Marco La Cognata
INFN-LNS, Catania

Nuclear Astrophysics with SPES

Outline

- ✓ *Why nuclear astrophysics at SPES?*
- ✓ *What nuclides are involved?*
  - *Light nuclei (A≤~50)*
  - *Heavy nuclei (A≥~50)*
- ✓ *Focus on heavy n-rich nuclei (main aim of SPES)*
  - *S-process*
  - *R-process*
- ✓ *Indirect methods*
  - *THM*
  - *ANC*
  - *Surrogate reaction*
- ✓ *Review of the submitted LOIs*
  - *Detectors for nuclear astrophysics*
  - *Nuclear physics studies with astrophysical implications*
  - *Nuclear astrophysics @ SPES*

What is nuclear astrophysics?

In 1920 A. Eddington said:
"What is possible in the Cavendish Laboratory may not be too difficult in the sun"

~ 100 years later we can extend this sentence to many laboratories and the whole Universe:
"What is possible in a nuclear physics laboratory may not be too difficult in the cosmos"

Indeed, it is difficult to exclude any nuclear physics process from the list of those having an interest in the field of astrophysics

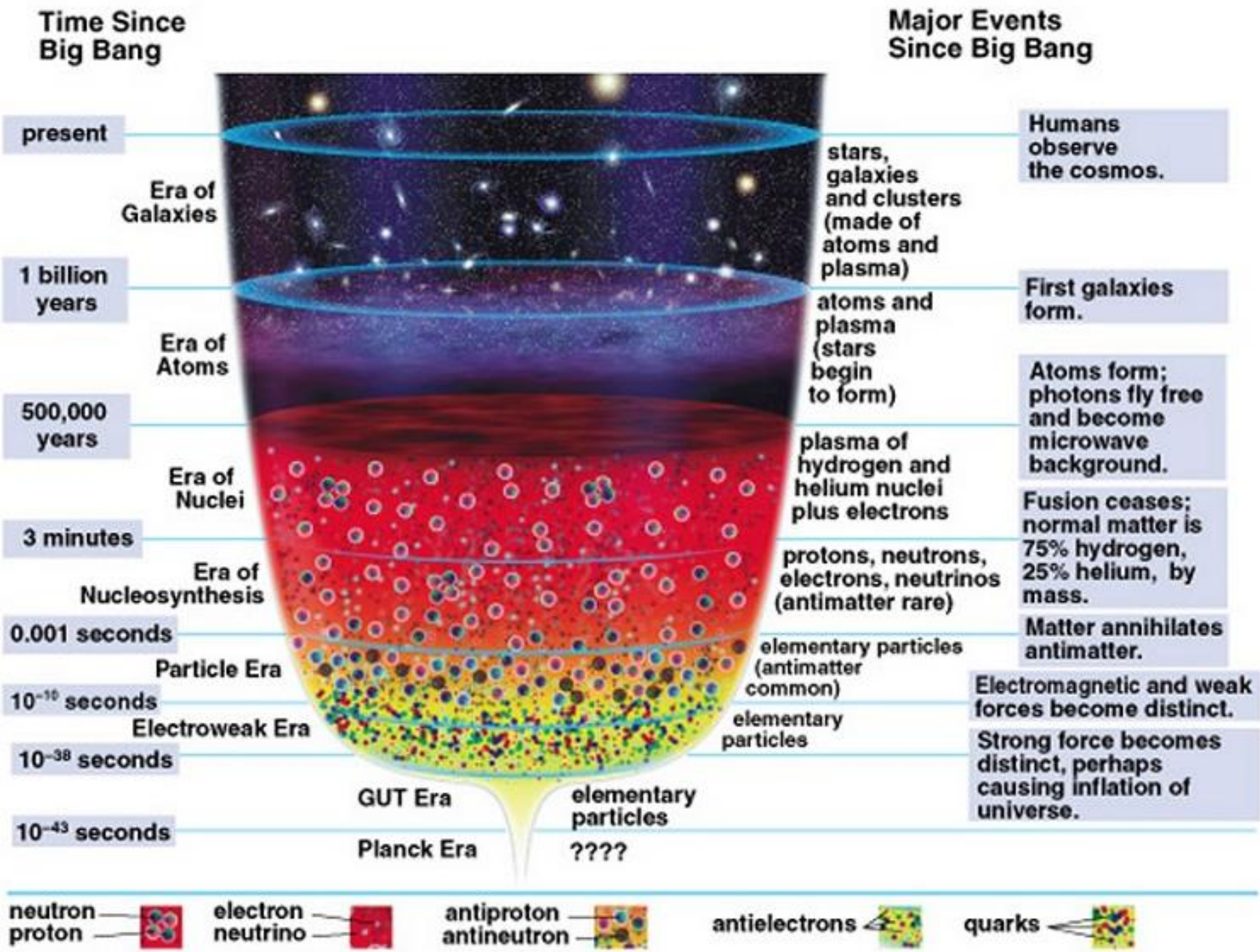
A definition of nuclear astrophysics from Cauldrons in Cosmos (by C. Rolfs):

The detailed understanding of [our cosmic] heritage combines astrophysics and nuclear physics and forms what is called ***nuclear astrophysics****.*

