Experimental approaches in nuclear astrophysics

Nicolas de Séréville (nicolas.de-sereville@ijclab.in2p3.fr)
Laboratoire de Physique des 2 Infinis Irène Joliot Curie
Université Paris Saclay

Outline

Lecture 1: Introduction to nuclear astrophysics

Lecture 2: Nucleosynthesis processes in the Universe

Lecture 3: Cross-sections and thermonuclear reaction rates

Lecture 4: Experimental approaches in nuclear astrophysics

1. Generalities
2. Direct measurements of charged particle induced reactions
   1. Stable beams for quiescent burning studies
   2. Radioactive ion beams for explosive burning studies
3. Direct measurements of neutron induced reactions
   1. The activation method
   2. The time of flight method
4. Indirect measurements: the case of the transfer reaction method

1. Generalities

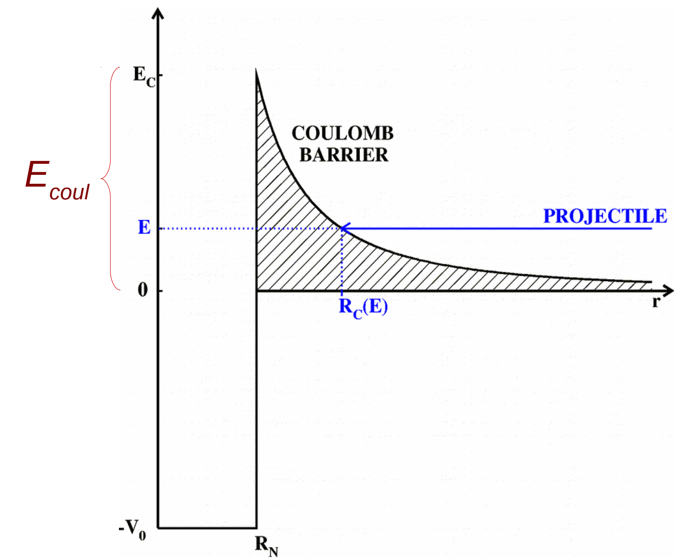
Reactions in nuclear astrophysics

- The energies of astrophysical interest where measurements should be carried out (Gamow peak) are very small $E_0 << E_{coul} = Z_1 Z_2 e^2/r$

- Quiescent burning → E_0 ~ few keV – hundreds keV
  - Our Sun (T ~ 15 MK)
    → ^{7}Be + p ⇒ E_0 ~ 18 keV E_{coul} = 1.52 MeV
  - Red giants (T ~ 200 MK)
    → ^{12}C + α ⇒ E_0 ~ 300 keV E_{coul} = 3.43 MeV

- Explosive burning → E_0 ~ hundreds keV – few MeV
  - X-ray bursts (T ~ 0.9 GK)
    → ^{30}S + α ⇒ E_0 ~ 1.7 MeV E_{coul} = 7.54 MeV

- Very small cross sections: **10^{-18} b ≤ σ ≤ 10^{-9} b** → Major experimental challenge



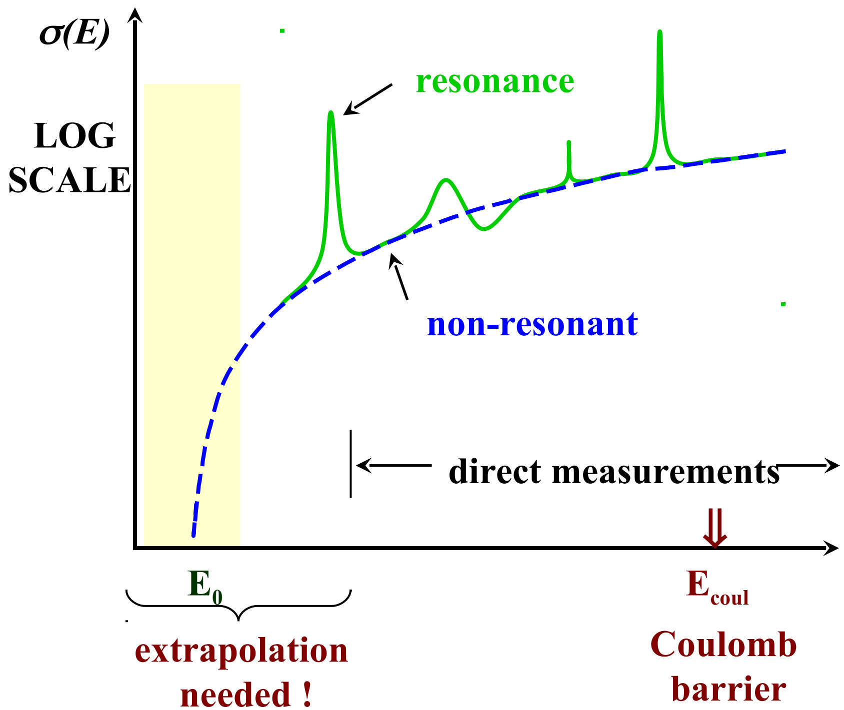
Experimental strategy

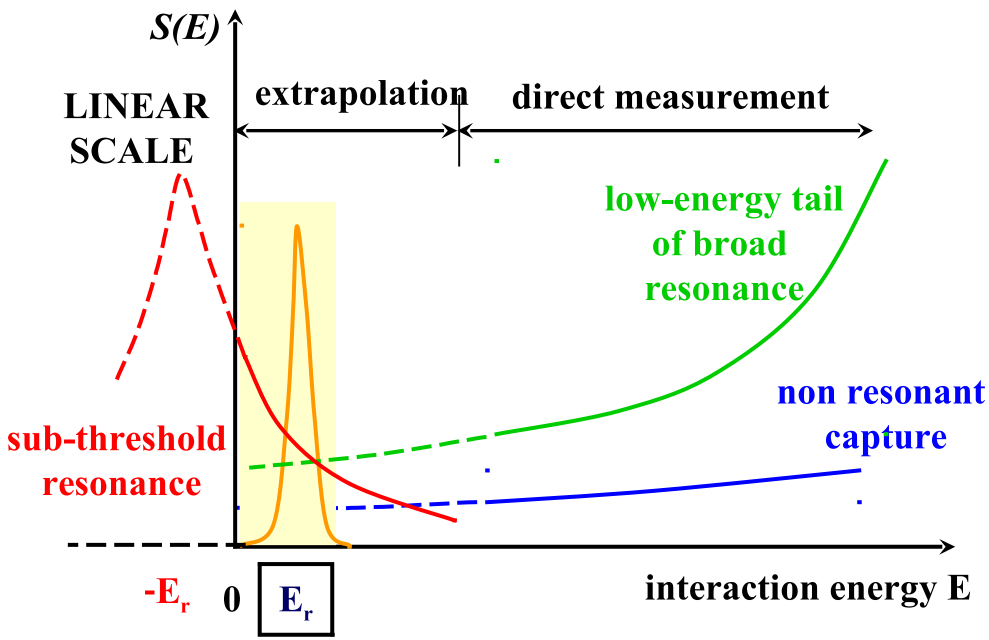
Cross section

$$\sigma(E) = \frac{1}{E}\, S(E)\, \exp\left(-2\pi\eta\right)$$

Astrophysical *S*-factor

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



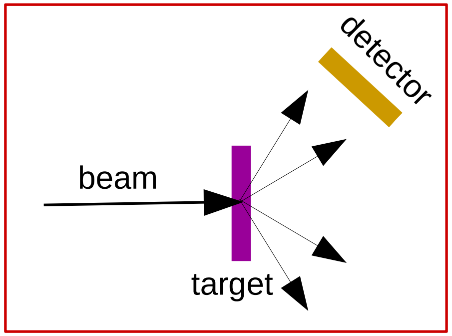


Problems with EXTRAPOLATION !

- Measurement of cross section at higher energies and extrapolation to astrophysical energies E_0 → direct measurement approach
- Determination of resonant state properties (E_R, partial widths Γ_i, J^π) → indirect measurement approach

Cross section measurements

- Number of reactions per second: $N_{reac} = N_i \times (n_t \times \Delta x) \times \sigma$
  where n_t is the number of target atoms per cm^{-3}, Δx (cm) the target thickness and N_i the number of projectile per second



- Number of detected events (s^{-1}): $N_{detec} = N_{reac} \times \epsilon$
  where ε is the detection efficiency (geometrical + intrinsic)

- Examples: at E = 20 keV (typical energy in the core of the Sun)
  - ^{3}He(^{3}He,2p)^{4}He (strong interaction): σ(20 keV) = 5 × 10^{-13} b
    assuming $n_t\Delta x = 10^{18}$ atoms/cm^2 and $N_i = 10^{15}$ s^{-1}
    $\Rightarrow N_{reac}$ = 1.8 per hour
  - ^{3}He(α,γ)^{7}Be (electromagnetic interaction): σ(20 keV) = 3 × 10^{-18} b
    $\Rightarrow N_{reac}$ = 9.5 per century
  - p(p,νe^{+})^{2}H (weak interaction): σ(20 keV) = 5 × 10^{-25} b

Kinematics and experimental setup

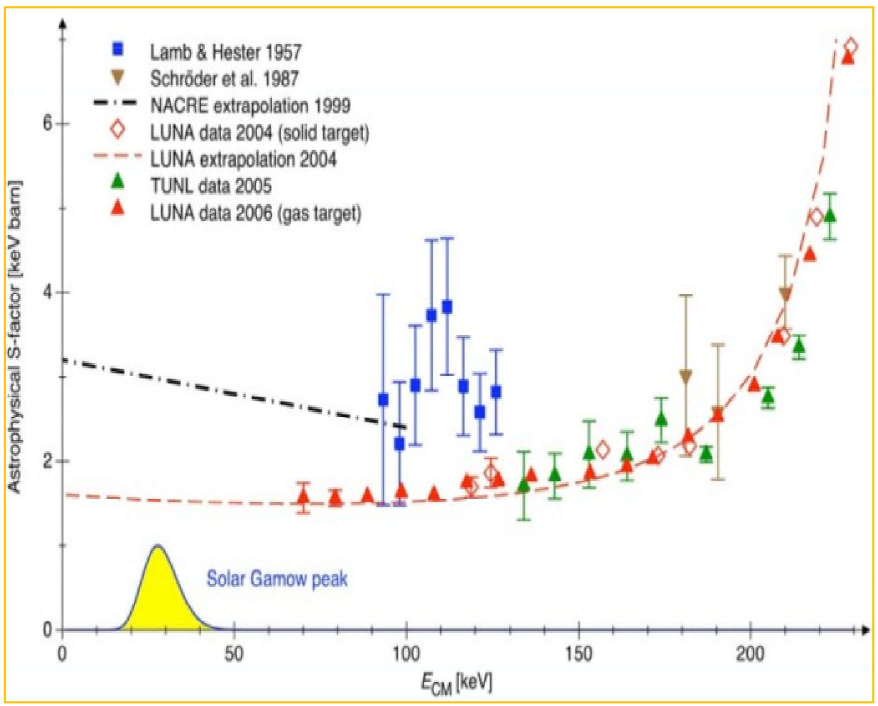
There are two “kinematic” ways of measuring a cross section depending on the mass of the beam nuclei (A_{beam}) wrt the mass of the target nuclei (A_{target})

	Direct kinematic ($A_{beam} < A_{target}$)	Inverse kinematic ($A_{beam} > A_{target}$)
Reaction	^{23}Na(α,p)^{26}Mg ^{30}Si(p,γ)^{31}P	^{4}He(^{23}Na,p)^{26}Mg p(^{30}Si,γ)^{31}P
Beam	stable	Stable, radioactive
Target	solid	Gas, solid
Heavy recoil	E ~ 100’s keV → stay in target	$E \sim E_{beam}$ → escape from target
Light particle	~4π solid angle	Forward focus
Detection	Charged particle, γ-rays	Heavy recoil, charged particle, γ-rays

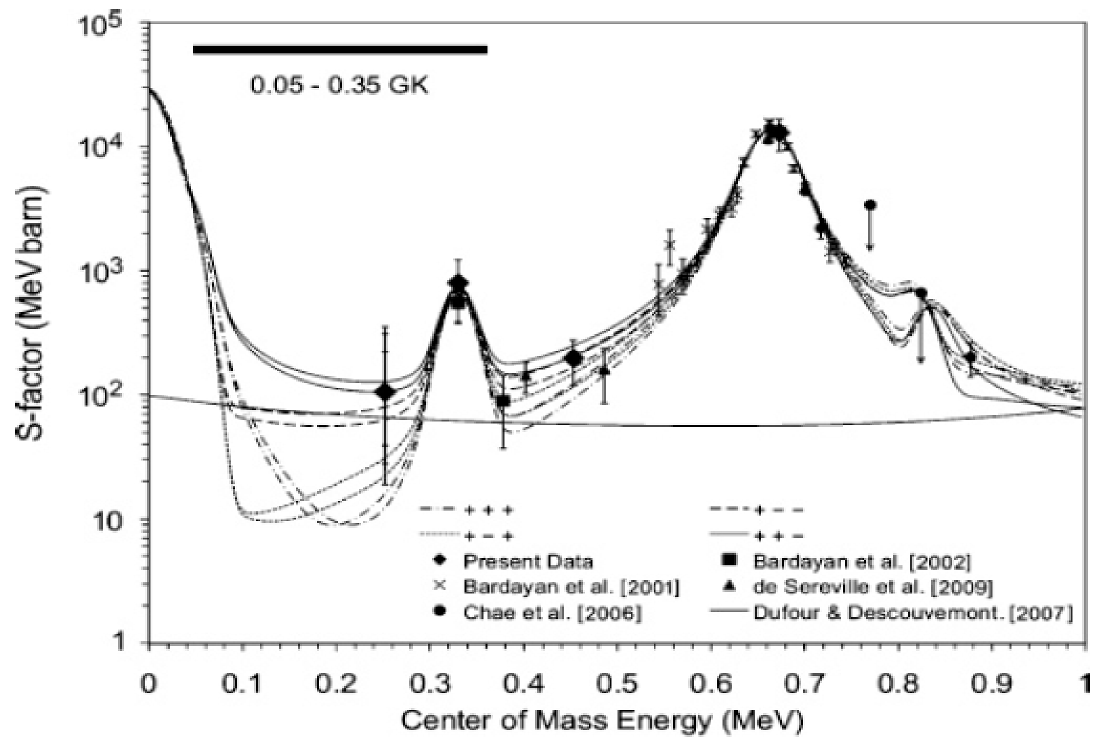
The choice of a direct or inverse kinematic approach has a profund impact on the experimental setup

2. Direct measurements of charged particles induced reactions

The $^{14}N(p,\gamma)^{15}O$ reaction



The $^{18}F(p,\alpha)^{15}O$ reaction



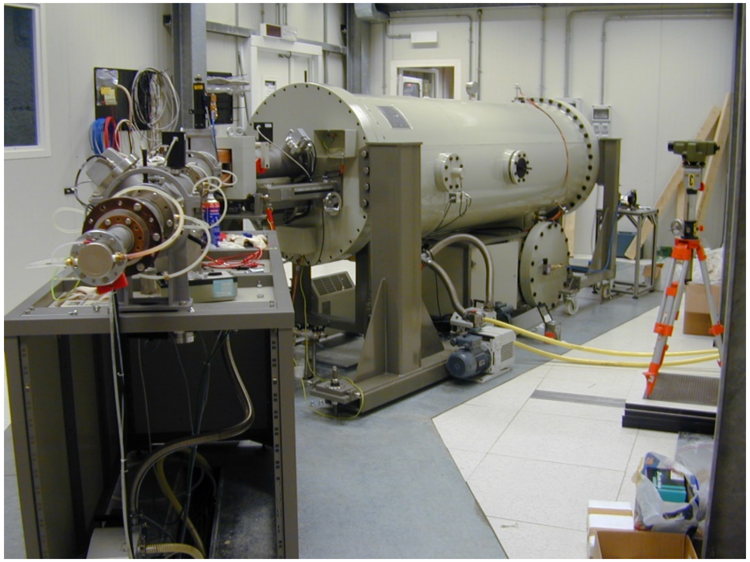
Stable nuclides only

Unstable nuclide (^{18}F) involved

2.1 Stable beams for quiescent burning

ANDROMEDE – Van de Graaff 1 – 4 MV – Orsay

LUNA 400 kV accelerator



Requirements and challenges

Low cross section → low yields → poor signal-to-noise ratio

Sources of background

- Beam induced
  - Reactions with impurities in the target
  - Reactions on beam collimators/apertures
- Non beam-induced
  - Interaction from cosmic muons with detection setup
  - Charged particles / γ-rays from natural background
  - Neutron induced reactions

Requirements & challenges → Improving signal-to-noise ratio

- Improving signal
  - Very long measurements (weeks, months…)
  - High beam intensities: heating effects on target (limitation)
  - Thicker targets (?): exponential drop of the cross section
  - High detection efficiency
- Reducing noise/background
  - Ultra pure targets: difficult
  - Dedicated experimental setup →
    - Coincidence measurements (STELLA…)
    - Recoil mass separator (DRAGON…)
    - Underground laboratory (LUNA...)

