Atomic mass spectroscopy for nuclear physics experiments with lasers

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Premise

Mass spectrometry is a very wide and complex field, that spans virtually all scientific disciplines.

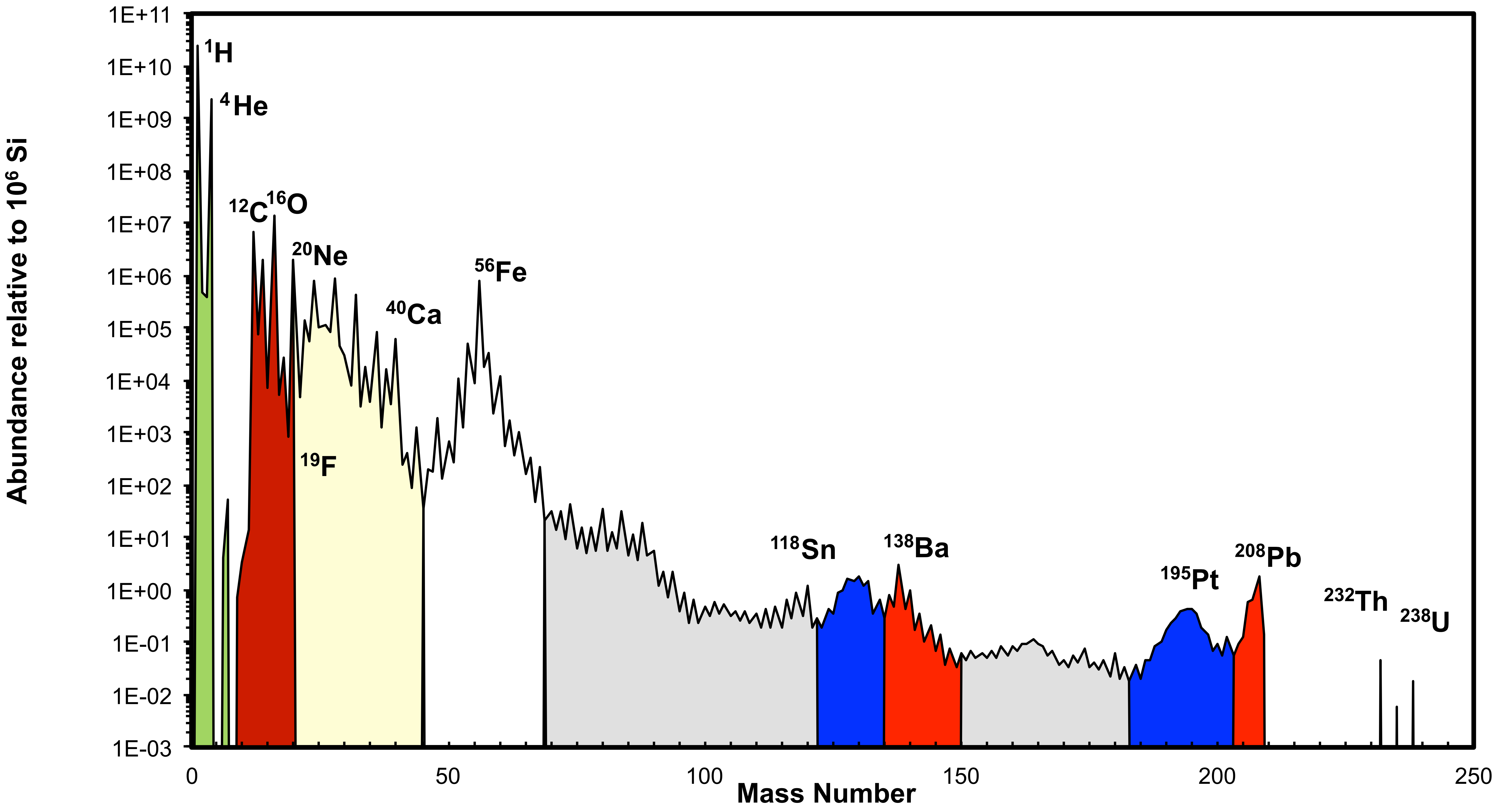
I'm not an expert in Mass Spectrometry in the widest sense, however throughout my research I used mass spectrometry for measurements in fundamental nuclear physics.

