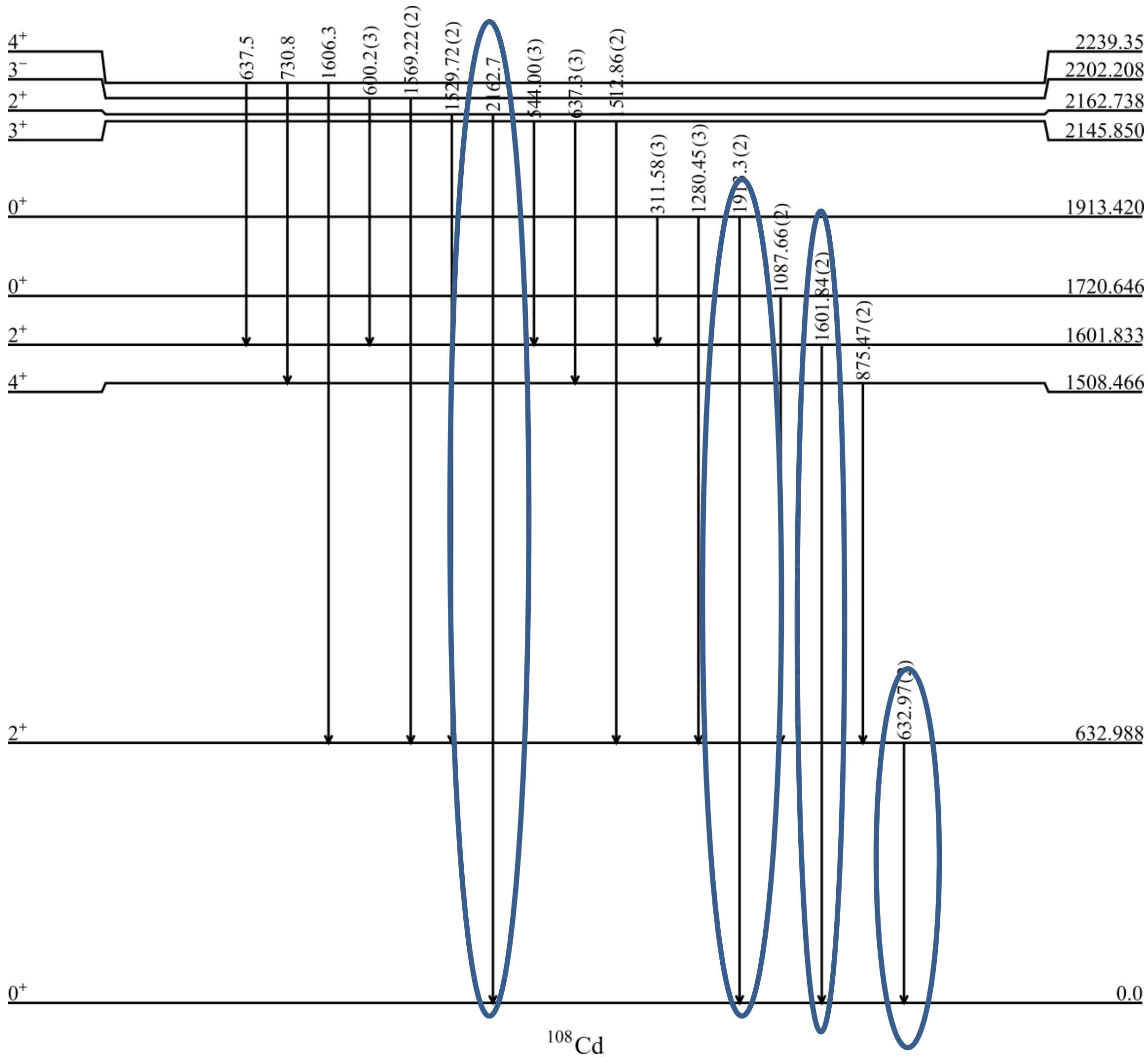
Μετρήσεις In-beam

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

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

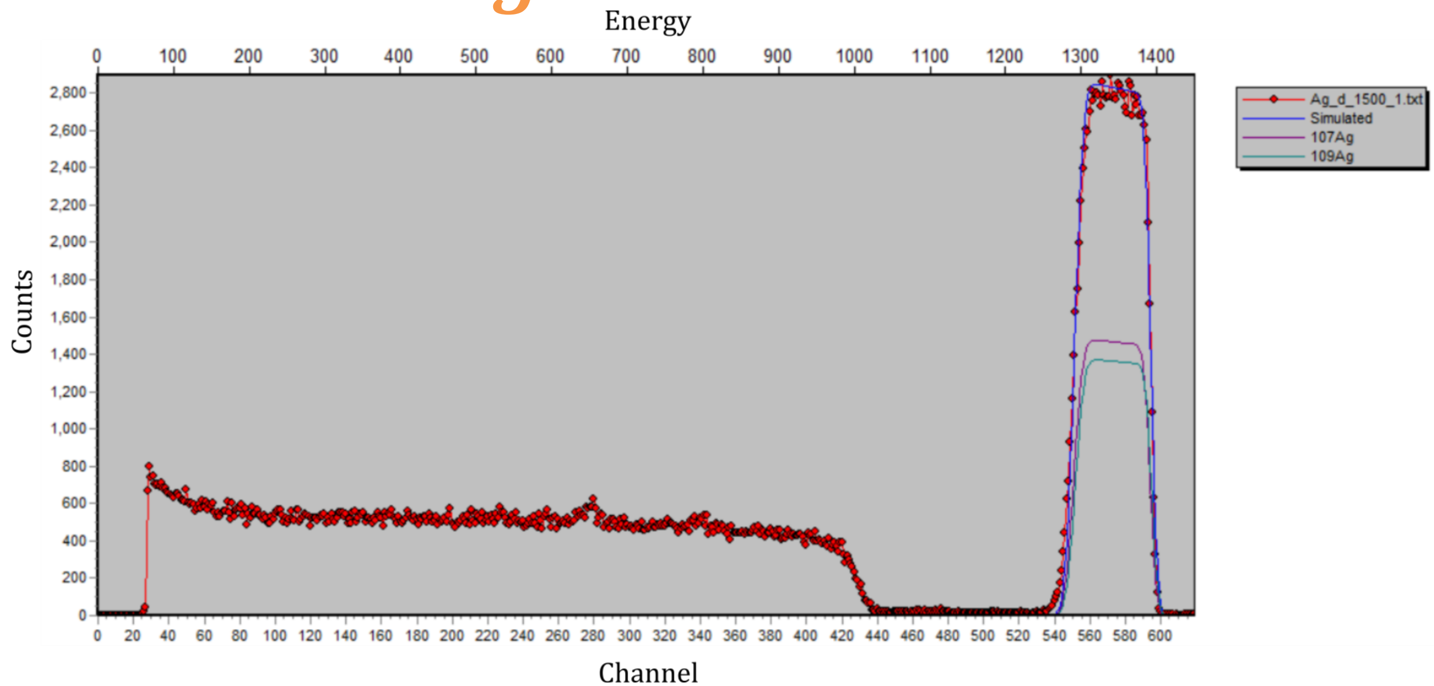
$$W(\theta) = A_0(1 + a_2 P_2(\cos\theta) + a_4 P_4(\cos\theta) + \ldots)$$

$$S(E) = E\sigma(E)\exp\left(0.9895 Z_{\mathrm{a}} Z_{\mathrm{X}} \sqrt{\frac{m_{\mathrm{aX}}}{E}}\right)$$



Target

- Target of ^{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.