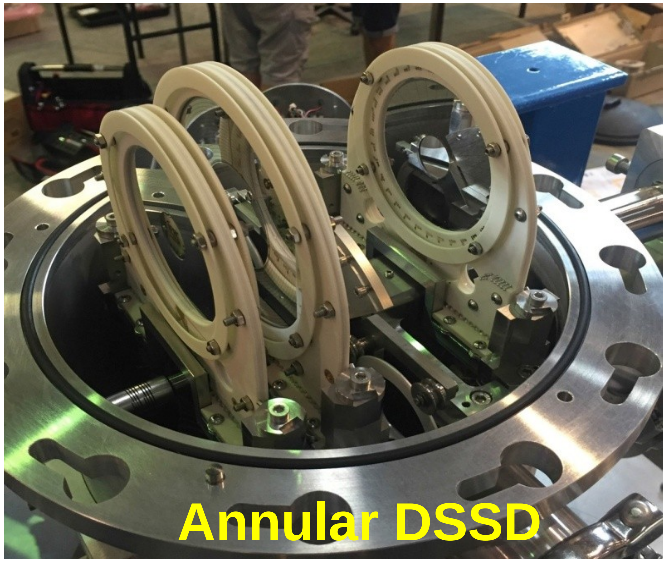
The STELLA project

Coincidence measurement

- Direct measurement of the $^{12}C+^{12}C$ cross section @ ANDROMEDE-Orsay (4 MV Pelletron)
- Carbon burning in massive stars ($M \geq 8\ M_\odot$)

ε_γ = 8% (440 keV), 5% (1634 keV)

γ-ray / particle coincidence measurement

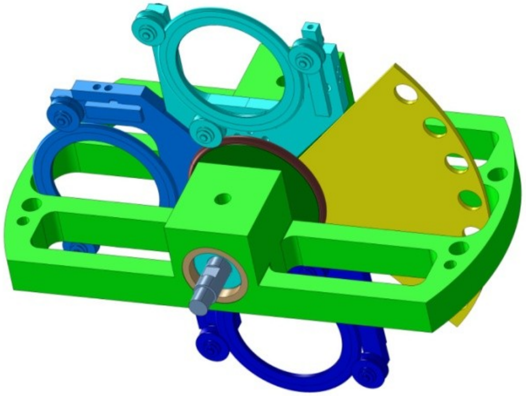


$\Delta\Omega$ = 24% of 4π

Courtin+ (2017)

- Cryogenic pumping
- Rotating target system (> 1000 rpm)

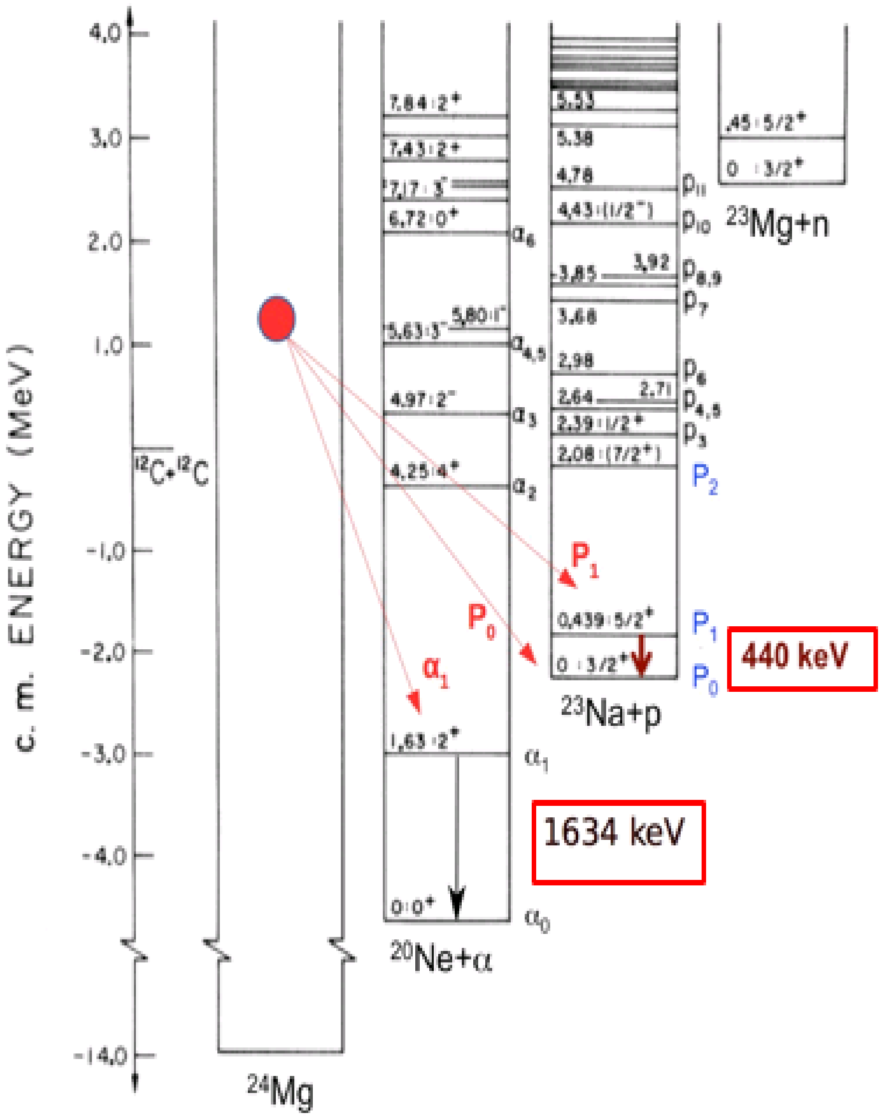
→ I > 1 pμA



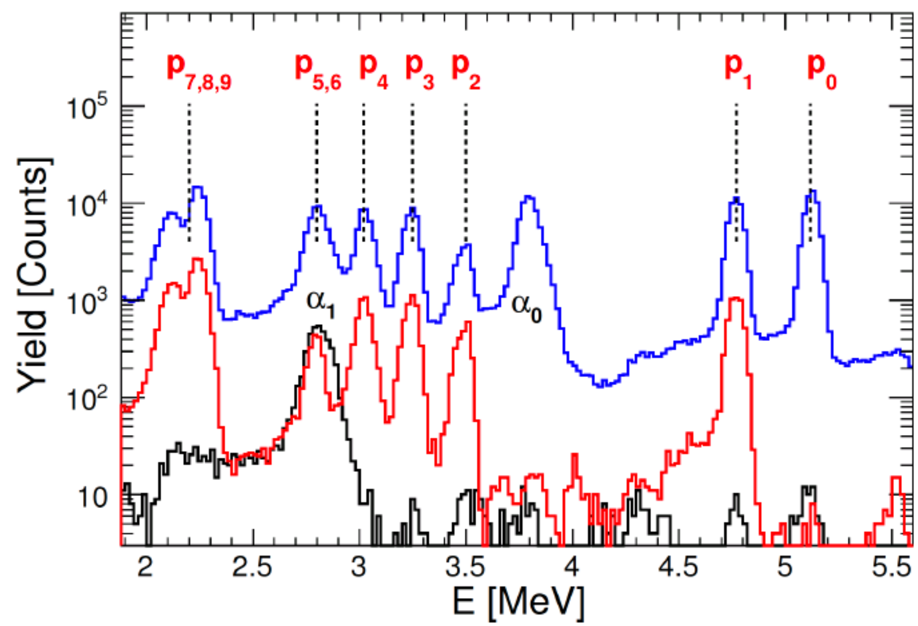
IPHC and GANIL collaboration

Measurements down to E_{cm} ~ 2.1 MeV (E_{coul} = 8.69 MeV)

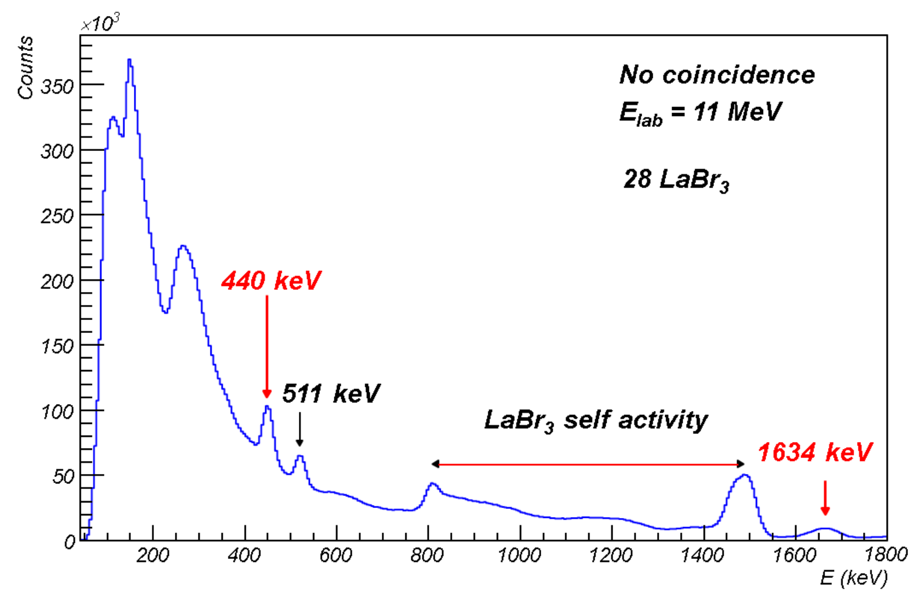
The STELLA project



Without coincidence; Coincidence with E_γ=440 keV; with E_γ=1630 keV



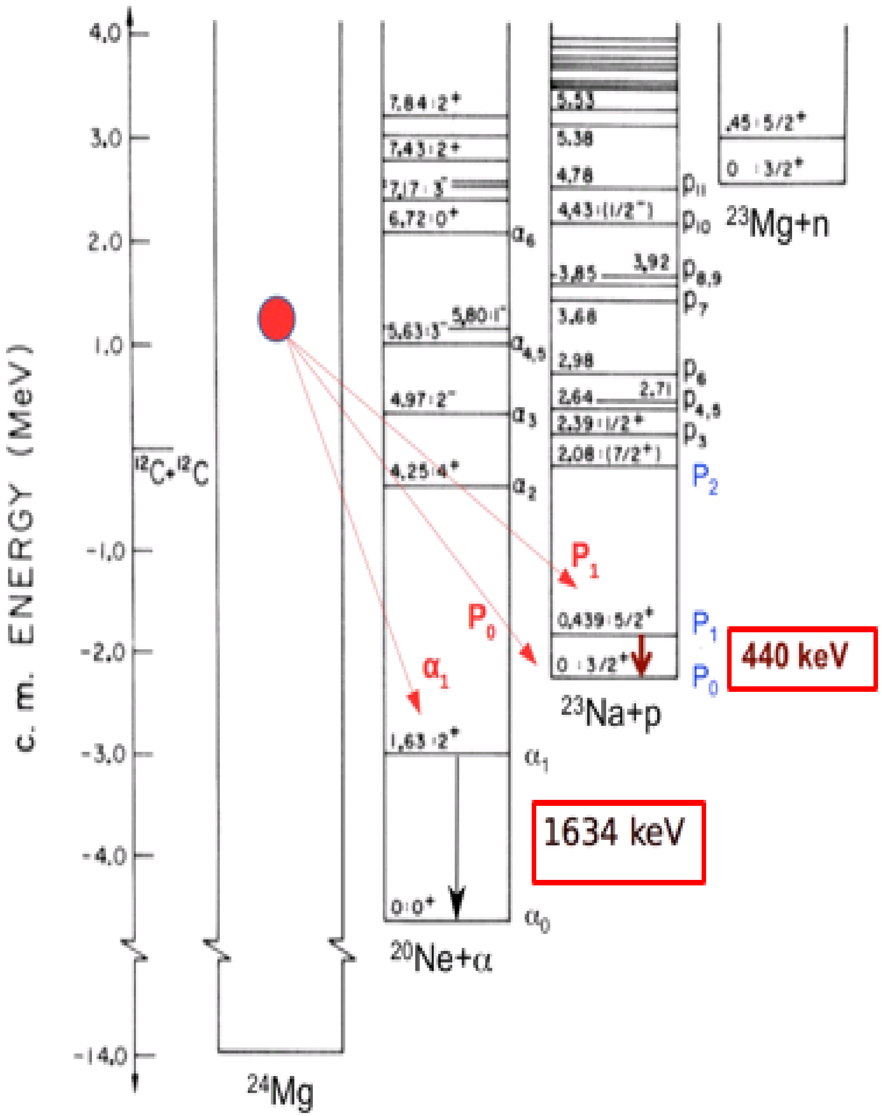
Particle spectrum



γ-ray spectrum

The STELLA project

Coincidence measurement



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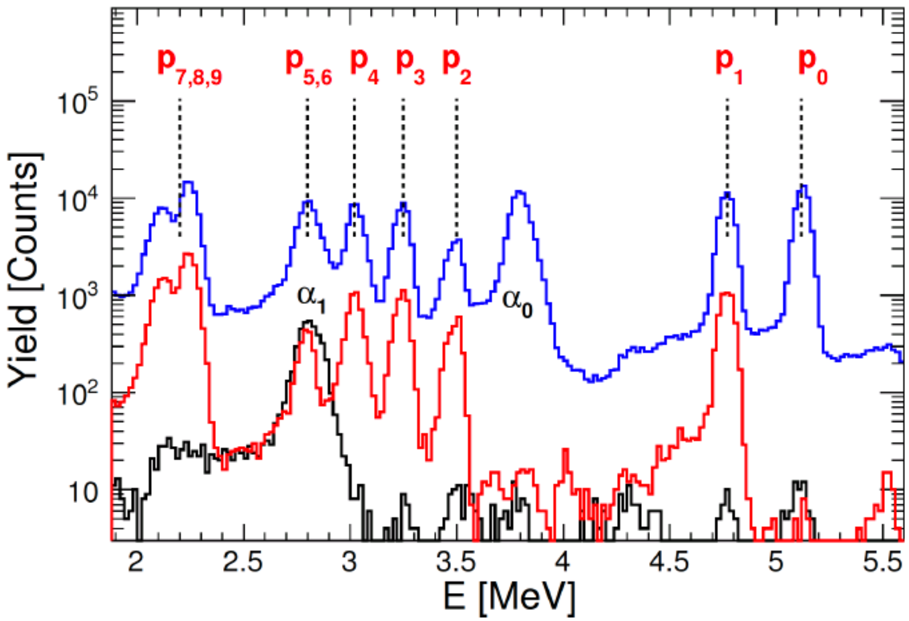
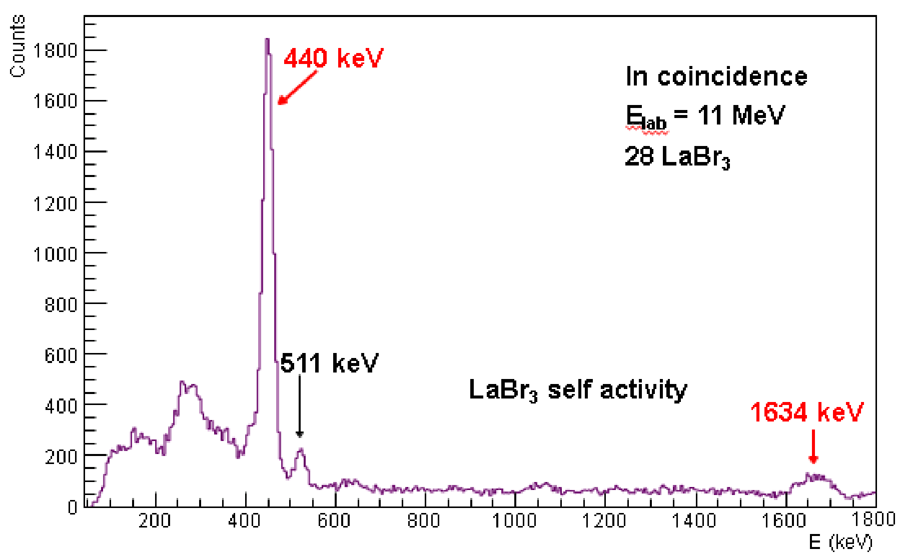
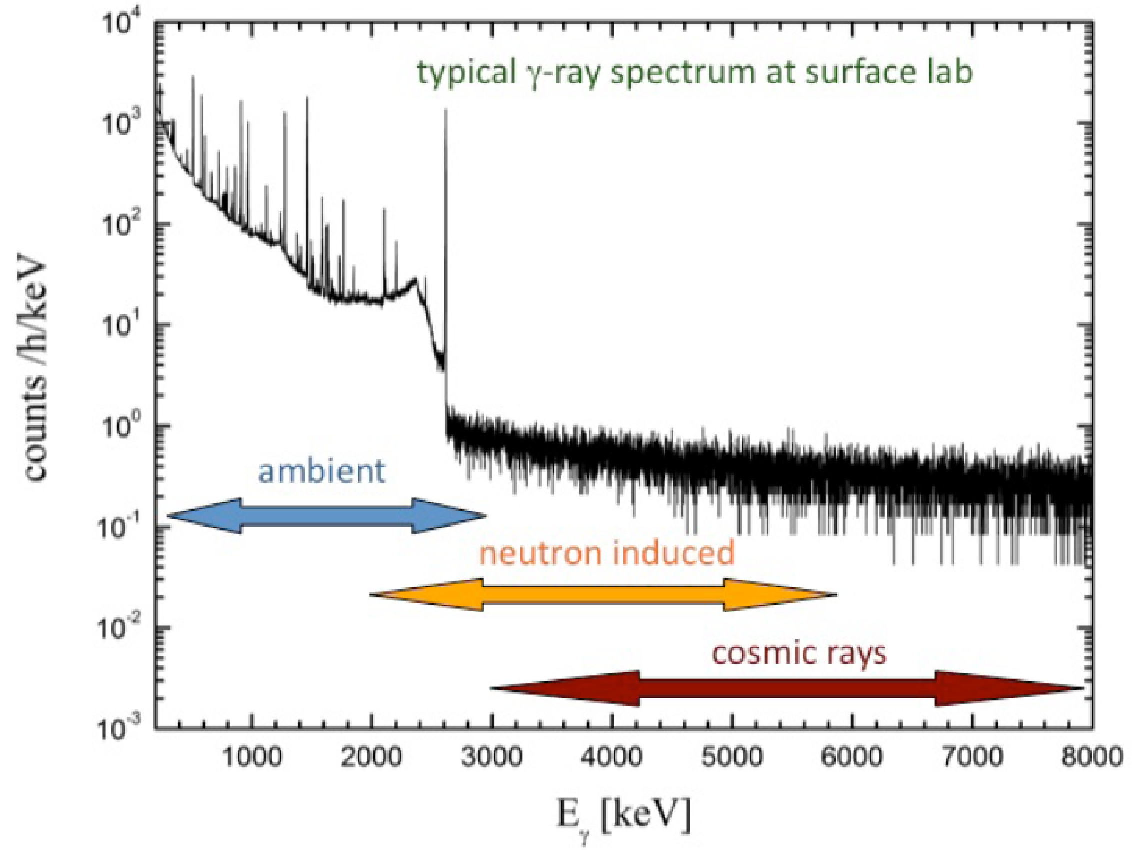