…

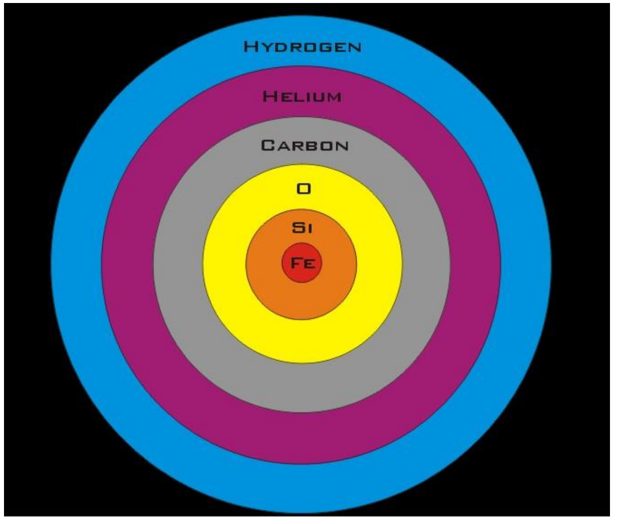
nuclear astrophysics involves much of astrophysics, because there are few important events in astronomy, cosmogony, and cosmology that have not left nuclear clues.

An example?



Time Since Big Bang
Major Events Since Big Bang
present
Era of Galaxies
1 billion years
Era of Atoms
500,000 years
Era of Nuclei
3 minutes
Era of Nucleosynthesis
0.001 seconds
Particle Era
10⁻¹⁰ seconds
Electroweak Era
10⁻³⁸ seconds
GUT Era
10⁻⁴³ seconds
Planck Era
stars, galaxies and clusters (made of atoms and plasma)
atoms and plasma (stars begin to form)
plasma of hydrogen and helium nuclei plus electrons
protons, neutrons, electrons, neutrinos (antimatter rare)
elementary particles (antimatter common)
elementary particles
elementary particles
????
Humans observe the cosmos.
First galaxies form.
Atoms form; photons fly free and become microwave background.
Fusion ceases; normal matter is 75% hydrogen, 25% helium, by mass.
Matter annihilates antimatter.
Electromagnetic and weak forces become distinct.
Strong force becomes distinct, perhaps causing inflation of universe.
neutron
proton
electron
neutrino
antiproton
antineutron
antielectrons
quarks

Light nuclei (A≤~50)



Nuclei lighter than A~50 are generally produced by fusion reactions.

- H-burning via PP chain (low-mass stars, M<1.3 solar masses) and CNO cycle (M>1.3 solar masses)

- He-burning begins with formation of Red Giant ($T=10^8$K)
  $3\,^4He \rightarrow {}^{12}C+\gamma$
  ${}^{12}C + {}^4He \rightarrow {}^{16}O+\gamma$

Then: Carbon burning, Oxygen burning, **Silicon burning (and beyond)**

The reaction ${}^{28}Si + {}^{28}Si \rightarrow ({}^{56}Ni)^*$ does not occur owing to the large Coulomb inhibition. Rather photodisintegration followed by radiative captures leads to iron group elements
Long timescales → no radioactive nuclei involved

However many radioactive nuclei can be produced also produced during quiescent burning stages

→ **^{26}Al is the best example,** since it it plays a key role in constraining the circumstances and conditions of the solar system birth and of the chemical evolution of the Galaxy
→ **Relevant reactions ^{26}Al(n,p), ^{26}Al(n,α)**

Explosive nucleosynthesis

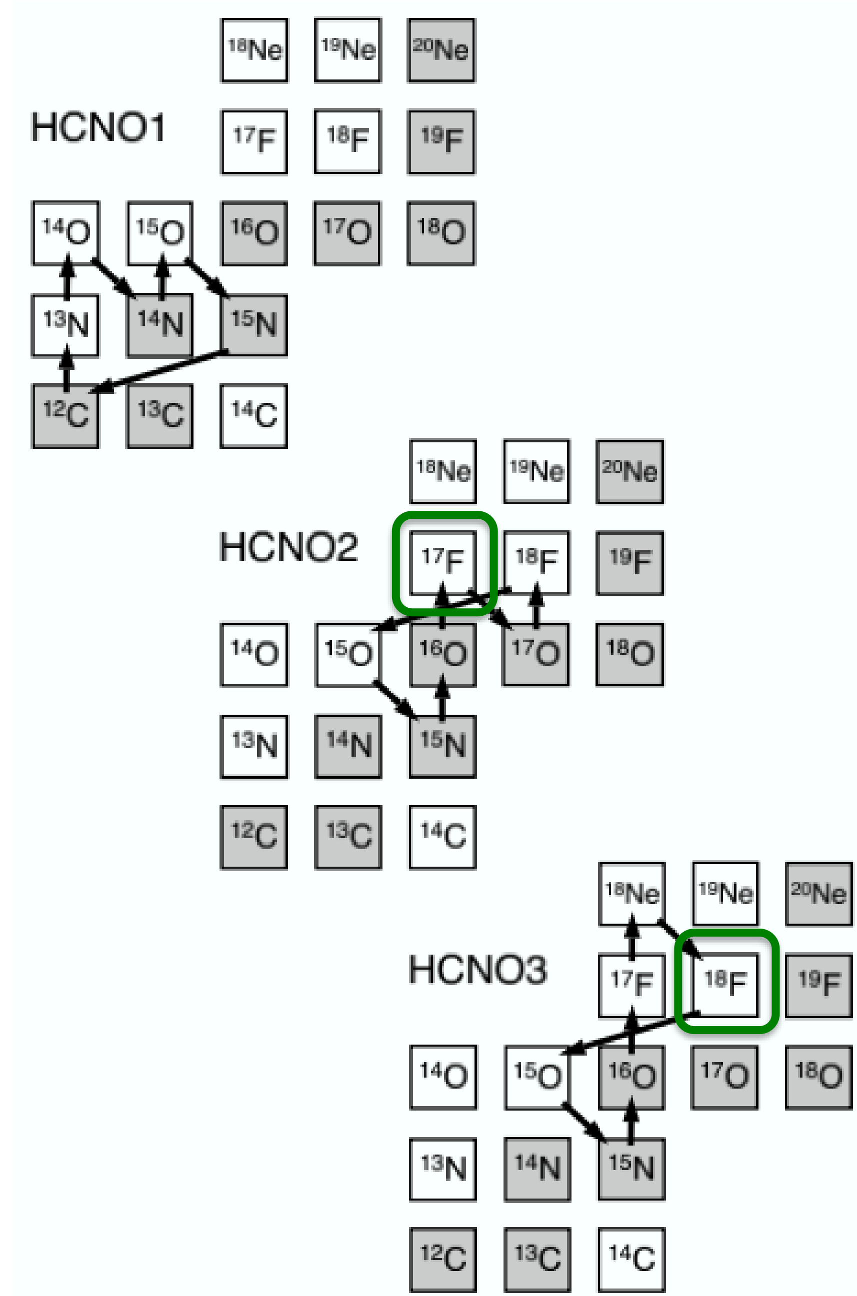
Examples:

- ✓ Big bang
- ✓ Novae
- ✓ Supernovae
- ✓ X-ray bursts
- ✓ …

In explosive scenarios, temperatures are so high (~10^9 K) that timescales are short enough for **unstable nuclei to play a role**

- ✓ Big bang nucleosynthesis: **^{7}Be(n,p)^{7}Li and ^{7}Be(n,α)^{4}He reactions**
- ✓ **HCNO cycle** → see examples on the left
- ✓ rp- and αp-processes
- ✓ **r-process → see next slides**

Other nuclei of interest: **^{22}Na** (Novae)
^{22}Mg and **^{26}Si** in the αp-process in X-ray bursts



Light exotic beams at SPES

				$T_{1/s}$ (s)	I@5μA (cps)	E_{max} (MeV)	SIS	LIS		FEBIAD
Be*	7	4	3	4.60E+06	**2.E+07 ** **	**9**		**2**		**2**
Be*	10	4	6		**3.E+07 ** **	**13**		**2**		**2**
F *	17	9	8	6.48E+01	**2.E+07 ** **	**15**		**4**		**4**
F *	18	9	9	6.58E+03	**2.E+06 ** **	**14**		**4**		**4**
Na*	21	11	10	2.25E+01		**18**	**5**			
Na*	22	11	11	2.60E+00		**17**	**5**			
Mg*	22	12	10	3.86E+00		**17**		**5**		**4**
Mg*	23	12	11	1.13E+01		**16**		**5**		**4**
Al*	24	13	11	2.05E+00		**16**	**1**	**1**		
Al*	25	13	12	7.18E+00	**1E+04 ** **	**15**	**1**	**1**		
Al*	26	13	13	6.35E+00	**1E+04 ** **	**15**	**1**	**1**		
Si*	26	14	12	2.21E+00	**1E+03 ** **	**17**				**4**
Si*	27	14	13	4.16E+00	**1E+03 ** **	**16**				**4**
P*	29	15	14	4.10E+00		**15**				**4**
Cl*	34	17	17	1.53E+00	**5E+03 ** **	**15**				**4**

Heavy nuclei (A≥~50)

Nuclei heavier than A~50 are synthesized by means of neutron captures (apart p-rich nuclei, produced with the P-process, of minor relevance for SPES)

S-process: when β decay is faster than neutron captures

Neutron densities → $10^6 - 10^7$ n/cm^3

Site: Asymptotic giant branch (AGB) stars, red giants with a C/O core and H and He shell burning (main component), massive stars (weak component), metal poor AGB stars (strong component)

Why are unstable nuclei important for the s-process?

→ Branch points: the nucleosynthesis path is determined by the interplay between decay and neutron captures, **thus both measurement of half lives and of neutron capture cross sections are important**

Some key nuclides: **^{108}Ag**, **^{110}Ag** (uncertainties on decay mode), **^{121}Sn** and **^{123}Sn** (uncertainties on lifetimes, isomeric states?)

Some key reactions: (n,γ) captures on **^{65}Zn, ^{79}Se, ^{81}Kr, ^{85}Kr, ^{86}Rb, ^{121}Sn, ^{64}Cu, ^{108}Ag, ^{109}Pd, ^{123}Sn** and many others!

Only indirect methods are viable for n+unstable nucleus interaction (THM? Surrogate reactions? ANC?)