I will discuss some aspects mostly related to the possibility of using the highly ionized plasmas to study the variation of beta decay half-lives, relevant in Nuclear Astrophysics research.

Nuclear Astrophysics

Nuclear Astrophysics is the field that brings together Nuclear Physics and Astrophysics to understand how stars shine and produce the known elements (nucleosynthesis).

Stellar environments are quite often highly to full ionized environments.



Stellar Nucleosynthesis

- Complex problem
- Several stellar (hydro)dynamical processes to take into account
- Huge reaction networks, thousand nuclear processes need to be included to predict abundances of hundreds of nuclides (require reaction cross sections, decay rates that may depend on the local density and degree of ionization)

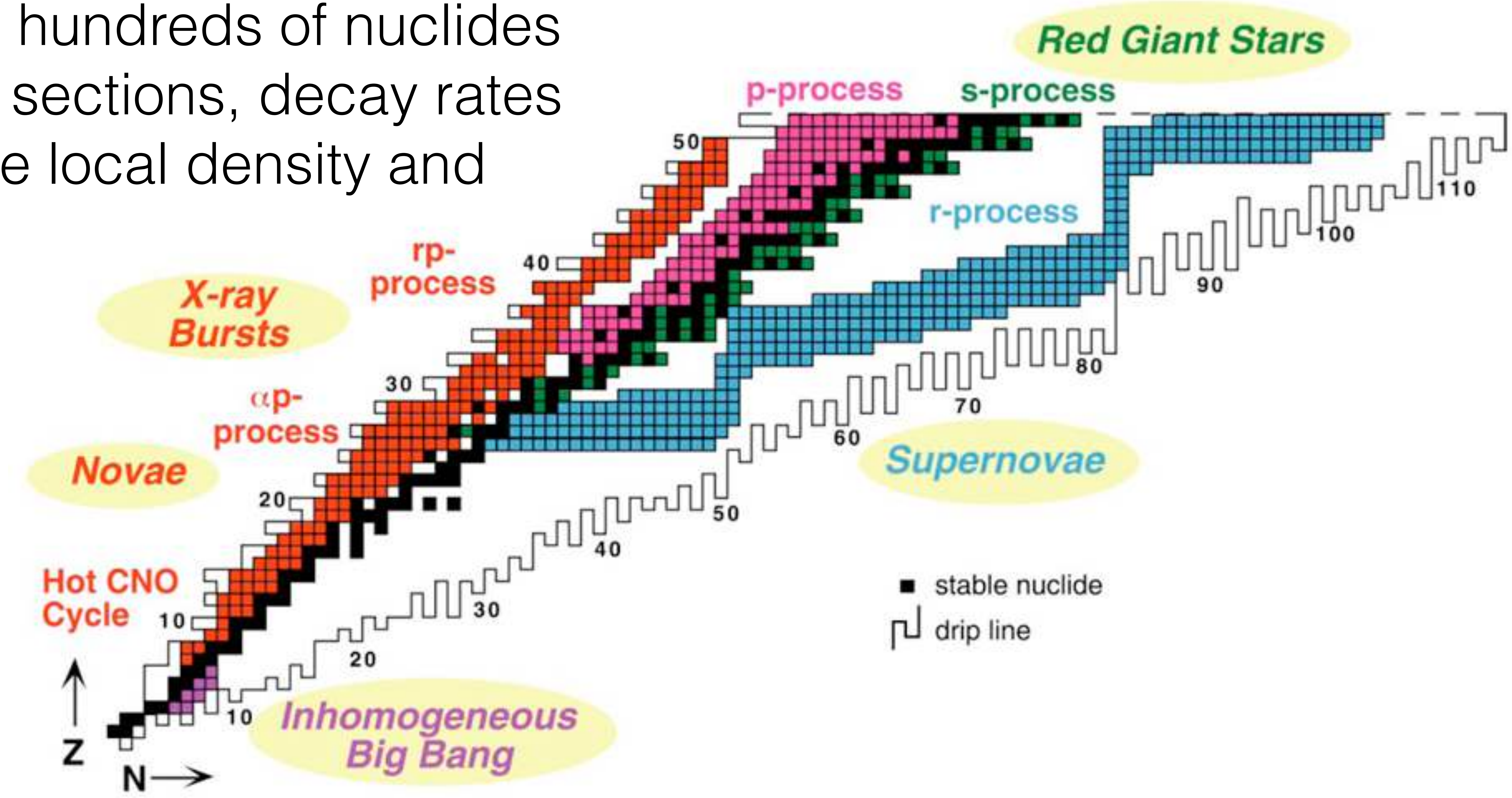


Figure from Smith and Rehm,
Annu. Rev. Nucl. Part. Sci. 2001. 51:91–130

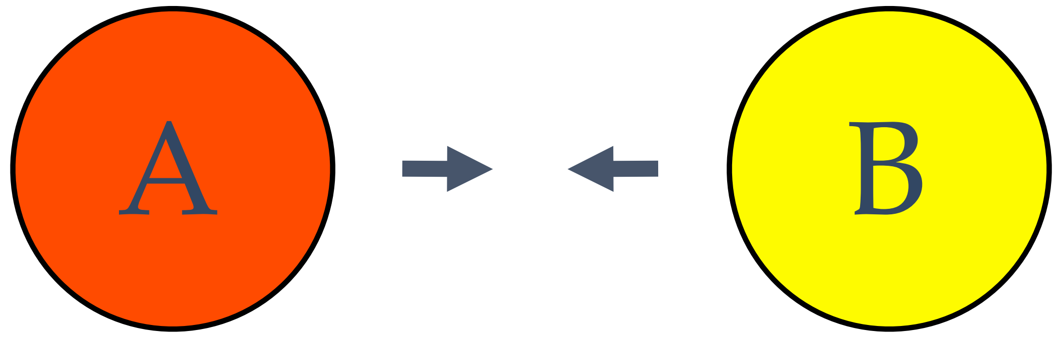
Useful ingredients

- Direct measurement of nuclear reaction cross sections
- Indirect techniques are essential to probe low energy nuclear structure and reaction features. Single or many particle transfers can be used used as surrogates, as occurs in THM and ANC methods
- Particle scattering, Coulomb dissociation studies, etc.
- **Lifetime measurements**
- Nuclear structure and reaction theory is necessary for providing guidance and setting limits in extrapolations to stellar energies