Sources of background at “sea” level

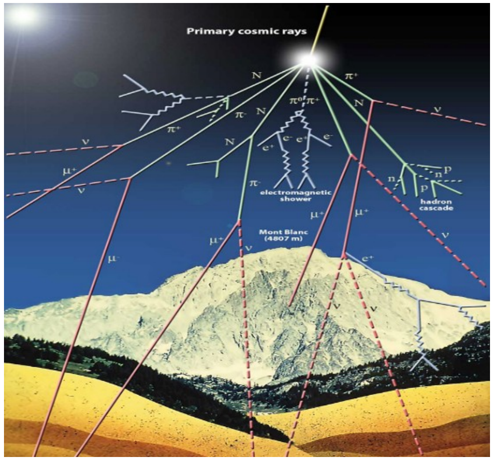
Main sources of γ-ray background

- Natural background (ambient)
  - Natural ^{238}U and ^{232}Th chains
  - Radon (^{232}Rn)
  - Long lived radionuclides (^{40}K…)
  - Cosmogenic radionuclides (^{14}C, ^{22}Na, ^{26}Al...)
- Cosmic rays (muons)
- Neutrons from (α,n) reactions and fission



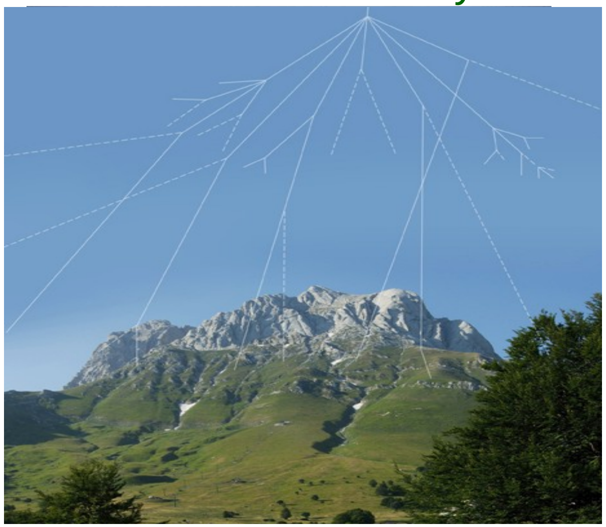
In case where background is dominated by cosmic rays (interaction of muons in experimental setup), poor signal-to-noise at surface level

→ going underground + low U/Th environment

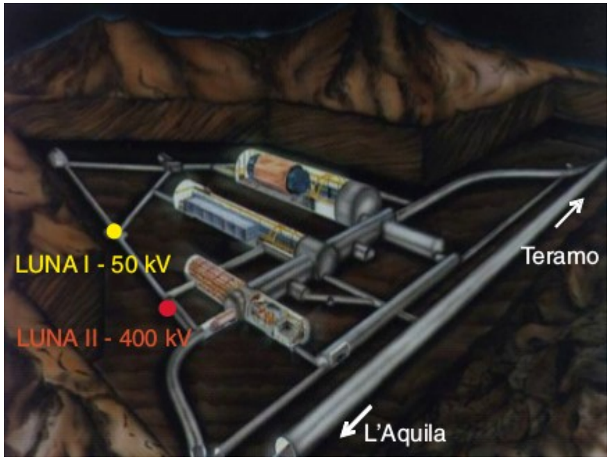


LUNA (Laboratory Underground for Nuclear Astrophysics) facility

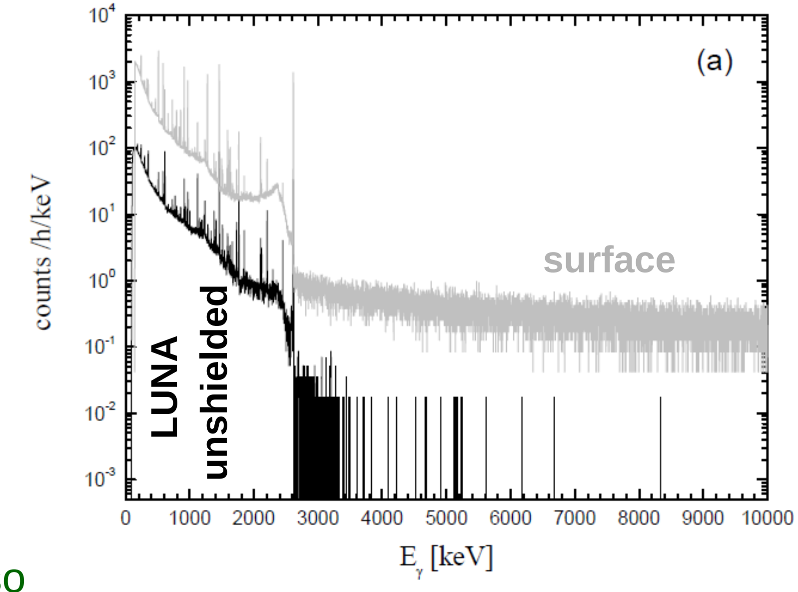
Gran Sasso – Italy

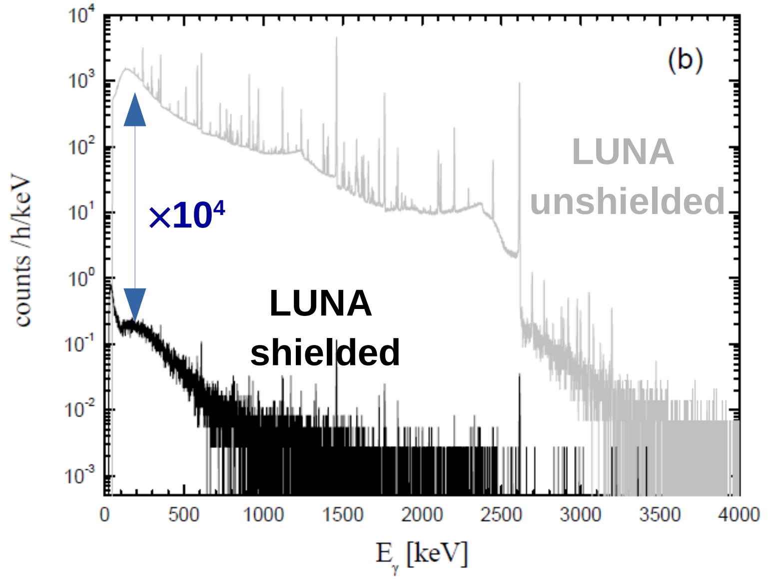


Laboratori Nazionali del Gran Sasso



1400 m rock





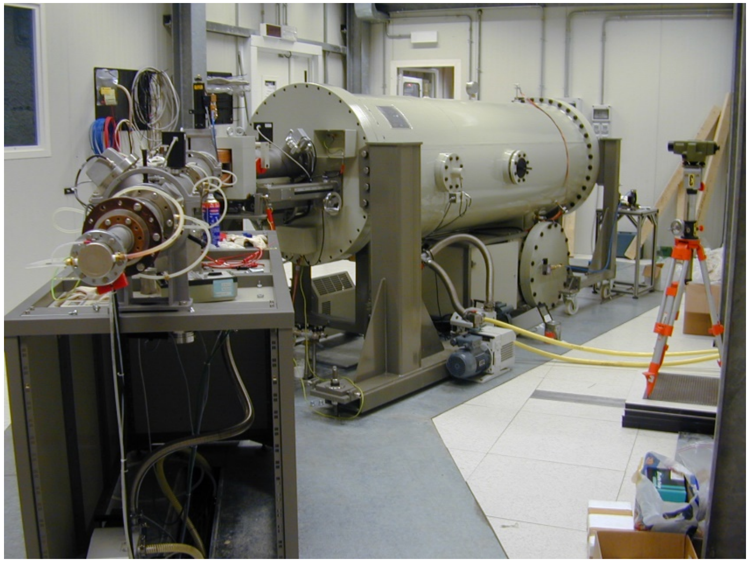
Background reduction in LNGS

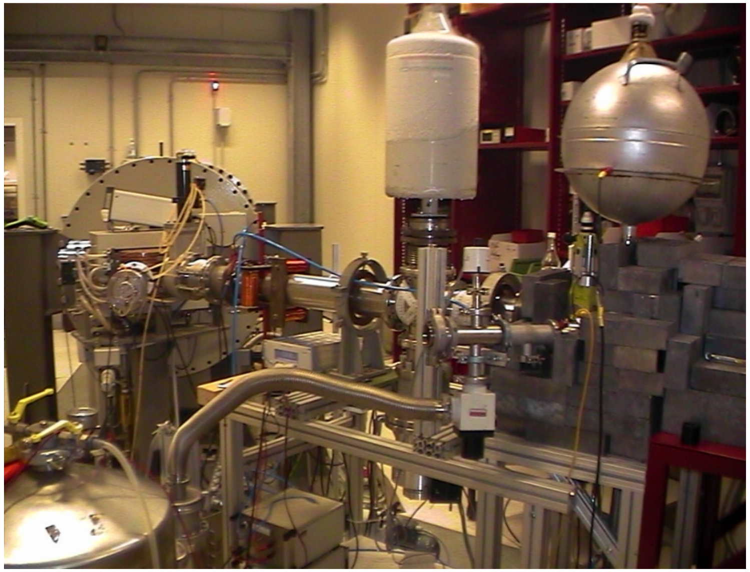
Radiation	LNGS/surface
muons	10^{-6}
neutrons	10^{-3}
photons	10^{-1}

Very high suppression factor with underground lead shielding

LUNA – Phase 2

400 kV accelerator (2002-2012)





Formicola+, NIMA (2003)

Voltage range: 50 – 400 keV
Output current: 1 mA Hydrogen, 500 μA He^{+}

Precise determination of beam energy E_B and beam energy spread ($\Delta E_B < 100$ eV) is extremely important at very low energies (e.g. < 100 keV) due to the exponential drop of cross section

⇒ Measurement of very well known ^{25,26}Mg(p,γ) and ^{23}Na(p,γ) resonances between 300- and 400-keV

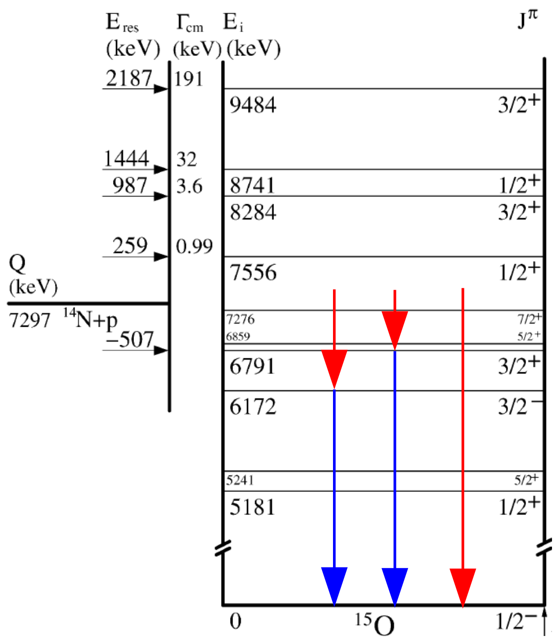
Case of the ^{14}N(p,γ)^{15}O reaction

- Error of 1.5 keV in E_B at E_p = 100 keV
  → ~ 20% error in cross section
- With an error of 300 eV in E_B at E_p = 100 keV
  → ~ 5% error in cross section

The $^{14}N(p,\gamma)^{15}O$ case – experiment

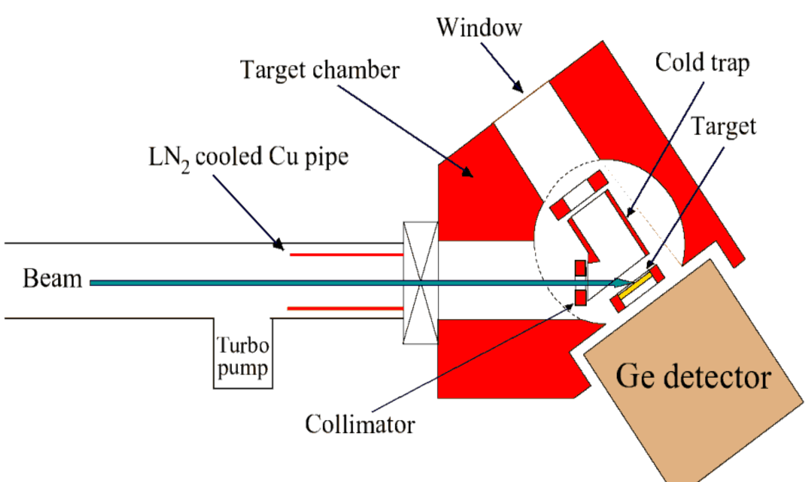
CNO solar neutrinos + Globular Cluster age

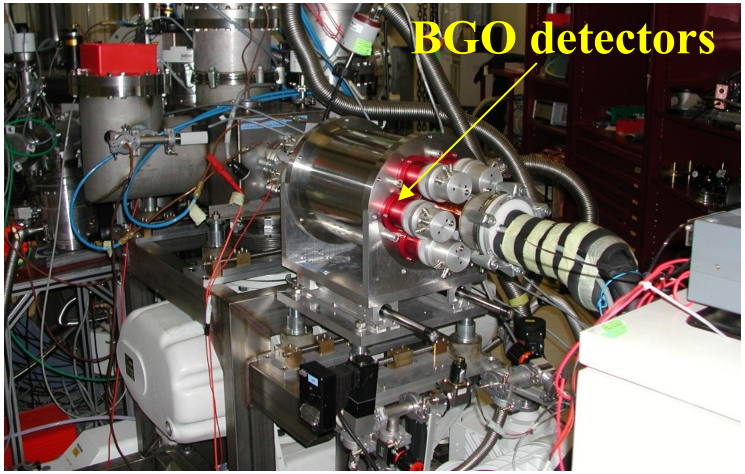
- Gamow peak: 30 – 110 keV
- Contributing resonances: low energy tail of E_r = 259 keV + subthreshold E_r = - 21 keV