S-process

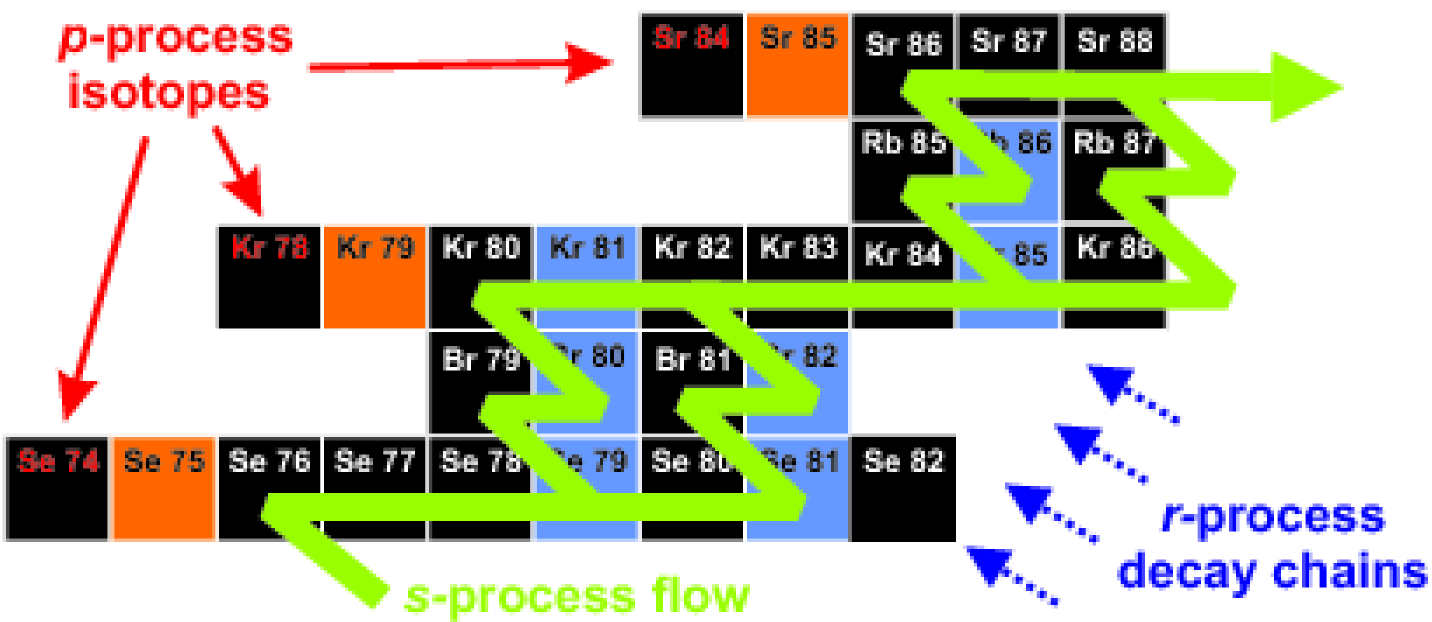
s-process → "**s**" is for "**slow**" [see M. Busso et al., *Annu. Rev. Astron. Astrophys.* 37 (1999) 239]

✓ occurs in helium-fusing stars where small quantities of free neutrons are made by processes like $^{13}C + {}^{4}He \rightarrow {}^{16}O + n$ and/or $^{22}Ne + {}^{4}He \rightarrow {}^{25}Mg + n$

✓ **adds neutrons very slowly**, so any unstable nucleus that forms has time to decay

✓ makes only nuclei which can be reached (directly or via decay) from a stable isotope

✓ anything surrounded by unstable isotopes cannot be produced



Heavy nuclei (A≥~50)

<u>R-process:</u> when neutron captures are faster than β decay

Neutron densities → 10^{20} n/cm^3

<u>Site</u>: core collapse supernova or γ-ray burst accretion disks.

<u>Mechanism</u>: neutron flux is so large that the whole nuclear chart **up to the neutron dripline** is populated

Therefore, a lot of nuclear data are necessary: half lives, masses, energy levels, spin, parities and single-particle strengths

Some key reactions: (n,γ) captures on ^{81}Ni, ^{76}Cu, ^{78}Zn, $^{80-81-85}$Ga, $^{86-88}$As, $^{81-85-86-87}$Ge, $^{87-90-91}$Se have been singled out as significant contributors to the abundance pattern along the r-path with 30<Z<34. Also: ^{123,131,133,134}Sn, ^{131}In, ^{133}Sb

Moreover: waiting point nuclei → nuclei with N=magic have small n-capture cross sections and long lifetimes determining a stop in the nucleosynthesis flow

Only indirect methods are viable for n+unstable nucleus interaction (THM? Surrogate reactions? ANC?)

R-process

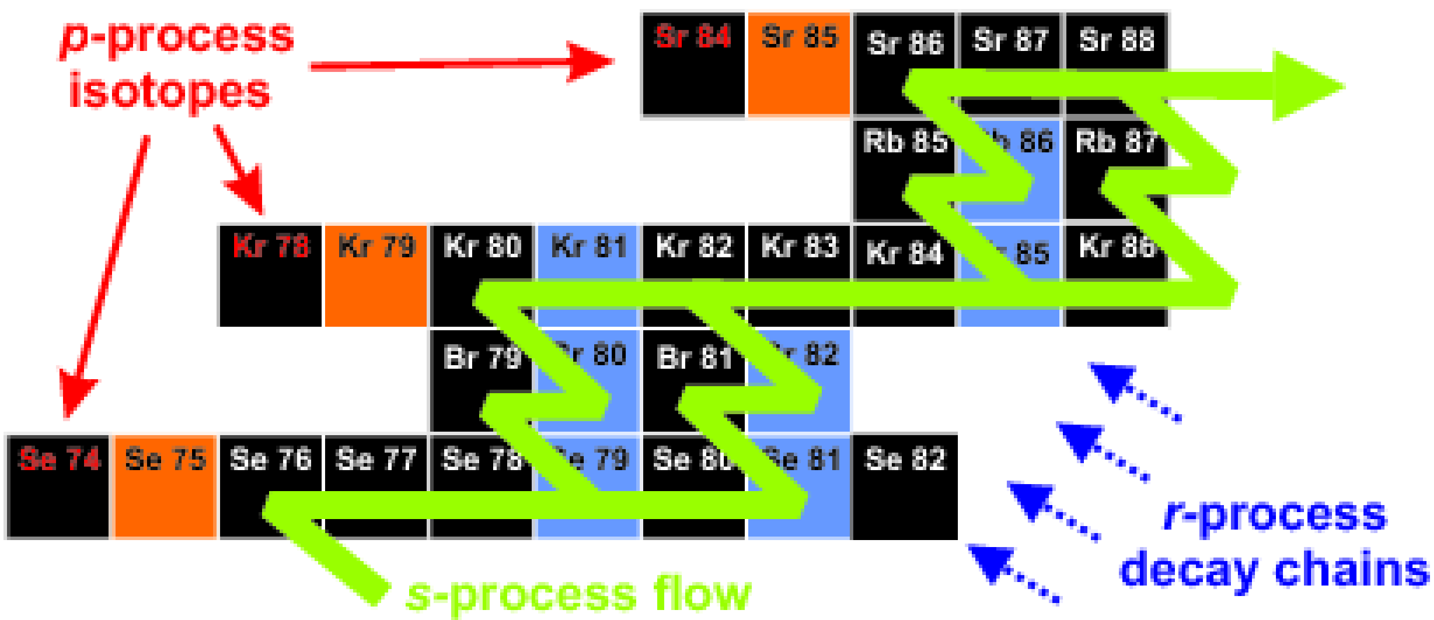
r-process (**rapid**) [see M. Arnould et al., Phys. Rep. 450 (2007) 97]