Nuclear reactions in stars

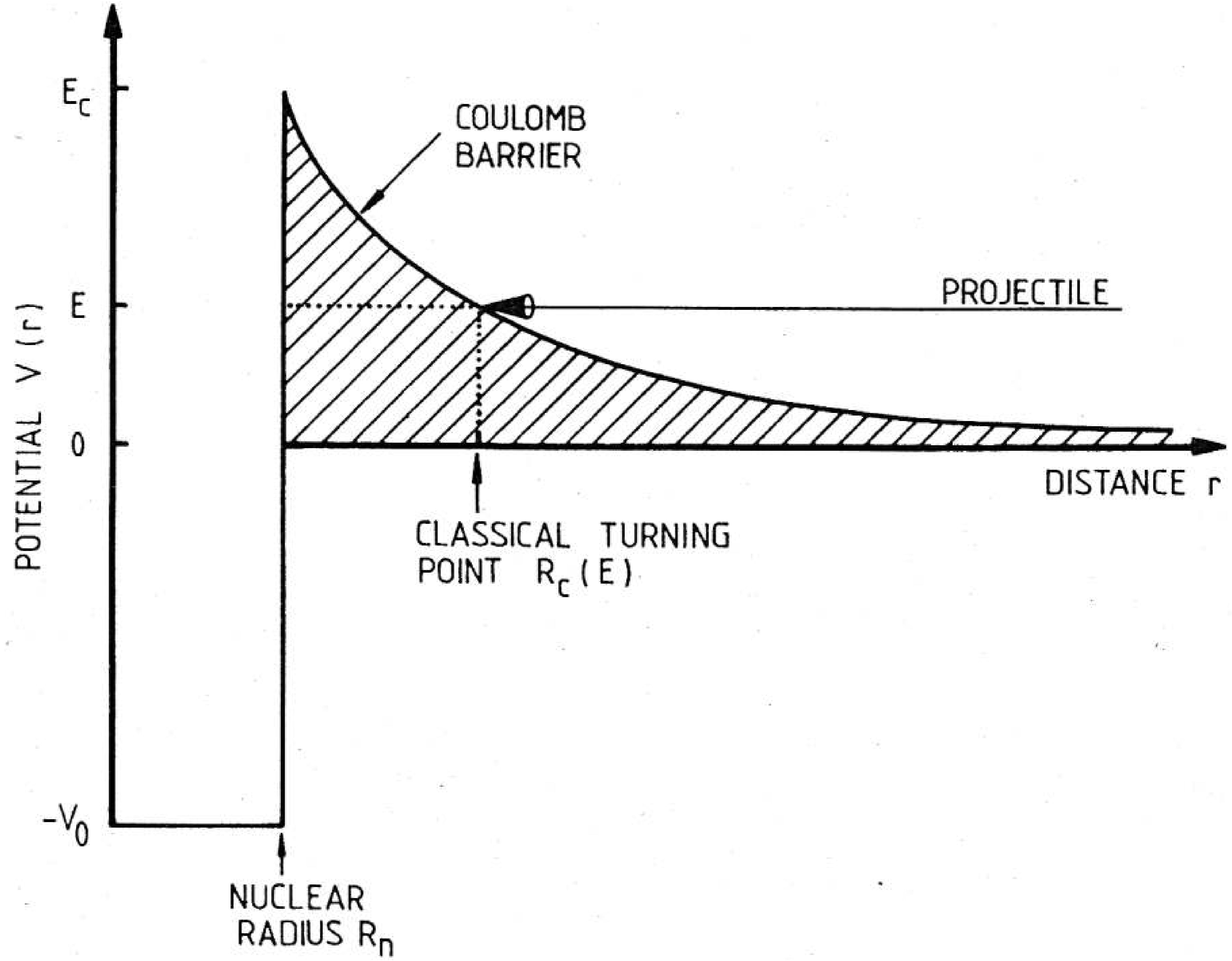
The temperatures characterizing astrophysical environments correspond to very low energies for nuclear processes. This implies that the reactions occur through quantum tunneling of the Coulomb barrier with very low probability. Measurements are thus quite challenging due to the very low cross sections.

A(B,C)D



$T_6 \sim 15\,\mathrm{K} \quad \Rightarrow \quad E \sim k_B T \sim \mathrm{keV}$

$E_c \sim Z_A Z_B / r_0 \sim \mathrm{MeV}$



Mass Spectrometry

Let me remind that mass spectrometry measurements are more than often relative measurements.

An AMS measurement provides the ratio between the amounts of a rare to the one of an abundant isotope in the same sample. In this determination one has to consider all efficiencies involved $\varepsilon(Z, M)$ due to a large variety of possible factors (source, transmission, detection, etc.).

The lowest observable isotopic ratio determines the sensitivity limit and is usually in the order of 10^{-15}.