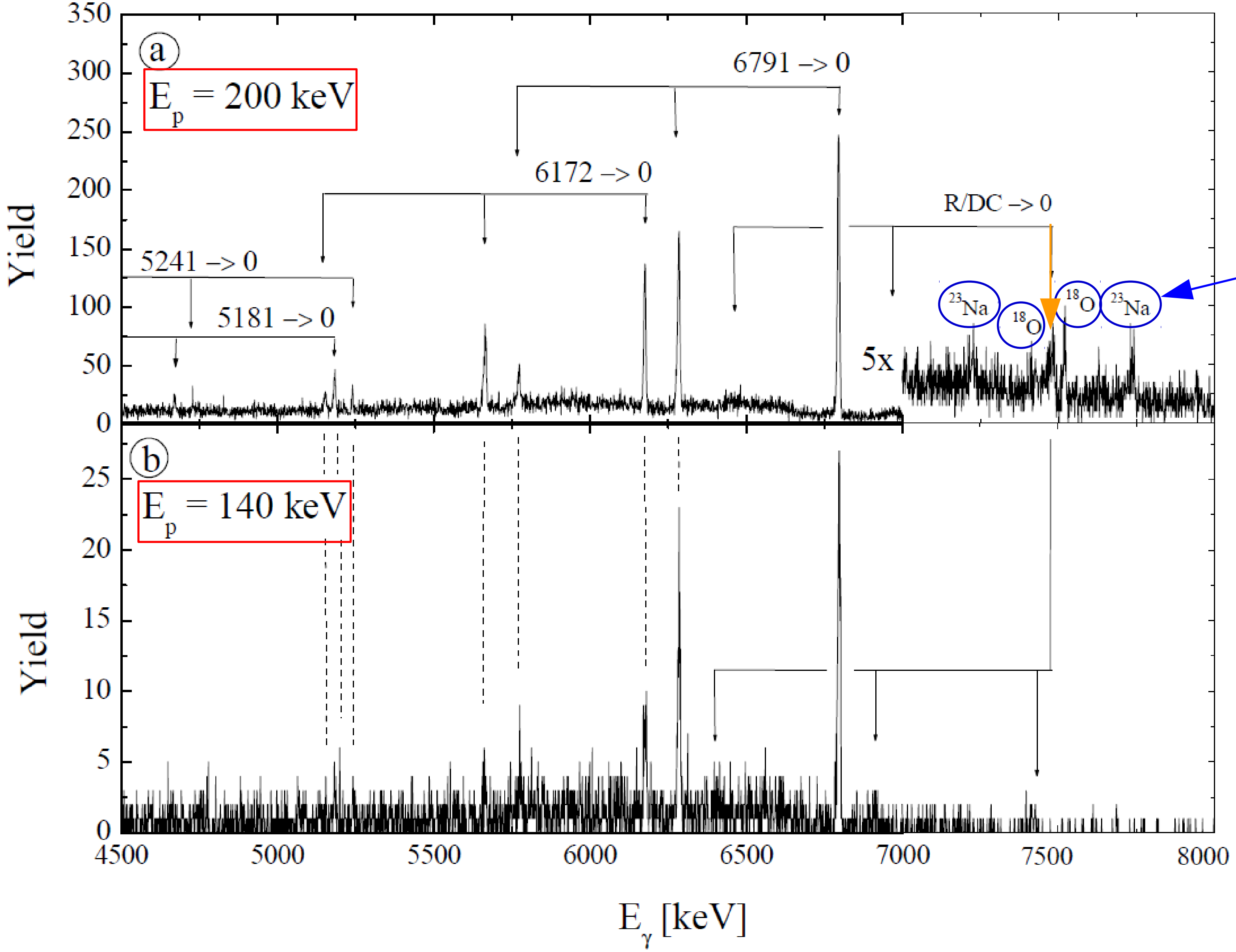
Measurements

- High-energy E_p = 114 – 367 keV (E_{cm} = 106 – 343 keV)
  → HPGe detectors + solid TiN target
  → high resolution measurement of all γ-ray transitions & branching ratios
- Low-energy E_p = 70 – 230 keV (E_{cm} = 65 – 215 keV)
  → BGO detectors + Nitrogen gas target
  → high efficiency measurement ($\varepsilon_\gamma \approx$ 70%) for 7 MeV γ-rays → total cross section measurement





$^{14}N(p,\gamma)^{15}O$ – “high” energy measurement



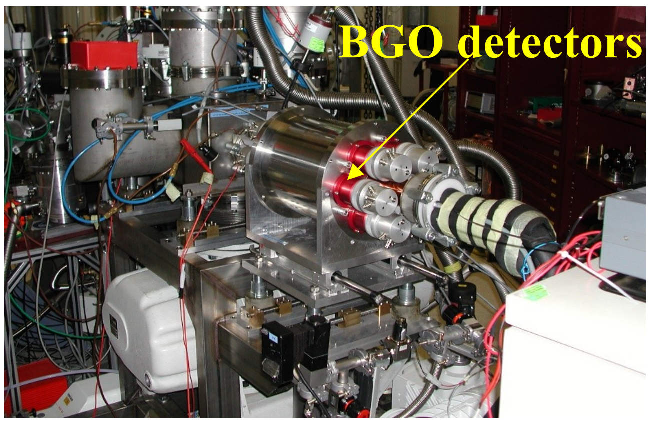
Q = 85 C
t = 62 h

Contamination in target

Q = 222 C
t = 396 h
= 16.5 days!

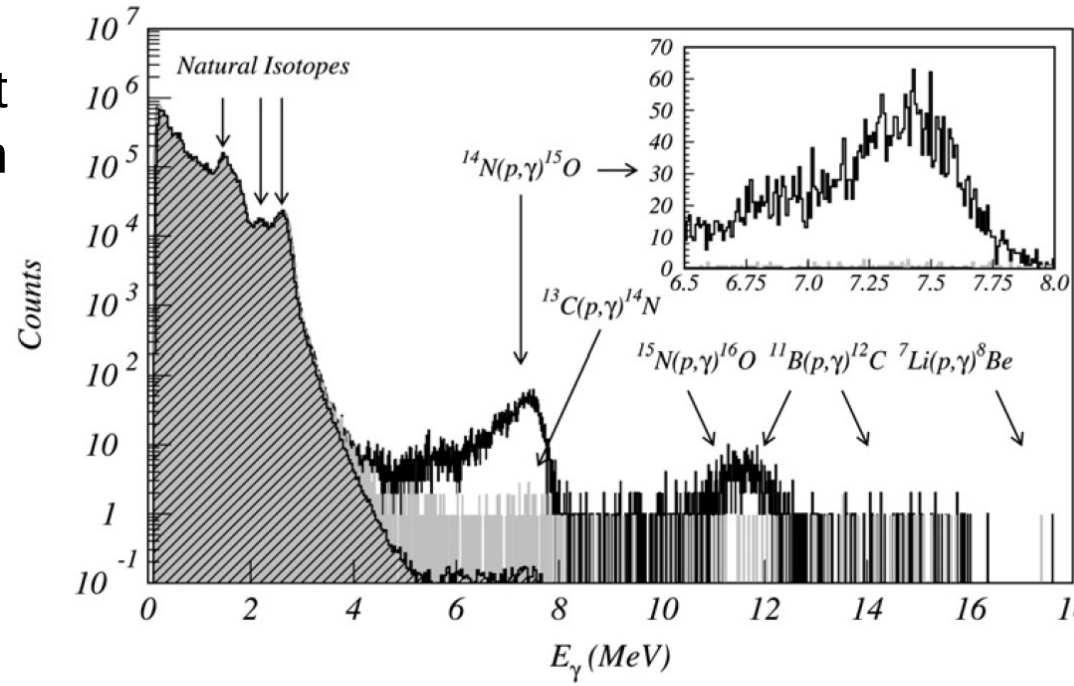
$^{14}N(p,\gamma)^{15}O$ – low energy measurement

- Low energy measurement needs high γ-ray detection efficiency
  → BGO array

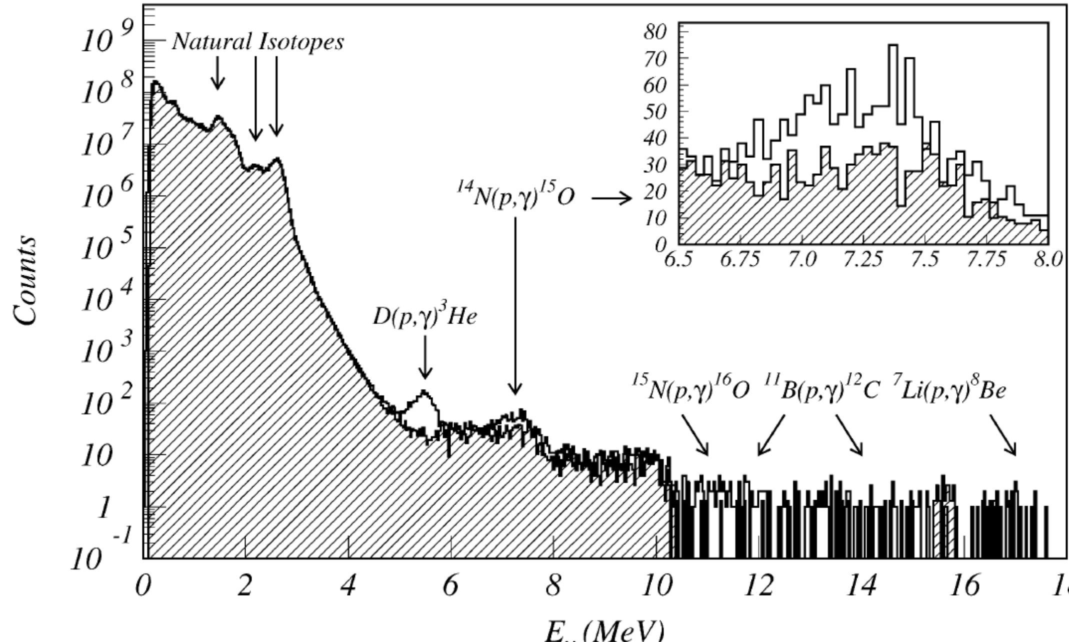


- Summing technique:
  → primary and secondary γ-rays arising from transitions to intermediate states of ^{15}O get summed in a "full energy" peak

Bemmerer+, NPA (2006)



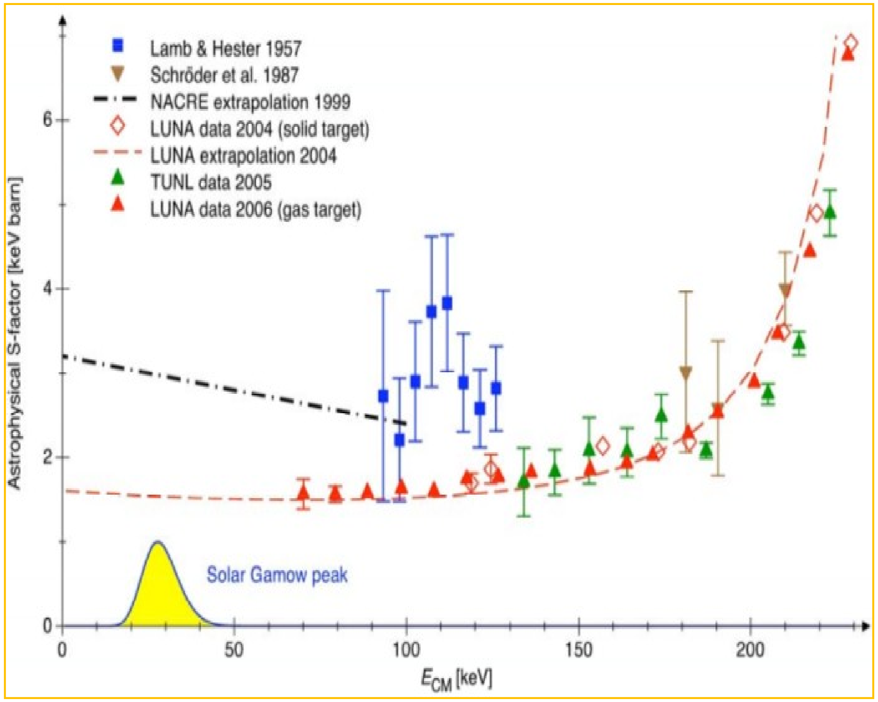
E_p = 141.1 keV
Q = 19.9 C
t = 0.9 day



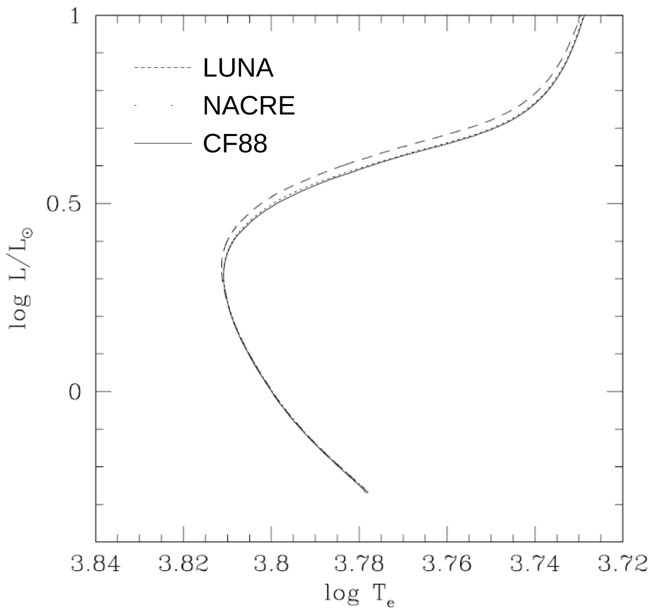
E_p = 80.9 keV
E_{eff} = 70 keV
Q = 928 C
t = 49.1 days

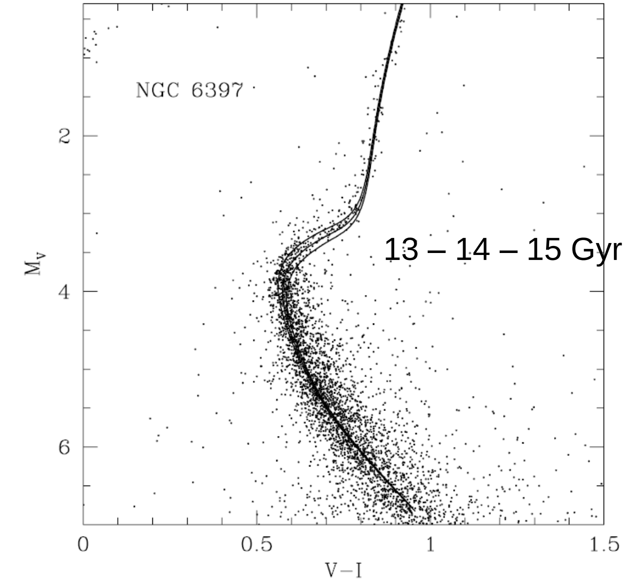
The $^{14}N(p,\gamma)^{15}O$ case – results

Astrophysical *S*-factor



Isochrones & Globular Clusters





Imbriani+, A&A (2004)

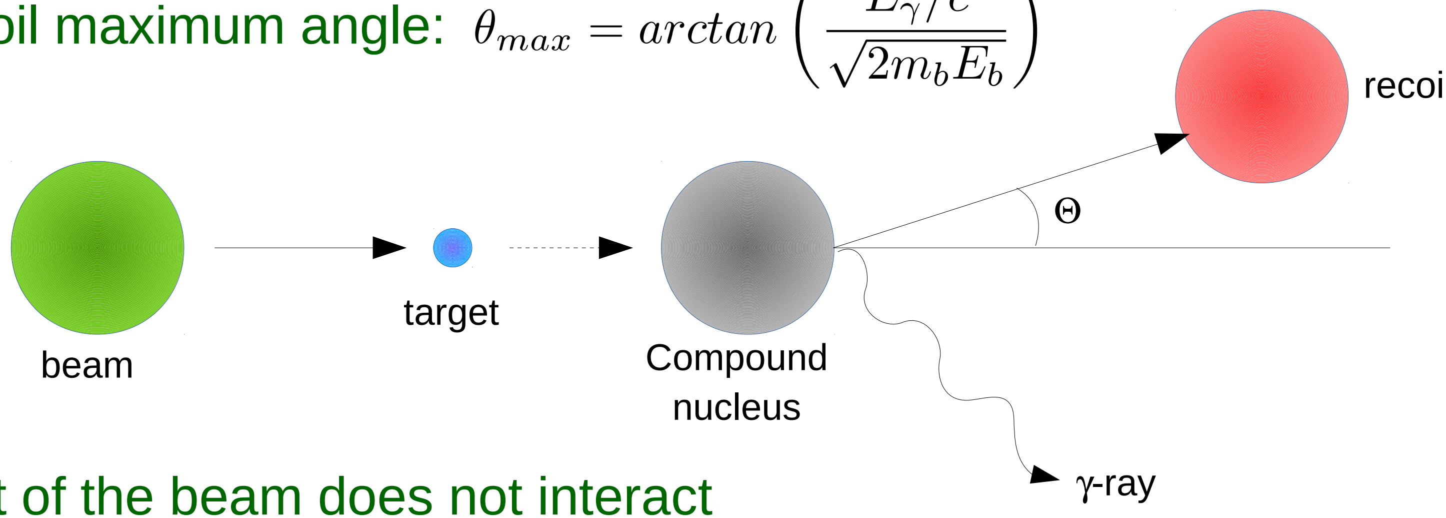
Astrophysical impact

- Solar neutrino flux from CNO cycle reduced by a factor of 2!
- Age of globular cluster increased by 1 Gyr!!