✓ occurs **in very neutron-rich environment**—probably during core-collapse supernovae

✓ adds neutrons rapidly, so many neutrons are added before the nucleus has time to decay

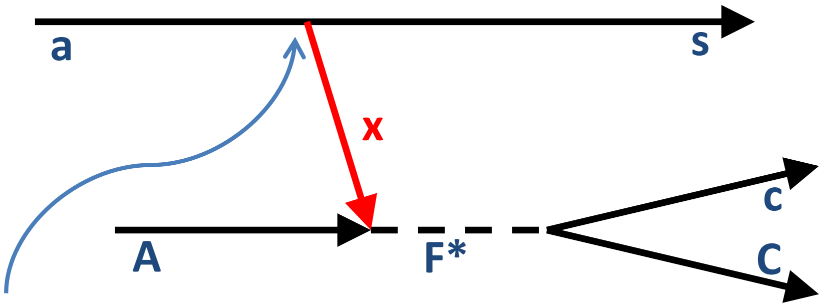
✓ initially makes **highly unstable, very neutron-rich nuclei** which subsequently decay to stable isotopes via β decay

✓ cannot make any nucleus which has a stable isobar with the same mass number but smaller atomic number



Indirect approaches 1: THM

In the "Trojan Horse Method" (THM) the astrophysically relevant reaction, in particular A(x,c)C, is studied through the 2→3 direct process → A(a,cC)s:



Upper vertex: direct *a* breakup

The process is a transfer to the continuum where x is the transferred particle, e.g. a proton or an alpha particle

Standard R-Matrix approach cannot be applied to extract the resonance parameters of the A(x,c)C reaction because x is virtual → Modified R-Matrix is introduced instead

In the case of a resonant THM reaction the cross section takes the form

$$\frac{d^2\sigma}{dE_{Cc}\, d\Omega_s} \propto \frac{\Gamma_{(Cc)_i}(E)\, |M_i(E)|^2}{(E - E_{R_i})^2 + \Gamma_i^2(E)/4}$$

$M_i(E)$ is the amplitude of the transfer reaction (upper vertex) e.g. from FRESCO
→ The resonance parameters can be extracted and in particular the strength

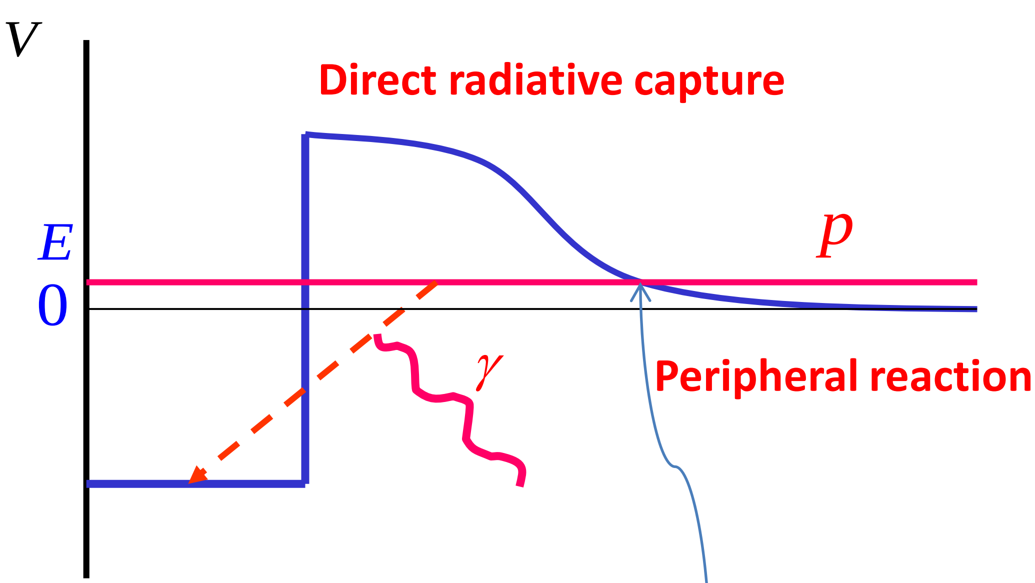
See R. Tribble et al., Rep. Prog. Phys. 77 (2014) 106901; M. La Cognata et al., PRL 109 (2012) 232701