Mass Spectrometry

It is worth noting that in the case of beta decays that will be discussed later, the ratio of the number of progeny with respect to its parent radionuclide depends solely on the lifetime and the observation time.

$$N_P = \varepsilon(M_P, Z_P) N_{P0} e^{-\frac{t}{\tau}}$$

$$N_D = \varepsilon(M_D, Z_D) \left[N_{D0} + N_{P0}(1 - e^{-\frac{t}{\tau}}) \right]$$

$$R = \frac{N_D}{N_P} = \frac{\varepsilon(M_D, Z_D)}{\varepsilon(M_P, Z_P)} \left[\frac{N_{D0}}{N_{P0}} e^{\frac{t}{\tau}} + \frac{(1 - e^{-\frac{t}{\tau}})}{e^{-\frac{t}{\tau}}} \right] = \frac{\varepsilon(M_D, Z_D)}{\varepsilon(M_P, Z_P)} \left[e^{\frac{t}{\tau}}(R_0 + 1) - 1 \right]$$

Isobars

Mass spectrometry of isobars, nearly but not strictly equal mass nuclei, is challenging.
Possible approaches include

- High resolution mass spectrometers
- Full stripping
- Passive absorbers
- Gas filled magnets
- Z identification capable detectors

Improvements can be achieved with selective resonant excitation and ionization with pulsed laser radiation (used especially at ISOL facilities).

Mass Spectrometry

Having to deal with somewhat *rare* processes high sensitivity Mass Spectrometry techniques might be successfully used in Nuclear Astrophysics measurements.

One may encounter

On-line mass spectrometry

- mass separators
- fragment separators

Off-line mass spectrometry of samples from natural archives or targets

- *conventional* Mass Spectrometry
- Accelerator Mass Spectrometry (AMS)

Mass separators

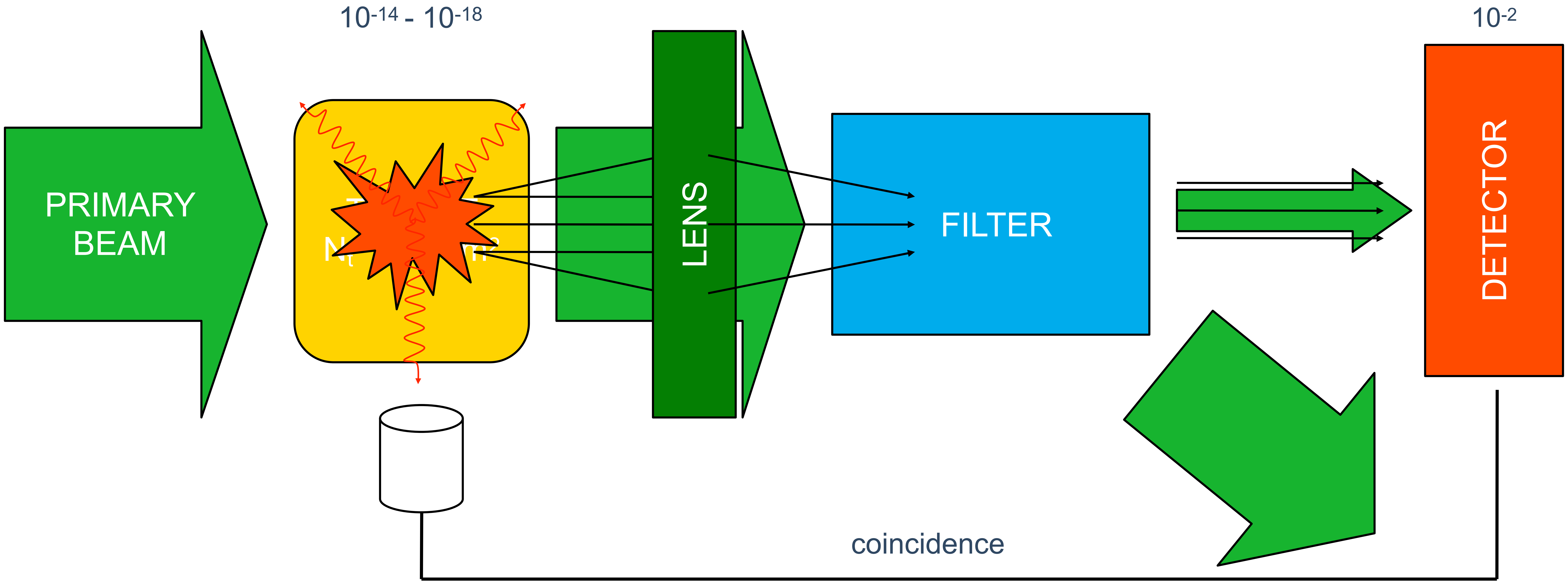
Mass Separators are widely used in Nuclear Physics, they are essential elements e.g. in Radioactive Ion Beams facilities.