Recoil separators

- Well adapted to study radiative capture reactions [(p,γ), (α,γ)] in inverse kinematics

- Recoil maximum angle: $\theta_{max} = arctan\left(\frac{E_\gamma/c}{\sqrt{2m_bE_b}}\right)$

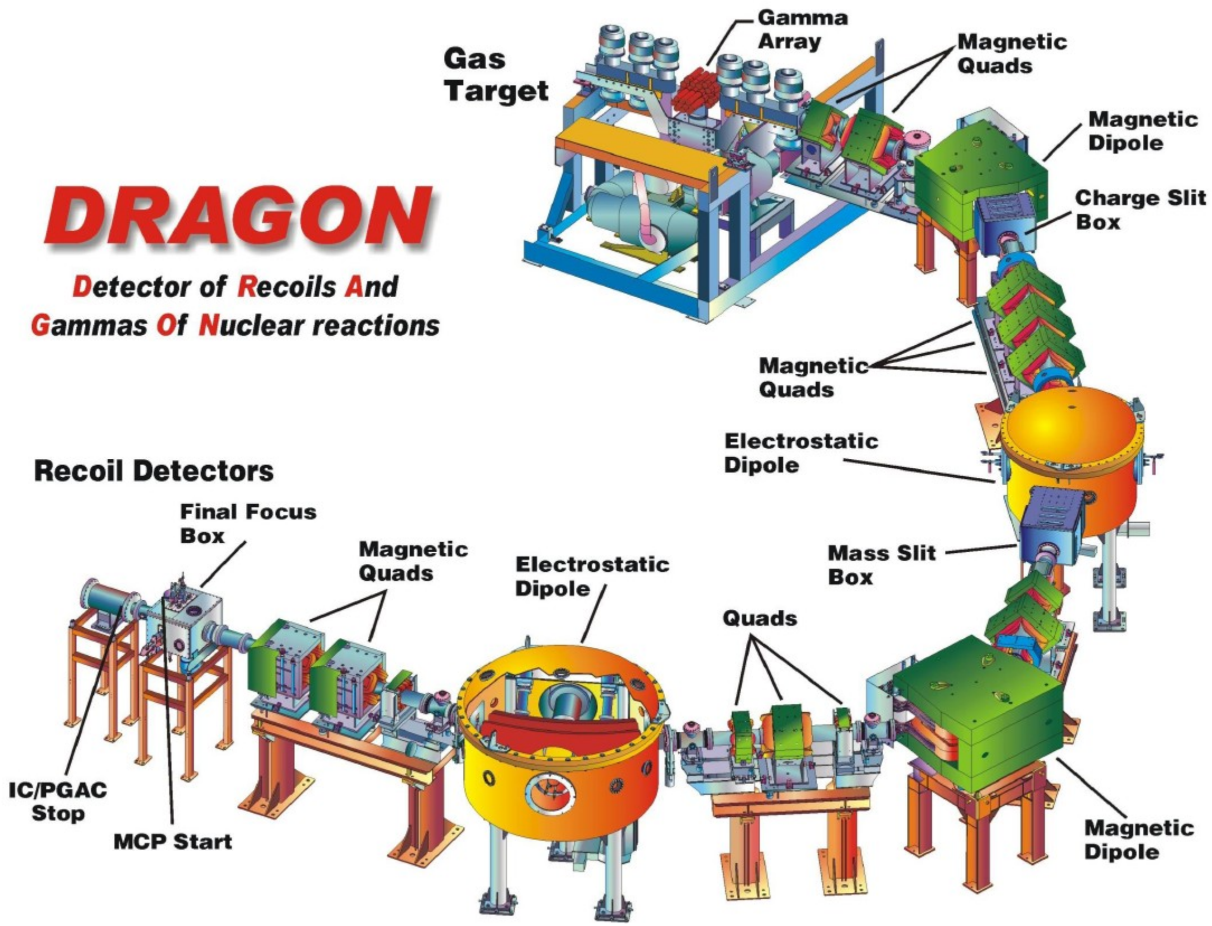


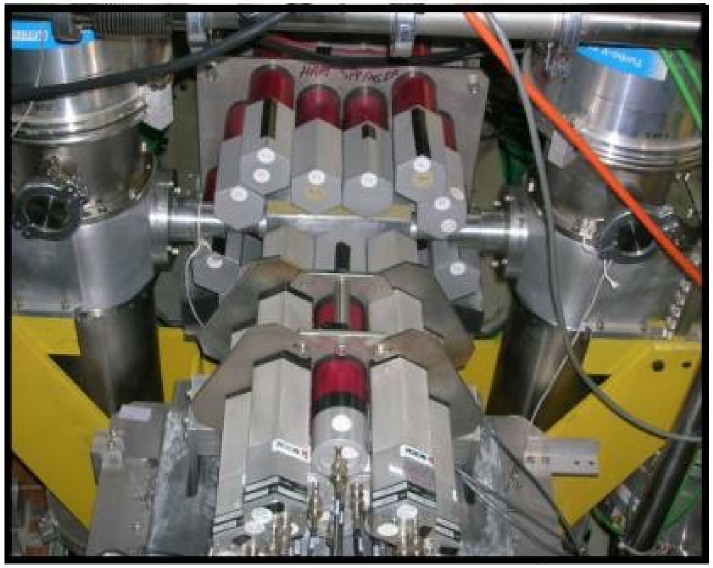
- Most of the beam does not interact
  → recoil separator system needed to:
  - Transport the recoil ions to a detection system (~100 % efficiency)
  - Reject the incident beam

- (few) examples of recoil separator
  - DRAGON (TRIUMF, Canada)
  - St George (NSL, Notre Dame)
  - SECAR (FRIB)

Requirements
- High beam suppresion factor $10^{10} – 10^{15}$
- Large acceptance [(α,γ)]

The DRAGON (1/2)

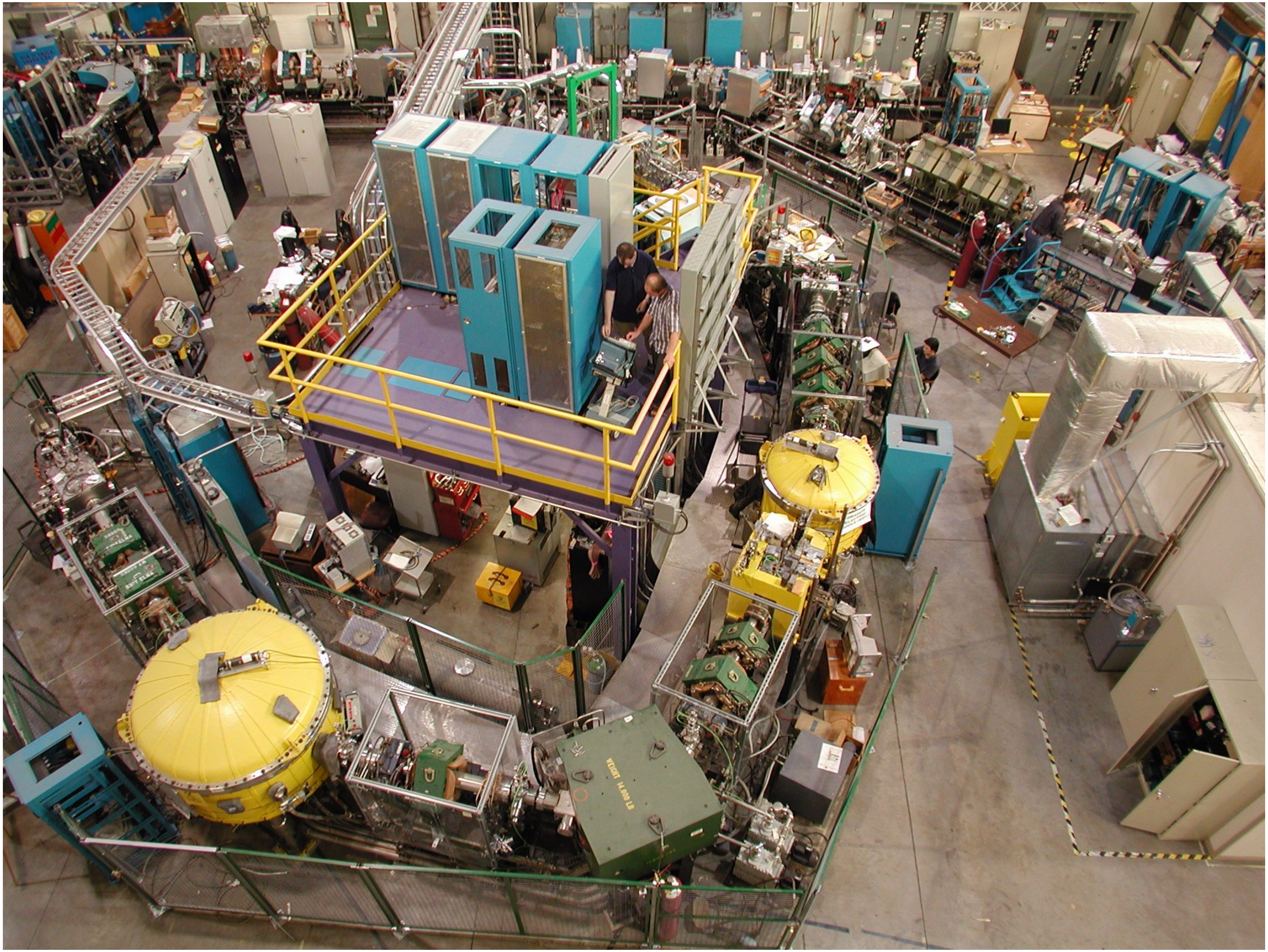




- ISAC 1: RIBs / stable (OLIS)
- 0° spectrometer
- Time of flight: 21 m
- Beam rejection: $10^{12} – 10^{15}$
- Angular acceptance: cone ±20 mrad

- Target: gas/solid
- Focal plane: DSSSD...
- BGO array: ε_γ = 5% @ 5 MeV

The DRAGON (2/2)



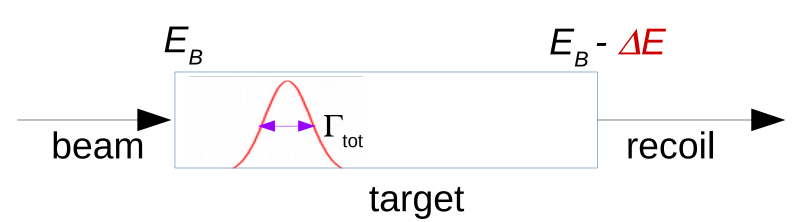
The $^{40}Ca(\alpha,\gamma)^{44}Ti$ reaction @ DRAGON

- ^{44}Ti produced in massive stars has been observed in supernovae remnant (Cas A)

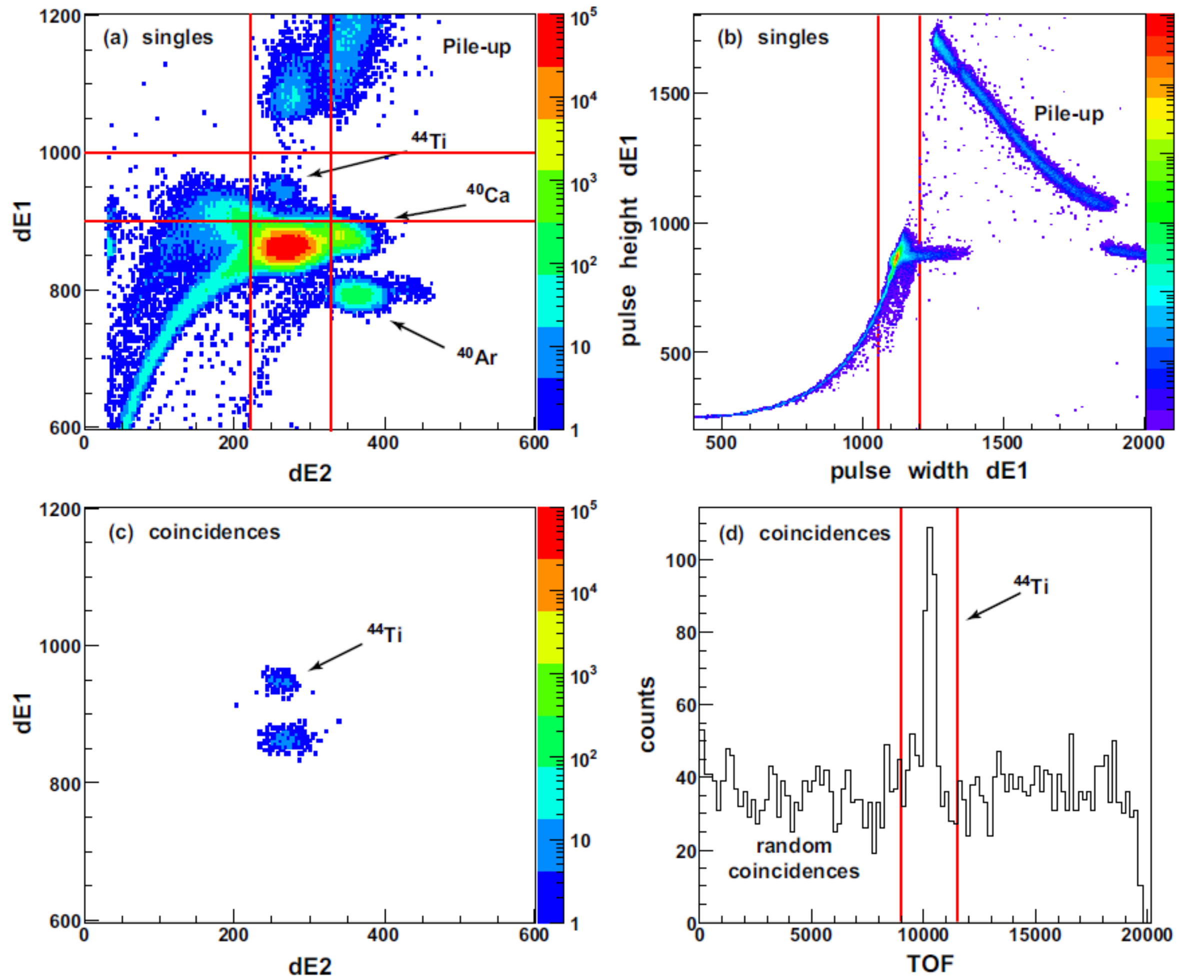
- Direct mesasurement of resonance strength using thick target yield formalism (Γ_{tot} < beam energy loss in the target)

$$\omega\gamma = \frac{2}{\lambda^2}\frac{m_t}{m_p + m_t}\left(\frac{dE}{dx}\right)Y$$

with *dE*/*dx* the stopping power of the projectile in the target



Selection of ^{44}Ti recoil events with the DRAGON



Vockenhuber+ (2007) PRC

Strong resonance @ E_x ~ 9.2 MeV (Y ~ 10^{-10})

Direct measurement: : your turn!

The cross section of the $^2H(p,\gamma)^3He$ reaction was measured at low energies at the LUNA laboratory using a 100 μA proton beam impinging a deuterium gas target (N_T = 1.485×10^{17} at/cm^2). The reaction chamber was surrounded by BGO detectors covering a large solid angle with an efficiency at 5.5 MeV of about 70 %.

Suppose that the total charge Q = 8.64 C was accumulated during an irradiation time of one day at $E_{c.m.}$ = 7.8 keV and that N_{ev} = 20000 γ-rays from the $D(p,\gamma)^3He$ were recorded during this time.

1) What is the reaction cross section at this energy and what is the value of the corresponding *S*-factor?

2) Assuming that the $D(p,\gamma)^3He$ *S*-factor is constant in this energy range, estimate the counting rate if the experiment was performed at $E_{c.m.}$ = 6.65 keV (corresponding to *T* = 15.6 MK).

3) Calculate the rate of the $D(p,\gamma)^3He$ reaction at *T* = 15.6 MK assuming a constant *S*-factor.

4) What is the lifetime at equilibrium of a deuterium nucleus in the core of the Sun with regard to the $D(p,\gamma)^3He$ reaction? Assume a proton density N = 4.5×10^{25} cm^{-3}.

Direct measurement: : your turn!

1) What is the reaction cross section at this energy and what is the value of the corresponding *S*-factor?

Number of incident protons (2 ways):

- $N_p = Q / e = 8.64$ C / 1.6×10^{-19} C = 5.4×10^{19}
- $N_p = I / \mathrm{e} \times \Delta t = 100\times10^{-6}$ A / 1.6×10^{-19} C $\times$ 1x24x3600 = 5.4×10^{19}

Reaction cross section:

- $\sigma = N_{ev} / (N_T \times N_p \times \varepsilon) = 20000 / (1.485\times10^{17}$ x 5.4×10^{19} x $0.7) = 3.56\times10^{-33}$ cm^2 = 3.6 nb

Astrophysical *S*-factor: (see Lecture 3, slide 11)

- $S(\mathrm{E}) = \sigma(\mathrm{E})\, E \exp(2\pi\eta) = 2.63\times10^{-4}$ keV b

2) What is the counting rate at $E_{c.m.} = 6.65$ keV assuming a constant *S*-factor?

Cross section at $E_{c.m.} = 6.65$ keV:

- $S(6.65) = S(7.8) \quad \Rightarrow \quad \sigma(6.65) = 7.8 / 6.65 \times \sigma(7.8) \times \exp[2\pi(\eta(7.8) - \eta(6.65)]$

  $\sigma(6.65) = 0.55 \times \sigma(7.8)$

Counting rate:

- $N_{ev}(6.65) = 0.55 \times N_{ev}(7.8) = 11000$ γ-rays / day

Direct measurement: : your turn!