Indirect approaches 2: ANC

See R. Tribble et al., Rep. Prog. Phys. 77 (2014) 106901; A. Mukhamedzhanov et al., PRC 92 (2015) 014625

Radiative *p* (α) capture at stellar energies

- Classical **barrier penetration** problem



- **low energies ⇒ capture at large radii**
- **very small cross sections**

The cross section is determined by ANCs

$$\sigma \propto |M|^2$$

$$M = \left\langle I_{Bp}^{A}(r_{Bp}) \middle| \hat{O}(r_{Bp}) \middle| \psi_i^{(+)}(r_{Bp}) \right\rangle$$

$$I_{Bp}^{A}(r_{Bp}) \overset{r_B > R_N}{\approx} C_{Bp}^{A} \frac{W_{-\eta_A, l+\frac{1}{2}}(2\kappa_{Bp} r_{Bp})}{r_{Bp}}$$

ANC → amplitude for tail of overlap function

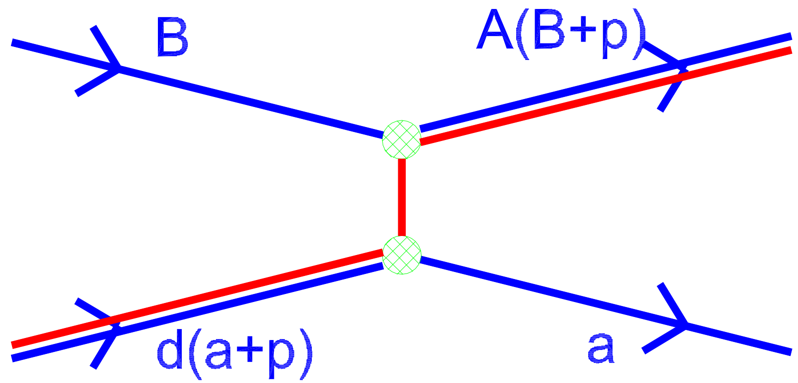
$$\sigma_{capture} \propto (C_{Bp}^{A})^2$$

ANCs determine the capture cross section at low energies.

How can we measure them?

Indirect approaches 2: ANC

Transfer reactions



Transition amplitude: $$M = \sum \langle \chi_f^{(-)} I_{Bp}^{A} | \Delta V | I_{ap}^{d} \chi_i^{(+)} \rangle$$

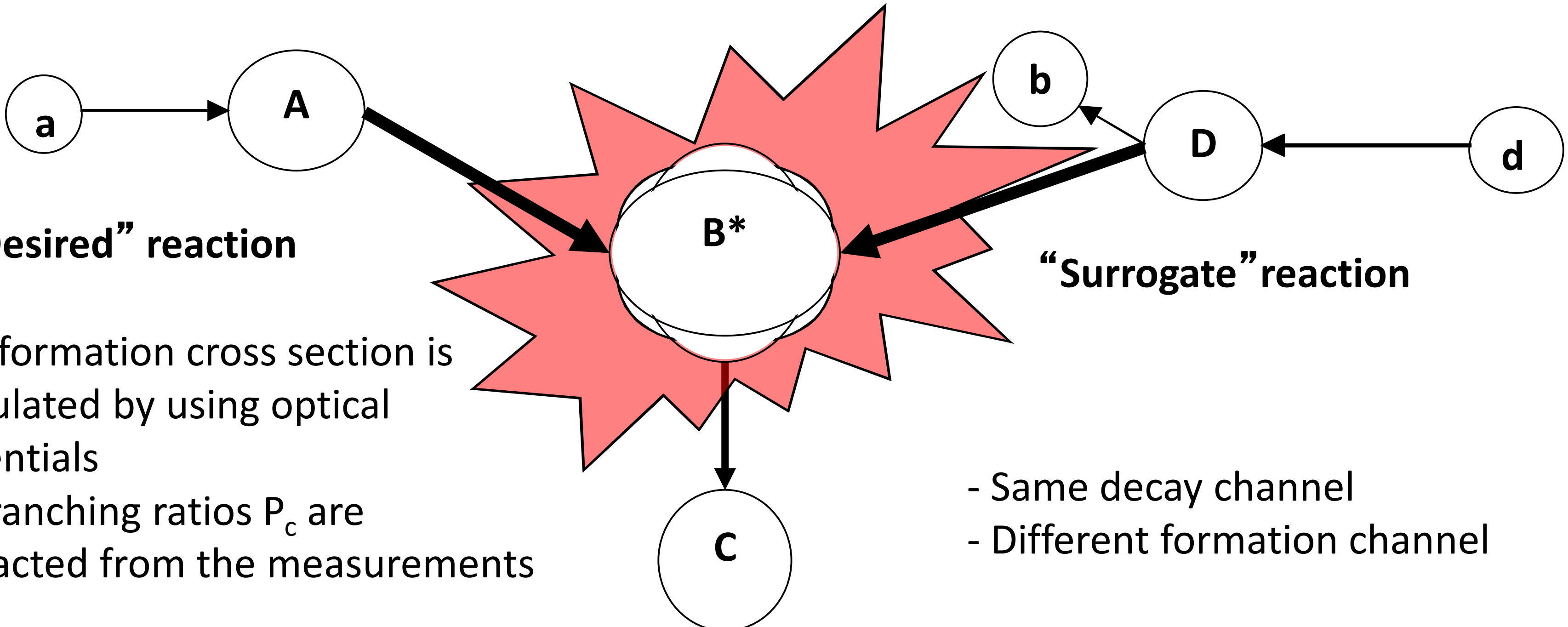
Peripheral transfer: $$I_{Bp}^{A} \overset{r_{Bp} > R_N}{\approx} C_{Bp}^{A} \frac{W_{-\eta_A, l+\frac{1}{2}}(2\kappa_{Bp} r_{Bp})}{r_{Bp}}$$