With the proper use of electrical rigidity (E/q) and magnetic rigidity (p/q) filters, or a combination of both, very efficient mass separation can be achieved.

Transport and mass selection need to be optimized on the actual case, usually the main figure of merit is the resolution, but others might be important depending on application.

Recoil Mass Separators

Recoil mass separators are highly specialized mass spectrometers that are tailored to the absolute precision measurement of the cross section of capture reactions (i.e. having a gamma ray in the outgoing channel), induced by high intensity particle beams in high density gas targets. They are not high resolution, rather have high efficiency, main FoM is *suppression*.



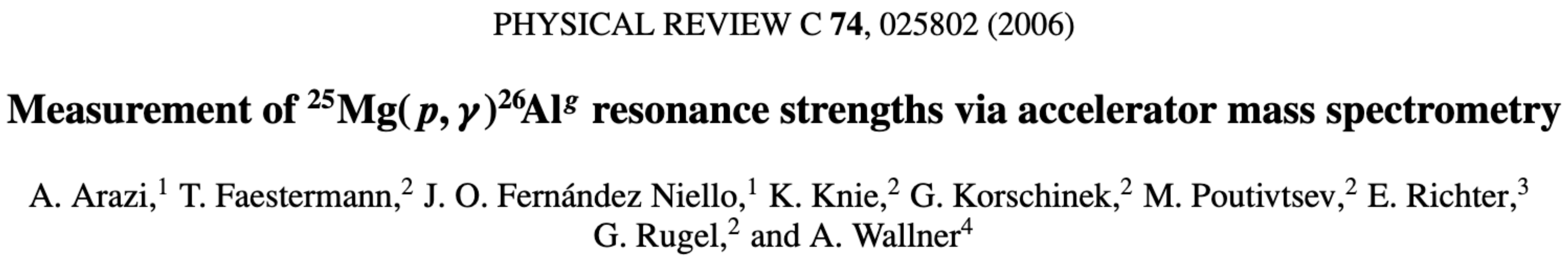
AMS following *activation*

The Accelerator Mass Spectrometry allows the determination of isotopic ratios with very high sensitivity. There are many applications of AMS, among others in Nuclear Astrophysics is well known the search for signatures of supernova events in the nearby Universe

- $^{60}\mathrm{Fe}$ in ocean crust samples
- $^{244}\mathrm{Pu}$ in stromatolites

Less known, but yet useful, is the AMS to quantify cross sections of nuclear reactions, e.g.