3) Calculate the rate of the D(p,γ)^{3}He reaction at T = 15.6 MK assuming a constant S-factor (Lecture 3, slide 34, 33)

$$\langle \sigma v \rangle_{123} = 7.20 \times 10^{-19} \frac{\tau^2 \exp\left(-\tau\right)}{Z_1 Z_2 \mu_{amu}} S(E_0) \text{ cm}^3\text{s}^{-1}$$

with $S(E_0)$ in keV b

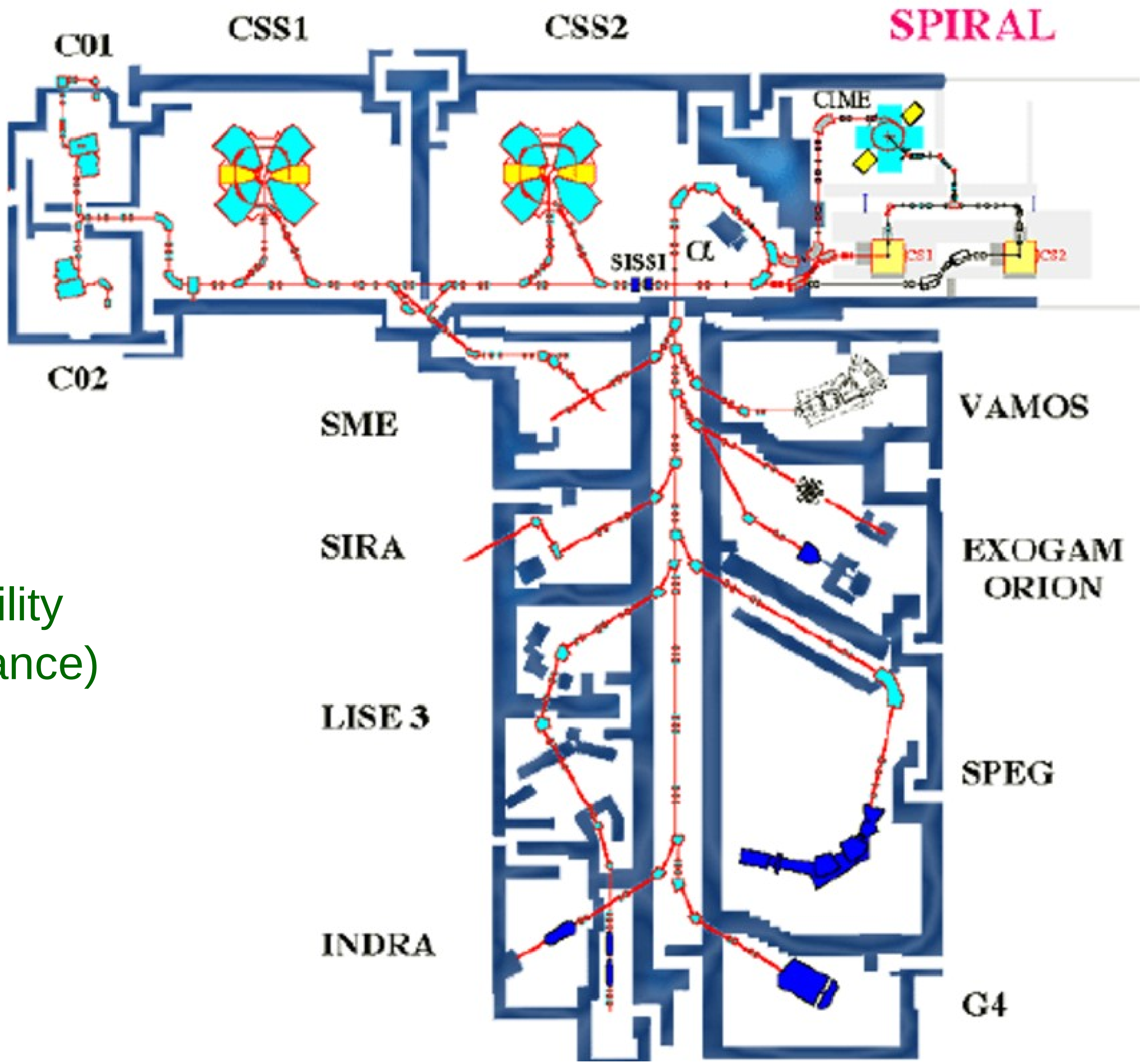
$$\tau = \frac{3E_0}{kT} = 42.46 \left(Z_1^2 Z_2^2 \mu_{amu}/T_6\right)^{1/3}$$

One get τ = 14.84, and $\langle\sigma v\rangle = 2.236\times10^{-26}$ cm^3 s^{-1}

4) Calculate the deuterium lifetime at equilibrium in the Sun core (Lecture 3, slide 26)

- $$\tau_p(D) = \frac{1}{N_p \left\langle \sigma v \right\rangle_{D(p,\gamma)^3He}} = 0.994s$$

2.2 Radioactive ion beams for explosive burning



GANIL facility
(Caen – France)

Characteristics & challenges

- In explosive burning scenarios, because of high temperature and density, the nuclear flow goes through a series of light particle captures forming nuclides far from the valley of stability → **radioactive nuclei**
- Energies E_0 ~ 100's keV – few MeV

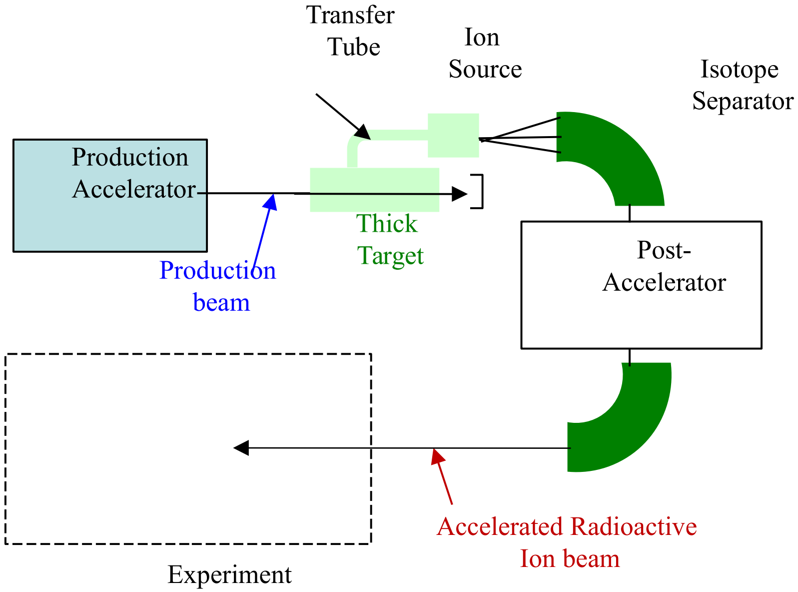
- Technique for measuring cross sections:
  - Radioactive targets: only possible for a few long-lived nuclide, e.g. ^{7}Be (53 d), ^{22}Na (2.6 y), ^{26}Al(0.7 My)
  - Radioactive beams:
    - Inverse kinematics (direct or indirect measurement)
    - Large solid angle detector array & high detection efficiency

- Challenges
  - Low beam intensities → 5 – 8 orders of magnitude lower than for stable beams
  - Usually beam contamination is present
  - Usually beam induces background

Radioactive beam production methods

ISOL (Isotope Separation On Line)

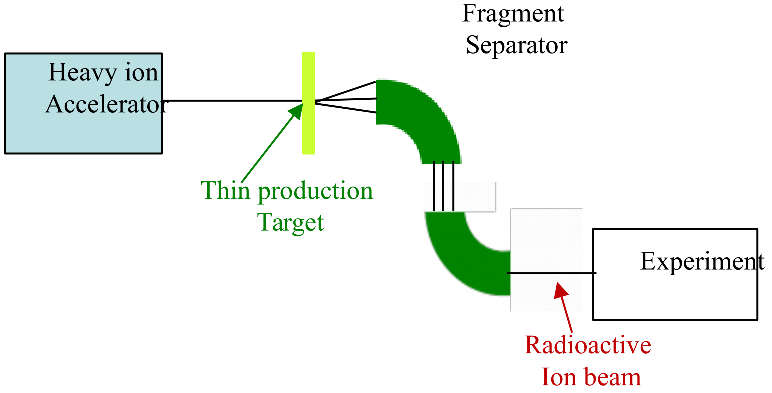
A radioactive beam is produced practically at rest in a thick target bombarded with a primary beam and post-accelerated (SPIRAL1 / GANIL, ALTO)



- ✔ Good beam quality (energy, emittance)
- ✔ High purity
- ✔ Acceptable (high) intensities
- ✖ Limited number of species, depends on chemical properties, limited to $T_{1/2} > 1$ s

Projectile fragmentation

A very high energy beam is fragmented in a low Z target. From the many reaction products, the desired one is selected in mass, charge and momentum via a fragment separator and transported to the experimental area without acceleration (GANIL, GSI, RIKEN, MSU)



- ✔ Independent from chemical properties, no limitation on $T_{1/2}$
- ✖ Beam energy too high for direct measurements
- ✖ Poor beam quality (energy, emittance)
- ✖ Beam contamination

Targets for inverse kinematic studies

H targets for (p,γ) and (p,α) studies

Solid CH_2 target:

- easy to handle
- Δx ~ 50 – few 1000 μg/cm^2

Fusion evaporation background induced from Carbon

Cryogenic solid target:

- No Carbon contamination
- More at/cm^2 for same energy loss

Not easy to handle

He targets for (α,γ) studies

Solid implanted target:

- Easy to handle

- Low concentration (~ 10^{15} – 10^{17} at/cm^2)
- Sputtering (He don't stay in target under irradiation)

Window-confined gas target:

- High concentration (depends on pressure)

Background induced by reactions on entrance and exit windows

Windowless supersonic gas jet target:

- High concentration 10^{19} at/cm^2 (e.g. JENSA)
- No contamination, no degradation

Differential pumping system

Detection setups (a few examples...)

Limited RIB intensities ($\leq 10^7$ pps) require large solid angle & efficient detection setups

Charged particles

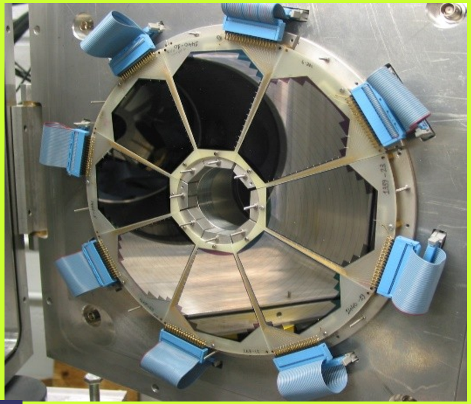
- Large area, highly segmented silicon strip detector arrays: LEDA, MUST2, ORRUBA, SHARC, MUGAST...

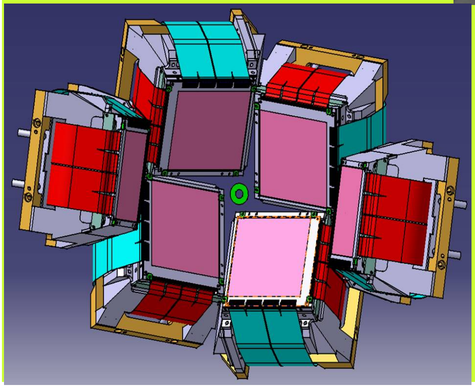
LEDA →

16 strips in θ

300 μm or

500 μm





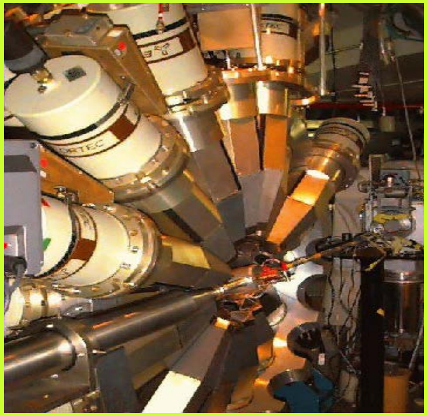
← MUST2 telescopes

3 stages:

- Si 128+128 strips (X, Y) 300 μm (10x10 cm²)
- SiLi 16 pads, 4.5 mm
- CsI, 16 cristals, 5 cm

γ-rays

- Close to 4π coverage to compensate low intrinsic detection efficiency: EXOGAM, AGATA, GRETINA...



Gammasphere

100 HPGe detector array

absolute efficiency: 9% for 1.33 MeV γ-ray

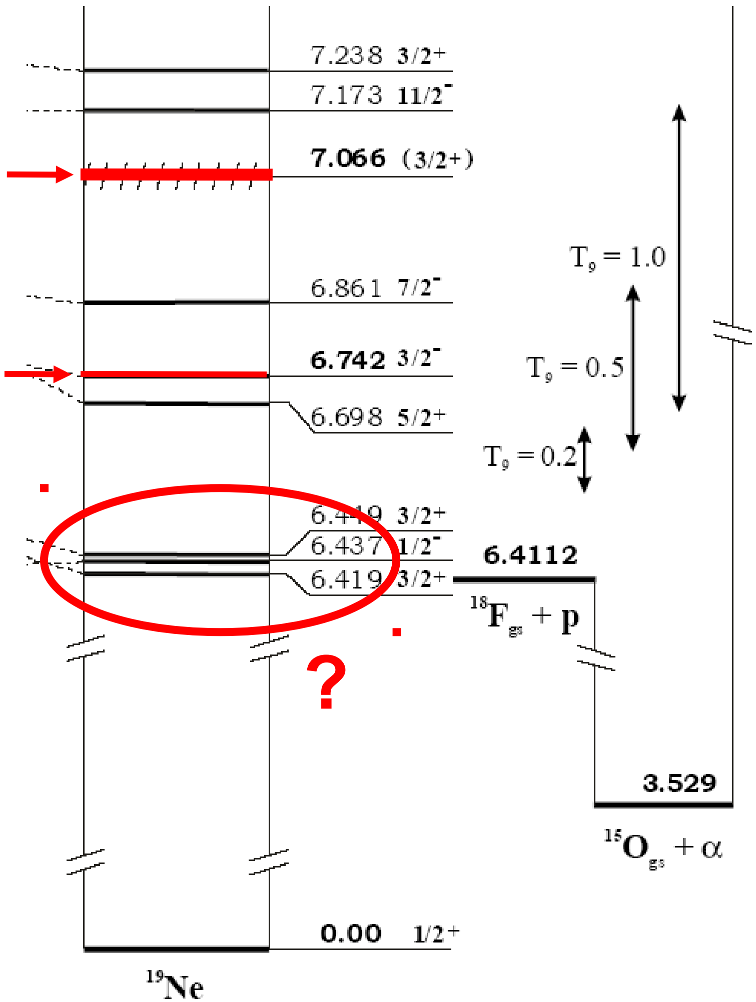
AGATA

4π: $\varepsilon_\gamma \sim 8\% - 14\%$

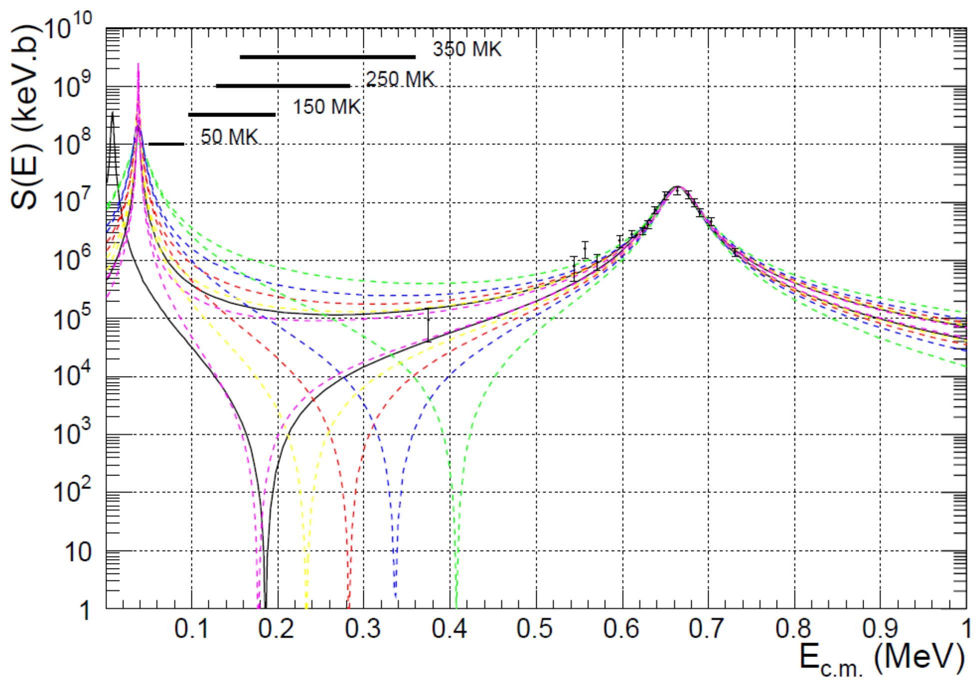
- Large induced γ-ray background from RIB β-decay