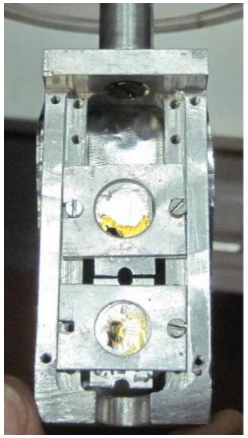


P. Tsavalas, 2015

x = 0.437 nm

$\xi = \rho\, x$ = 458 μg cm^{-2}

ξ_{nom} = 420 μg cm^{-2}



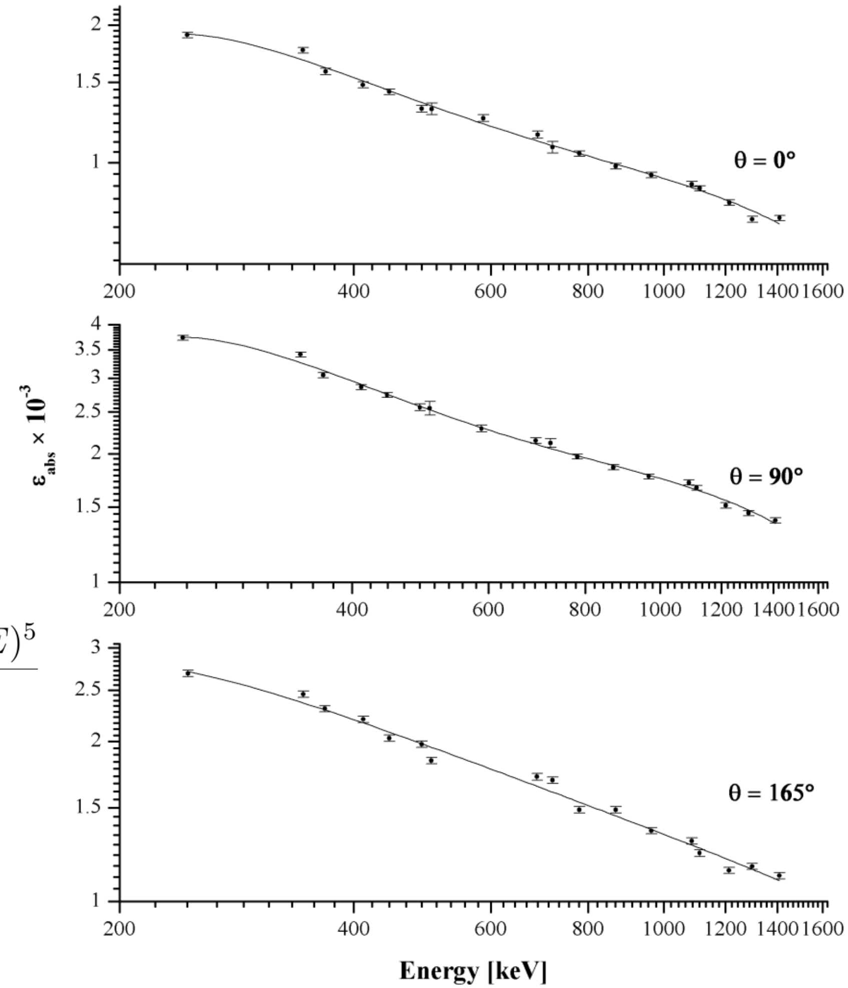
Absolute detector efficiencies

- 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:

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



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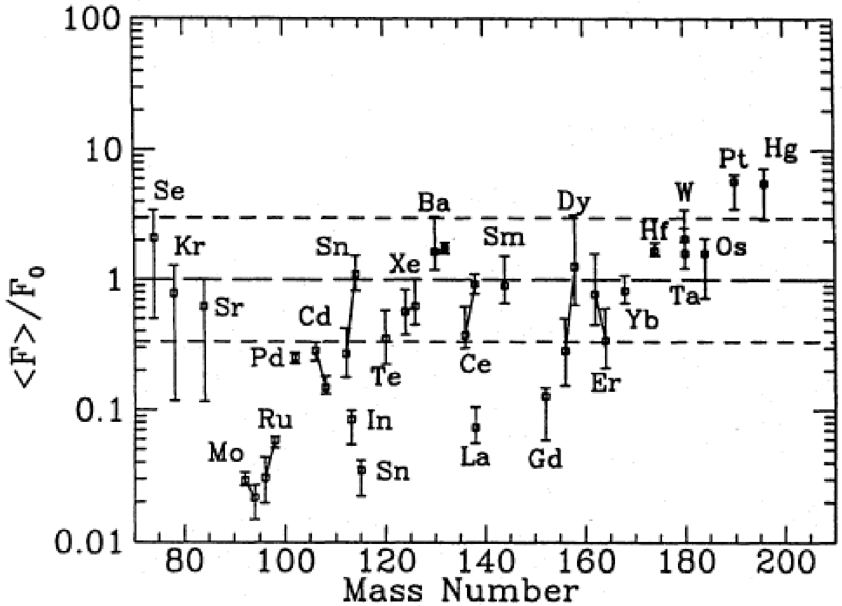
Abundances of p nuclei

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



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