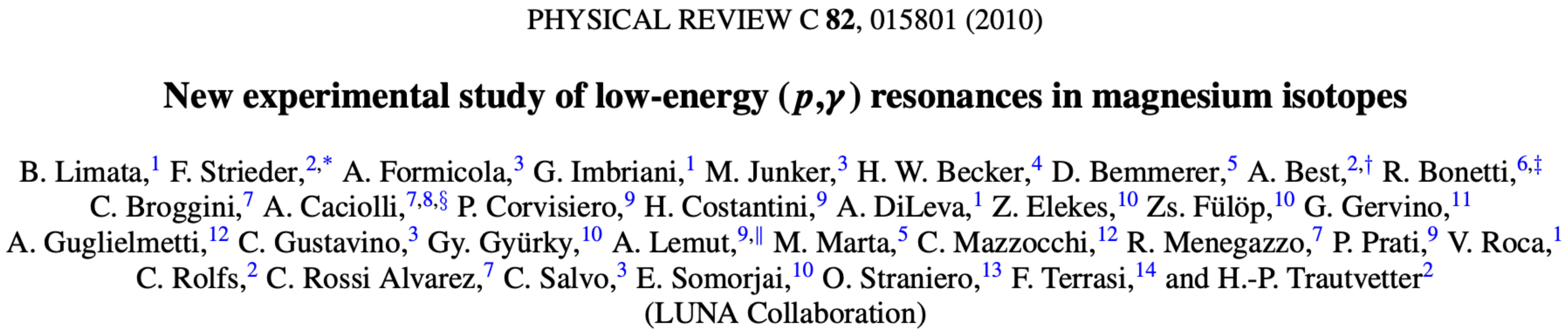
- $^{26}\mathrm{Al}$ production in $^{25}\mathrm{Mg}(p,\gamma)^{26}\mathrm{Al}$



PHYSICAL REVIEW C **74**, 025802 (2006)

Measurement of $^{25}\mathrm{Mg}(p,\gamma)^{26}\mathrm{Al}^g$ resonance strengths via accelerator mass spectrometry

A. Arazi,[1] T. Faestermann,[2] J. O. Fernández Niello,[1] K. Knie,[2] G. Korschinek,[2] M. Poutivtsev,[2] E. Richter,[3]
G. Rugel,[2] and A. Wallner[4]



PHYSICAL REVIEW C **82**, 015801 (2010)

New experimental study of low-energy (p,γ) resonances in magnesium isotopes

B. Limata,[1] F. Strieder,[2,*] A. Formicola,[3] G. Imbriani,[1] M. Junker,[3] H. W. Becker,[4] D. Bemmerer,[5] A. Best,[2,†] R. Bonetti,[6,‡]
C. Broggini,[7] A. Caciolli,[7,8,§] P. Corvisiero,[9] H. Costantini,[9] A. DiLeva,[1] Z. Elekes,[10] Zs. Fülöp,[10] G. Gervino,[11]
A. Guglielmetti,[12] C. Gustavino,[3] Gy. Gyürky,[10] A. Lemut,[9,‖] M. Marta,[5] C. Mazzocchi,[12] R. Menegazzo,[7] P. Prati,[9] V. Roca,[1]
C. Rolfs,[2] C. Rossi Alvarez,[7] C. Salvo,[3] E. Somorjai,[10] O. Straniero,[13] F. Terrasi,[14] and H.-P. Trautvetter[2]
(LUNA Collaboration)

MS in experiments with lasers

The case considered is the study of variation of beta decay lifetime of isotopes of astrophysical relevance in highly ionized plasma.

Provided that the nuclides can be loaded in the laser target material, different scenarios can be envisioned. I consider two cases, but many more possibilities can be envisioned.

MS in experiments with lasers

The radioactive nuclide and its progeny are efficiently accelerated by the plasma itself

a mass spectrometer might be used to measure the daughter to parent ratio

advantages:

- straightforward
- possibly a quite simple spectrometer might be sufficient

issues:

- isobars discrimination with absorbers might be challenging depending on ion energy and spread
- different unknown extraction efficiencies can influence the daughter to parent ratio

MS in experiments with lasers

The radioactive nuclide and its progeny remain trapped in the target

nuclei can be harvested and the daughter to parent ratio measured either online following re-acceleration or off-line through AMS

advantages:

- longer exposure of nuclei to the plasma can be exploited
- off-line counting very efficient

issues:

- harvesting from gaseous targets might be challenging
- on-line re-acceleration requires complex development
- at MeV energies AMS isobars discrimination can be difficult, a gas filled magnet might be needed

Thank you for your attention