The $^{18}F(p,\alpha)^{15}O$ reaction case

- Competition between the $^{18}F(p,\alpha)^{15}O$ reaction and ^{18}F β^+-decay has strong implication on the γ-ray emission at ≤ 511 keV in classical novae



- Interference effects in Gamow peak can significantly change the rate of ^{18}F destruction in classical novae
  - $3/2^+$ states: "8-, 38-" and 665-keV
  - $1/2^+$ states: sub-threshold + 1.4 MeV

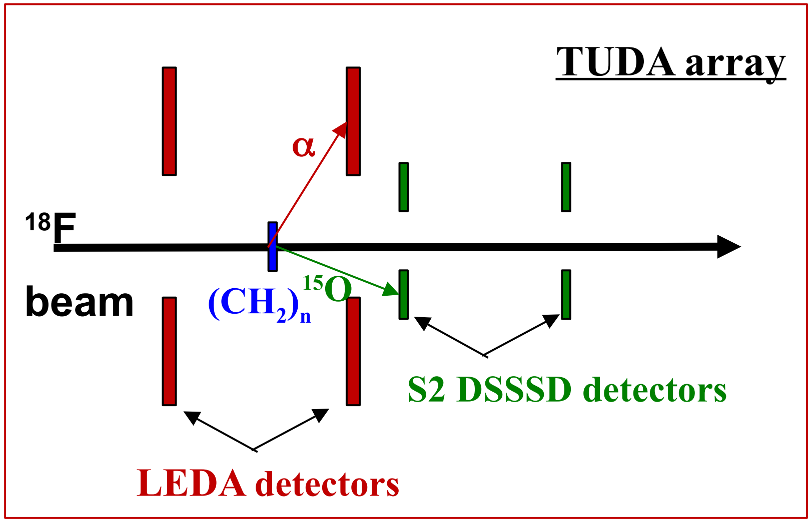


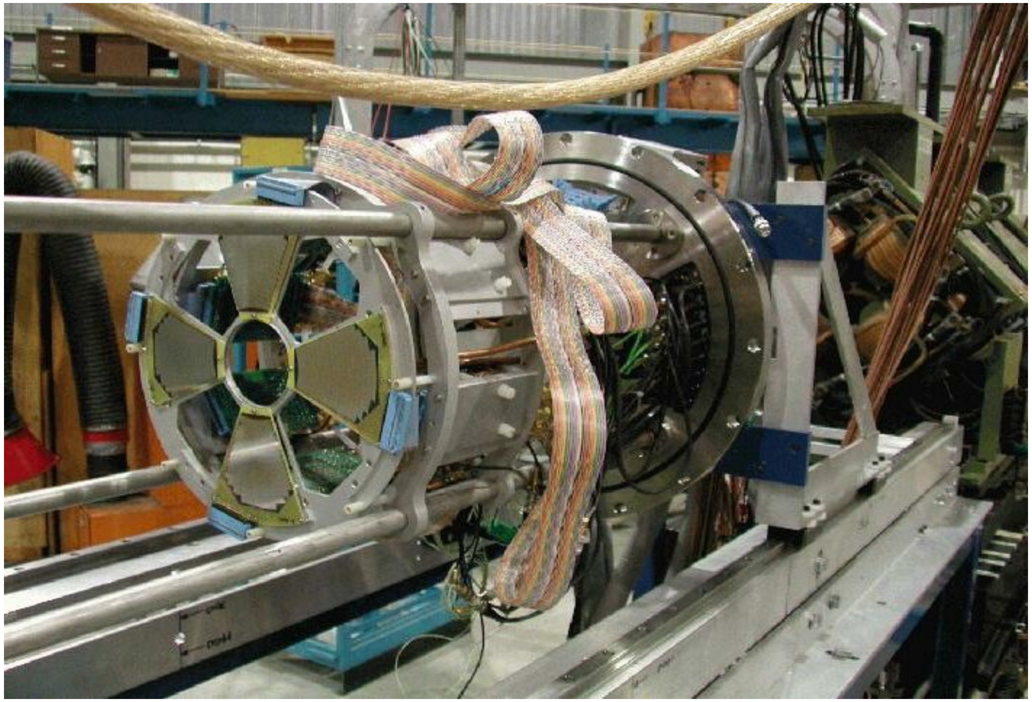
de Séréville+ (2005) NPA

Direct measurement of $^{1}H(^{18}F,\alpha)^{15}O$

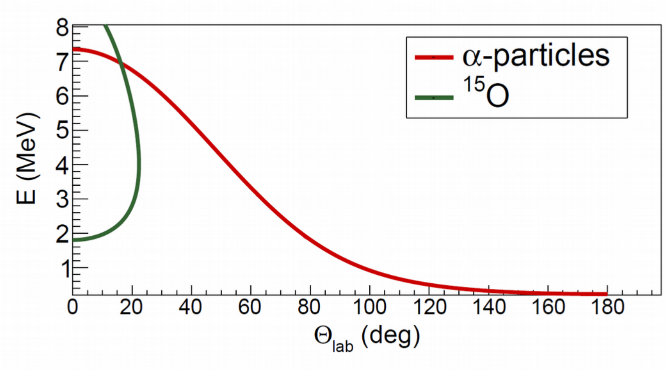
Experimental setup

→ coincident measurement

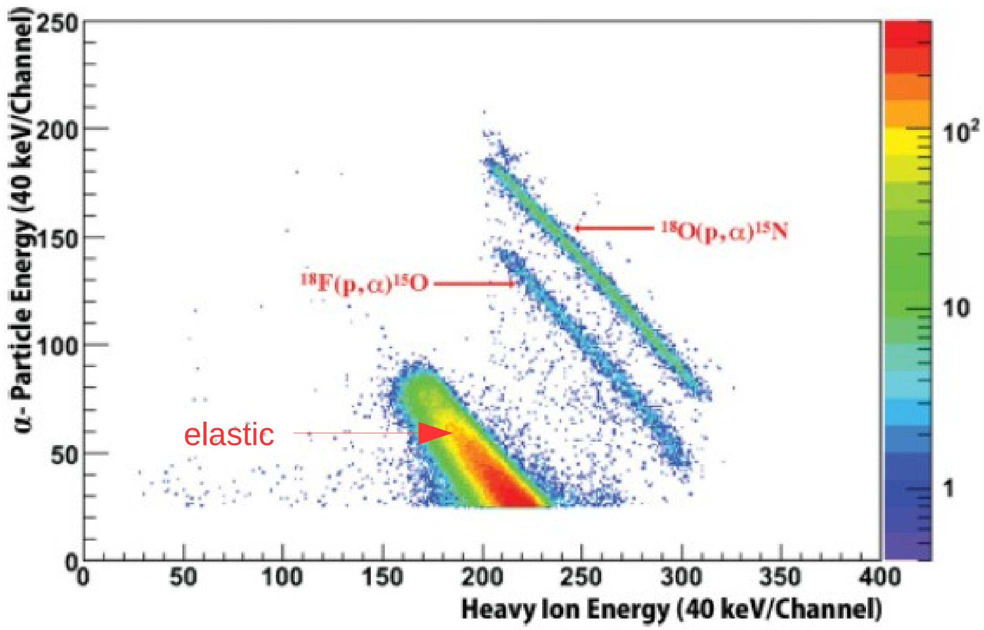


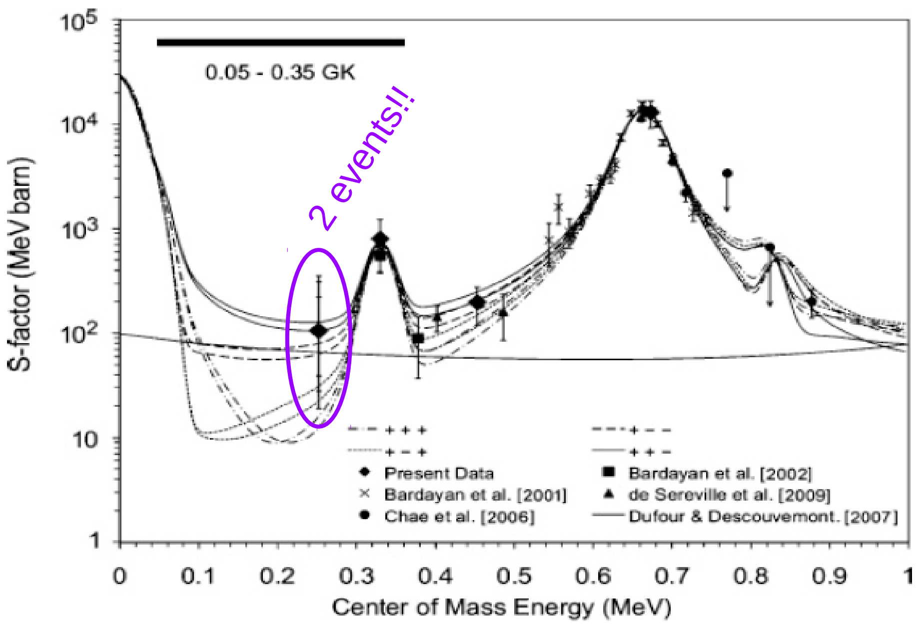


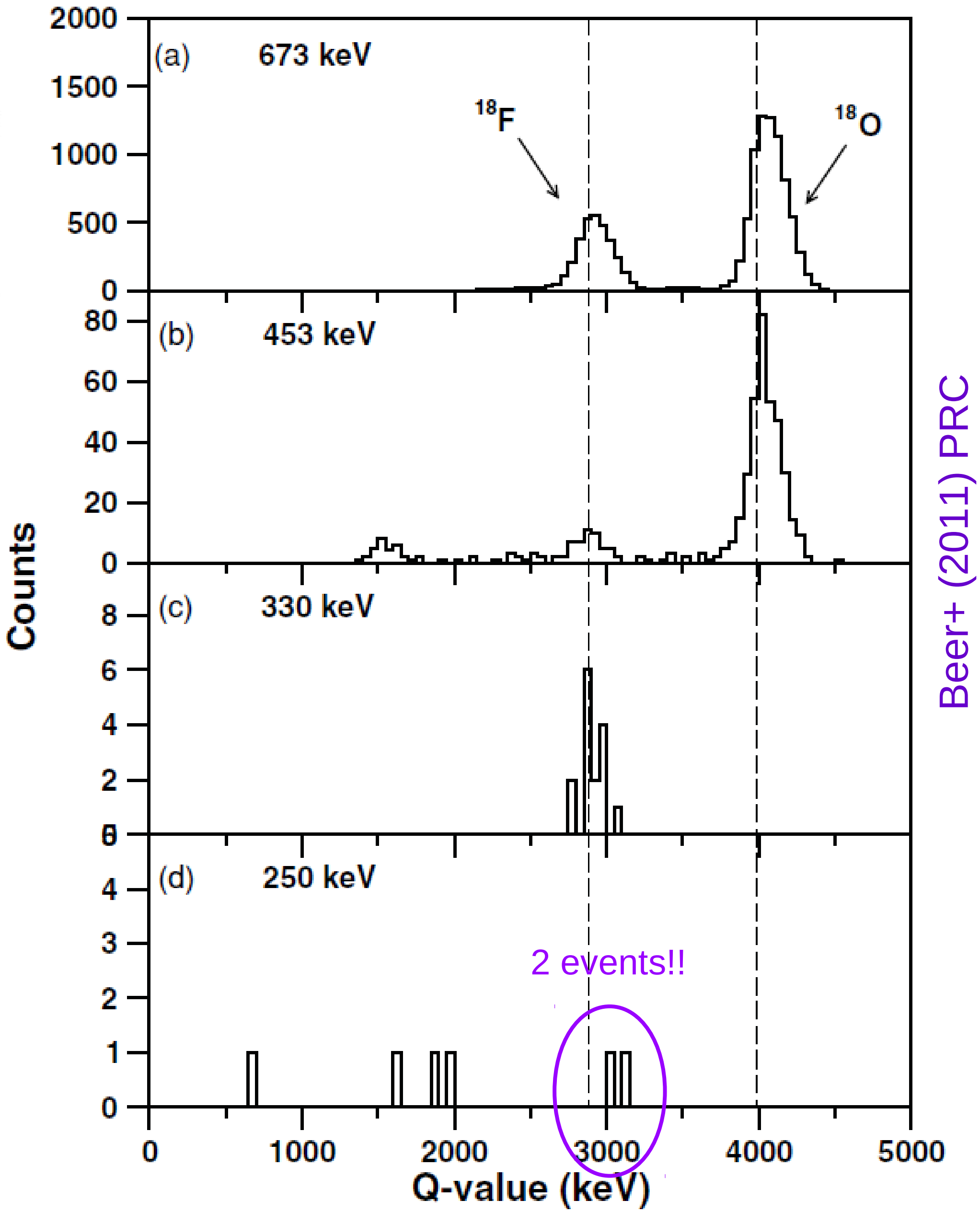
- Beam: ^{18}F (5×10^{6} pps) produced at ISAC (Isotope Separator & Accelerator; TRIUMF; Canada) by bombarding a thick target with 500 MeV proton (up to 100 μA)
- Target: 33 μg/cm^2 CH_2
- Charged particle detectors
  - LEDA → α-particles
  - S2 → ^{15}O



$^{1}H(^{18}F,\alpha)^{15}O$ – results







3. Direct measurements of neutron induced reactions (*s*-process)

Further reading:

- R. Reifarth et al., J. Phys. G.: Nucl. Part. Phys. 41, 053101 (2014)

Experimental approaches

- Maxwellian average cross section (MACS)

$$\langle\sigma\rangle \equiv \frac{\langle\sigma v\rangle}{v_T} = \frac{2}{\sqrt{(\pi)}} \frac{1}{(k_B T)^2} \int_0^\infty \sigma(E) E \exp\left(-\frac{E}{k_B T}\right) dE$$

with the most probable velocity $v_T = \sqrt{k_B T/\mu}$

- Neutrons are unstable particles ($T_{1/2}$ = 614 s), not (yet) possible to perform experiments in inverse kinematics
→ direct measurements of (n,γ) cross section on relatively long-lived samples

- Two different experimental approaches
  - Activation method
    - Produce neutron stellar spectrum in laboratory
    - Measure directly the stellar Maxwell averaged cross section by activation
  - Time of flight method
    - Measure the cross section $\sigma(E_n)$ by time of flight, e.g. 0.3 keV ≤ E_n ≤ 300 keV
    - Determine the MACS

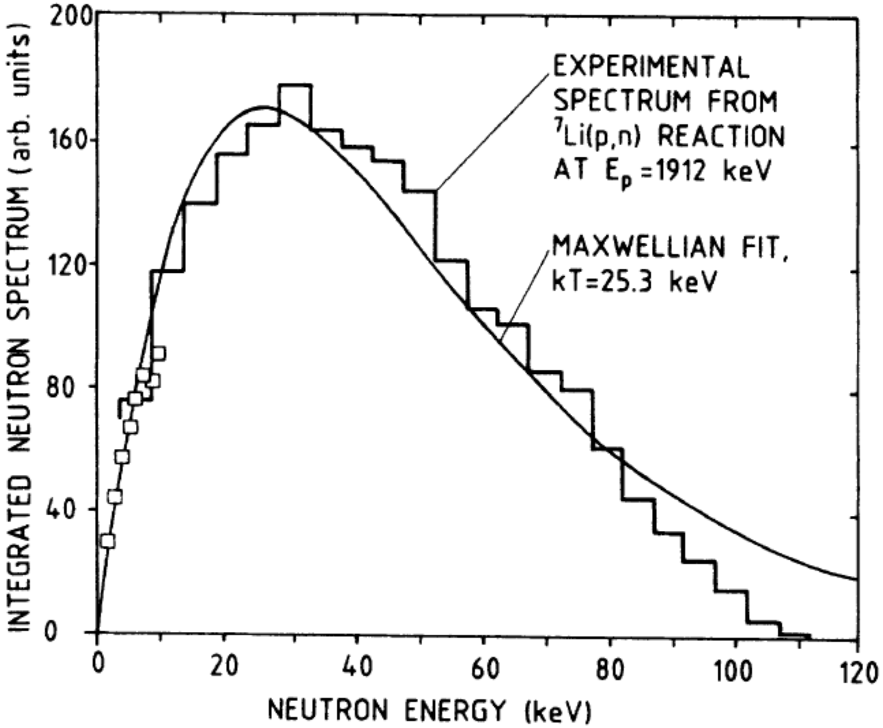
Activation method

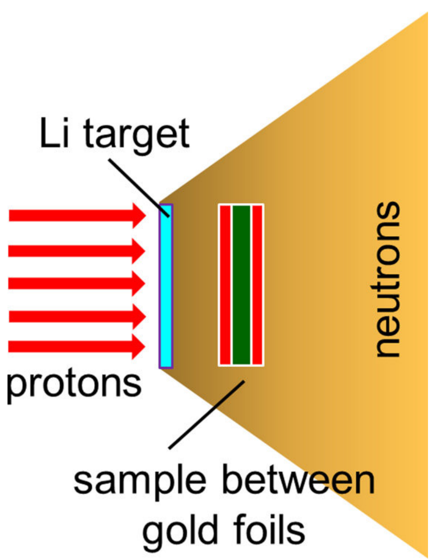
- Neutron produced using the ^{7}Li(p,n)^{7}Be reaction at E_p = 1912 keV