$$\frac{d\sigma}{d\Omega} = (C_{Bpl_A j_A}^{A})^2 (C_{apl_d j_d}^{d})^2 \frac{\sigma_{l_A j_A l_d j_d}^{DW}}{b_{Bpl_A j_A}^{2} b_{apl_d j_d}^{2}}$$

The transfer cross section is proportional to the needed ANCs → From a measurement @ several tens of MeV one can get the zero energy S-factor for a radiative capture reaction

Indirect approaches 3: Surrogate reactions

See W.Younes, H.C.Britt, PRC 67 (2003) 024610; J.E.Escher, F.S.Dietrich, PRC 74 (2006) 054601



The formation cross section is calculated by using optical potentials
→branching ratios P_c are extracted from the measurements

- Same decay channel
- Different formation channel

However: it is not working very well when applied to (n,γ) reactions using *d* to populate the compound system

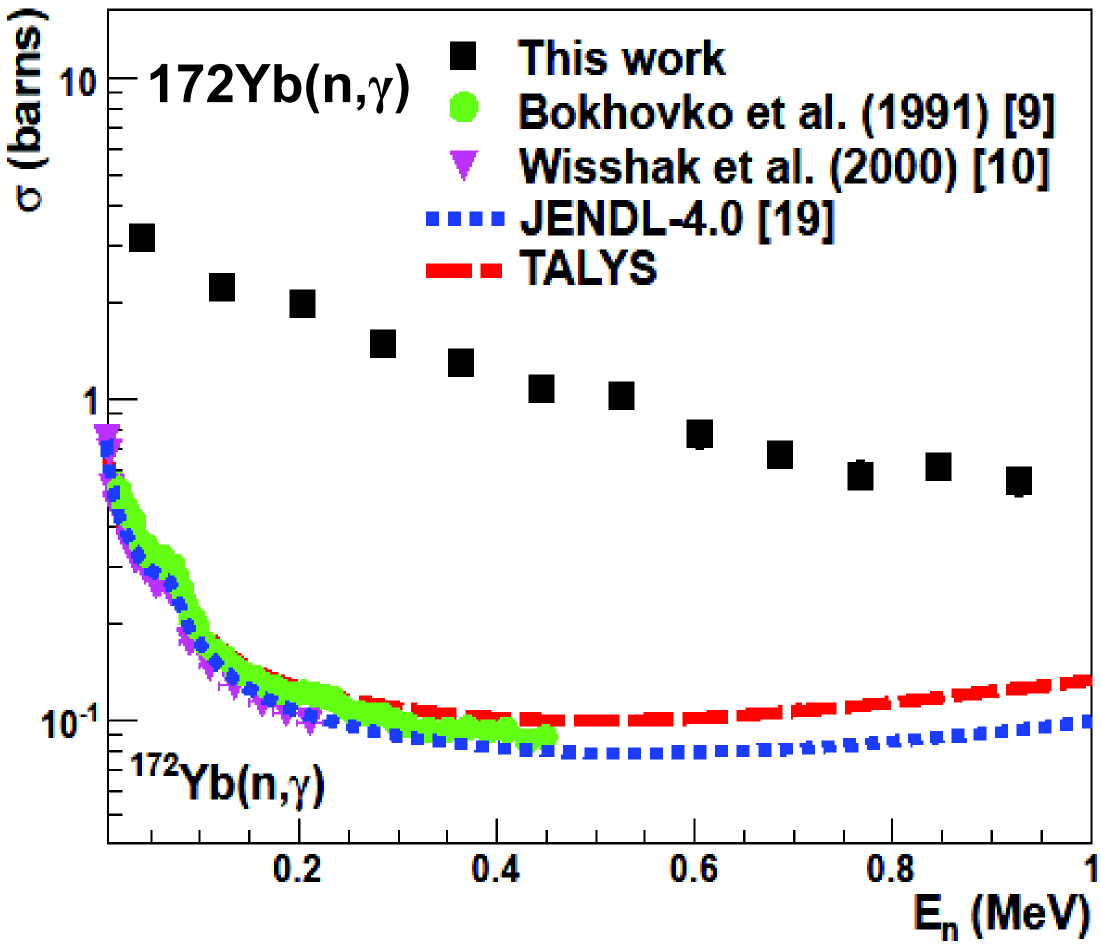
$$\sigma_{A(a,x)C} = \sum_{J,\pi} P_c(J,\pi,E_x)\,\sigma^{compreac}_{a+A}(J,\pi,E_x)$$

$$Weisskopf - Ewing:\ \sigma_{A(a,x)C} = P_C\,\sigma^{compreac}_{a+A}$$

Central assumption: Both reactions form a compound nucleus

Results for radiative capture

3He + 174Yb -> 4He + 173Yb



The cross sections obtained with surrogate method are in clear disagreement with n-induced data for capture!

G. Boutoux et al., Phys. Lett. B 712 (2012) 319

SPES LOI & nuclear astrophysics

About 50 LOIs have been submitted so far

We can distinguish 3 broad categories

1. Detectors that can be used for nuclear astrophysics experiments @ SPES

2. Nuclear physics problems influencing our understanding of nuclear astrophysics

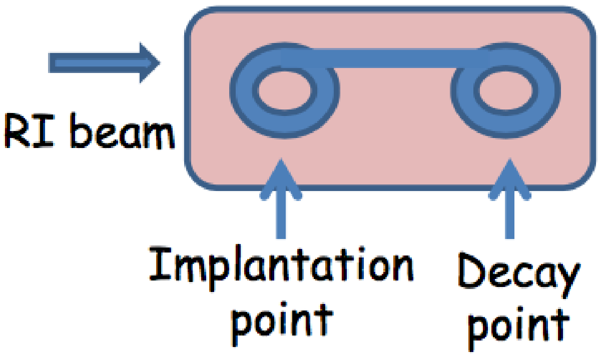
3. Nuclear astrophysics (proposal addressing particular astrophysical scenarios)

1. Detectors for nuclear astrophysics

- Tape-station setup

A standard tape-station setup comprises

- a movable tape system where the radioactive beam is implanted and then moved away
- A decay point is equipped with a fast-response plastic scintillator, to measure the emitted beta particles.

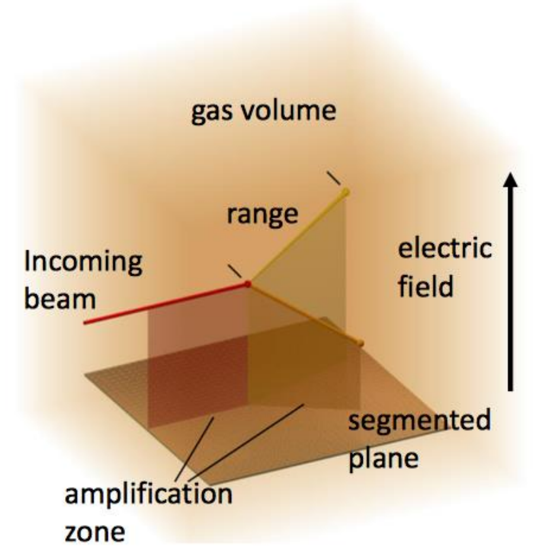


- Active target time projection chamber

Gas target & tracking detector useful for

- Transfer reactions
- Resonant reactions
- Inelastic scattering

Advantage: very thick target with very good resolution thanks to tracks reconstruction



More "detectors" you know very well!

- AGATA, GALILEO → HPGe detectors

- PRISMA → Large acceptance Magnetic Spectrometer

- NEDA → NEutron Detector Array (liquid scintillators)

- ORRUBA and superORRUBA → Silicon strip detectors array

2. Nuclear physics studies with astrophysical applications

May LOIs belong to this category, since astrophysics requires a large number of nuclear physics input.

Already mentioned: half lives, masses, energy levels, spin, parities and single-particle strengths in the r-process

Nuclear physics problem	Astrophysical application
Thermodynamical behavior of hot and deformed n-rich systems (isospin dependence of the nuclear EOS)	Physics of neutron stars and mechanism of explosion of supernovae and X-ray bursts
Superheavy nuclei (existence, lifetime, decay mode)	The r-process is probably halted by fission occurring in the region of unknown heavy nuclei with a large neutron excess
Clustering aspects in N≠Z nuclei	Influence on nucleosynthesis during explosive and quiescent burning stages
Modification of the shell model for N/Z far from stability (e.g. persistence of the N = 82 closure below Z = 50?)	Explosive neutron-capture nucleosynthesis processes
Nuclear spectroscopy, ANC, level energies and spectroscopic factors	Calculation of the reactions rates of processes of astrophysical relevance when measurements are not possible

3. Nuclear astrophysics at SPES

LOIs focused on solving open problems in astrophysics are 7:

- Measurement of the decay characteristics of nuclei around A=90 relevant to the r-process nucleosynthesis [T. Kurtukian-Nieto et al.]

- Measurement of astrophysical relevant reactions induced by alpha, protons and neutrons at the Gamow peak using the Trojan Horse method [M.L. et al.]

- Direct Reactions at SPES: Shell Evolution and Nuclear Astrophysics around Z~50 and N~82 [D. Mengoni et al.]

- Letter of Intent for transfer reaction measurements at SPES for r-process nucleosynthesis [S.D. Pain et al.]

- Letter of intents for measurements at SPES of n-capture cross sections on radioactive nuclei interesting for s-process nucleosynthesis [O. Trippella et al.]

- Study of beta-decay properties of neutron-rich isotopes approaching the r-process path [D. Testov et al.]

- Letter of Intents for measurements at SPES on beta-decay properties of nuclei belonging to the s-process path [S. Cristallo et al.]

Summary and outlook

- Many investigations that will be performed at SPES will strongly influence our present understanding of astrophysics, even those not really focused on astrophysics
- Owing to the beams delivered by SPES, the **r-process** will probably benefit more
- On the other hand, the r-process is one of the most uncertain scenarios in astrophysics
- Many different detectors will be needed to perform the necessary measurements, gamma arrays, silicon strip arrays, beta decay station, magnetic spectrometer…
- Standard approaches cannot be used to measure n+RIBs interaction: introduction of **indirect methods** such as the THM, the ANC, the surrogate reaction and others (transfer reactions? New ideas?)