  → simulates a stellar neutron spectrum for thermal energy of $k_B T$ = 25 keV

  → right in the temperature range 250 – 350 MK of *s*-process

3×10^9 neutrons/s @ 100 μA



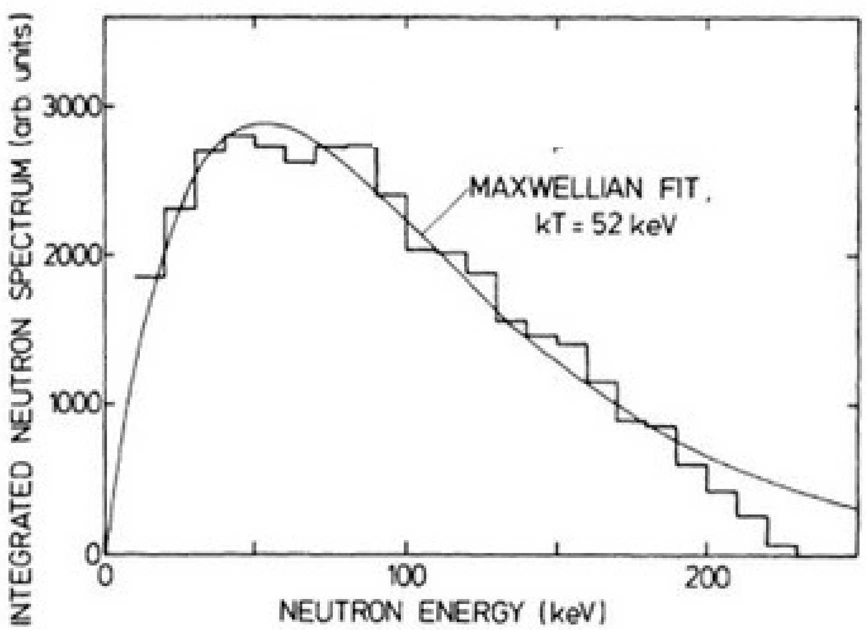


- $\Theta_n < 60°$
- Gold foils for normalization (well-known neutron capture cross section)

- Induced activity is measured after irradiation with HPGe detectors
- $A(n,\gamma)B \xrightarrow{T_{1/2}} C^*(\gamma)C_{g.s.}$

Alternative neutron sources

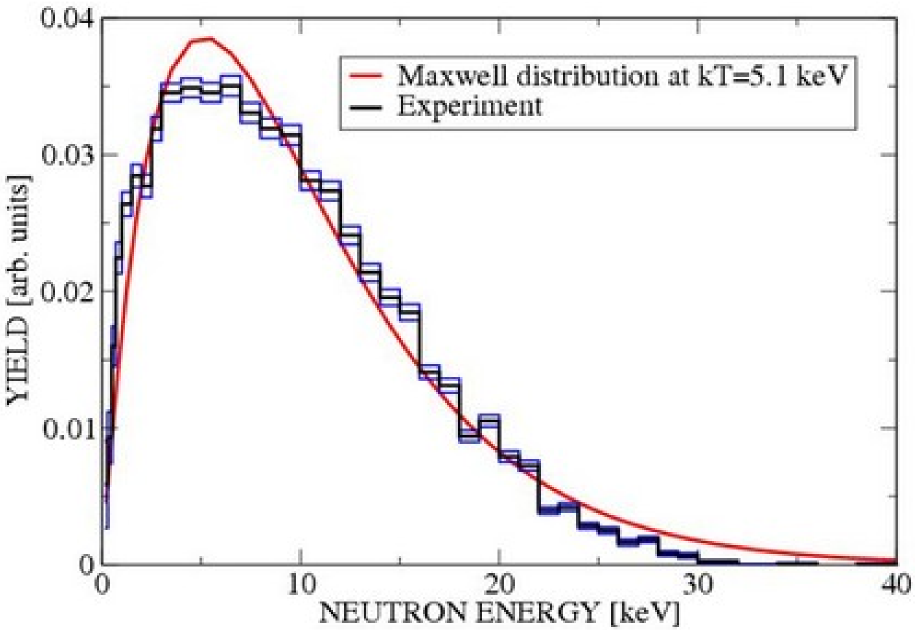
Experimental neutron energy spectrum from the $^3H(p,n)^3He$ reaction at E_p = 1099 keV



Stellar spectrum of k_BT = 52 keV

2×10⁸ neutrons/s @ 100 μA

Experimental neutron energy spectrum from the $^{18}O(p,n)^{18}F$ reaction at E_p = 2582 keV

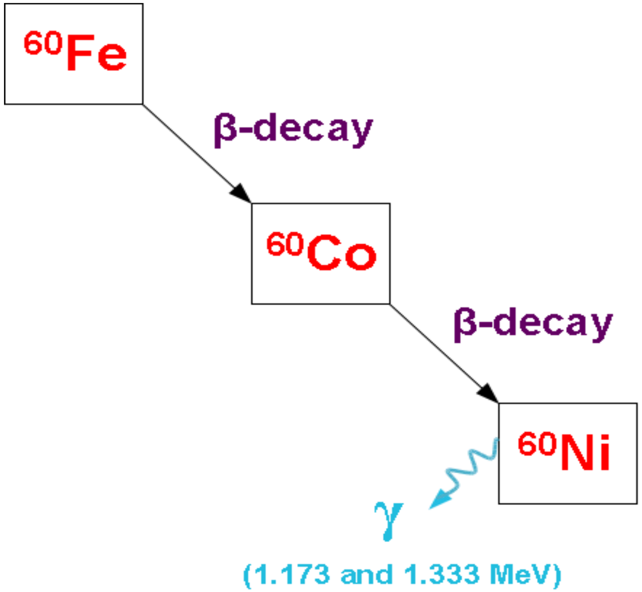


Stellar spectrum of k_BT = 5.1 keV

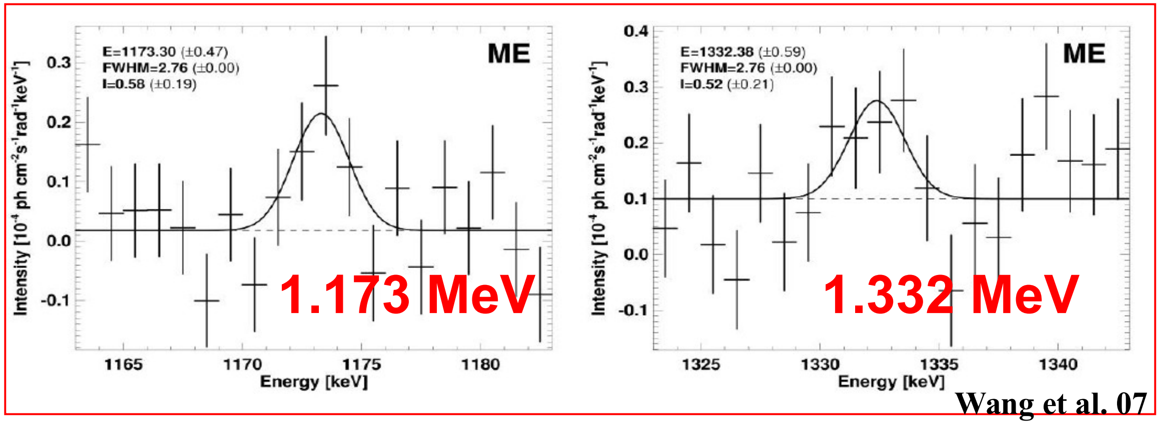
2×10^5 neutrons/s @ 100 μA

The $^{60}Fe(n,\gamma)^{61}Fe$ reaction

^{60}Fe ($T_{1/2}$ = 2.6 Myr) decay



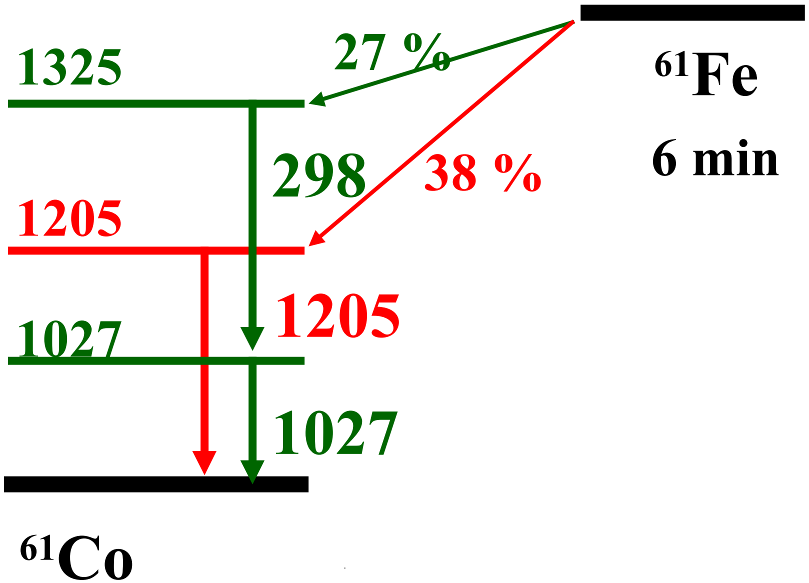
Detection of ^{60}Fe γ-ray emission in our Galaxy with RHESSI (2004) and INTEGRAL (2007)

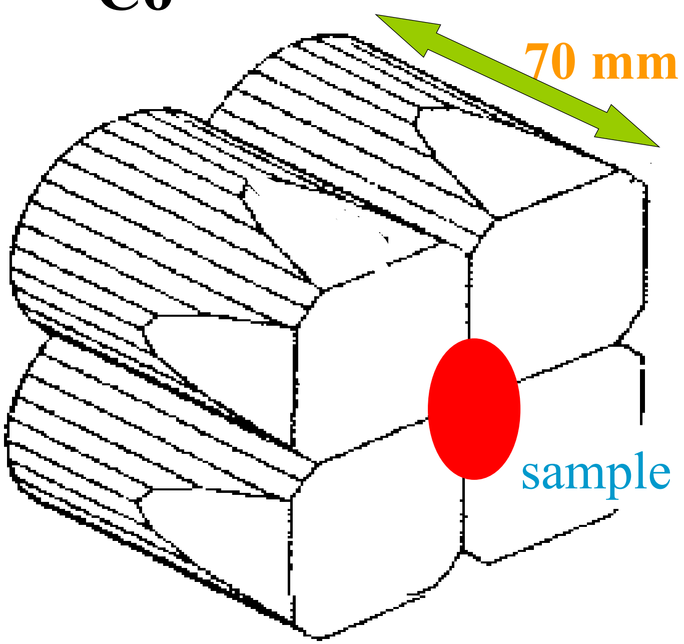


- ^{60}Fe mainly produced in massive stars & released in ISM by subsequent core collapse supernovae (type II) → stellar model test

- Production of ^{60}Fe strongly depends on the uncertain $^{59}Fe(n,\gamma)^{60}Fe$ and $^{60}Fe(n,\gamma)^{61}Fe$ cross sections.

$^{60}Fe(n,\gamma)^{61}Fe$ activation measurement

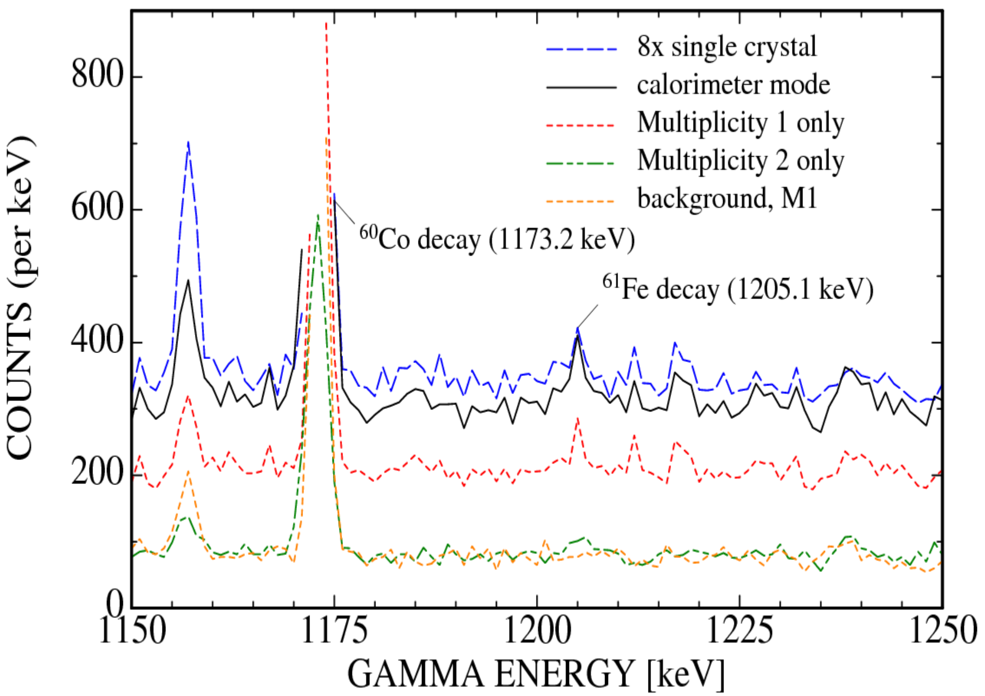




Clover Ge detector for γ-ray detection

^{60}Fe sample: 7.8×10^{15} atoms ~ 800 ng

^{60}Fe sample irradiated 40 times for 15 min, then activity counted for 10 min



Result: <σ> = 10.2 (2.9^{sys}) (1.4^{stat}) mb

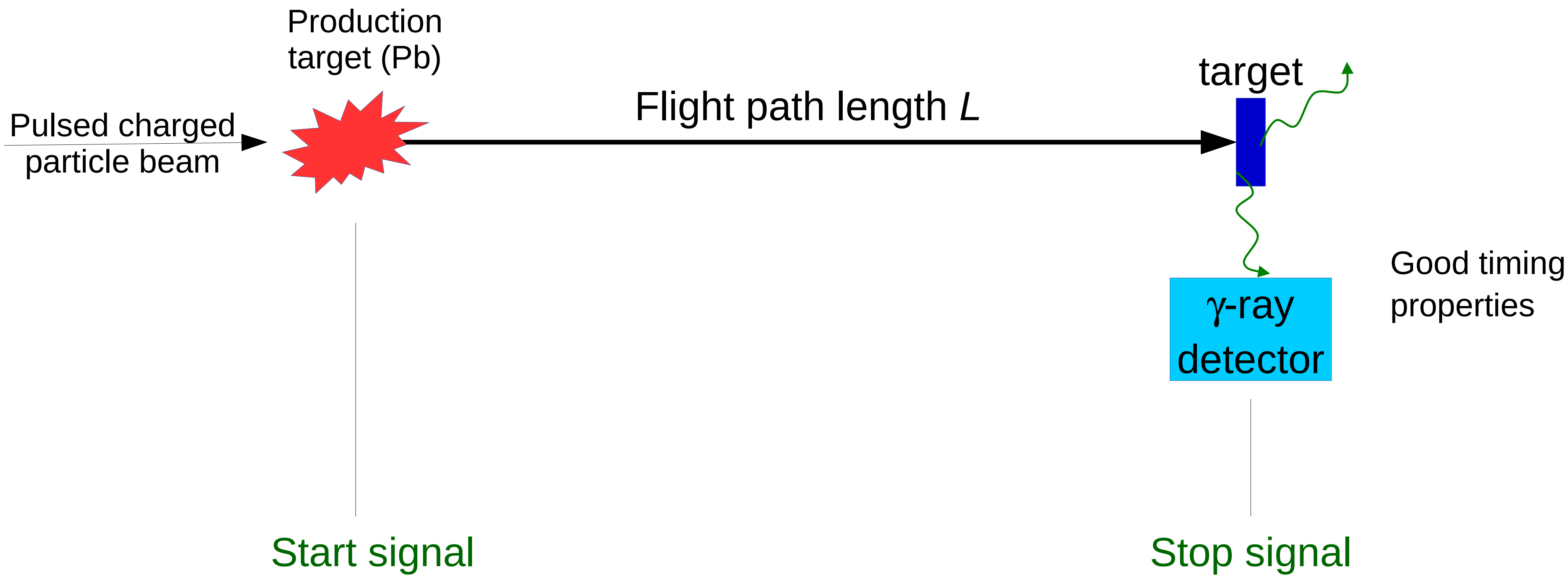
Activation measurement: pros/cons

- ✔ High sensitivity → small sample mass (e.g. 28 ng for ^{147}Pm(n,γ) measurement)
- ✔ Use of natural samples possible, no need for enriched samples
- ✔ Measurement of radioactive samples possible due to excellent energy resolution of HPGe detectors
- ✔ Direct capture component included

- ✖ Only possible when product nuclide is radioactive
- ✖ So far MACS determination only possible at thermal energies of $k_B T$ = 5-, 25- and 52-keV

  → stellar models for *s*-process need MACS between $k_B T$ = 5 to 90 keV

Time-of-Flight (ToF) method

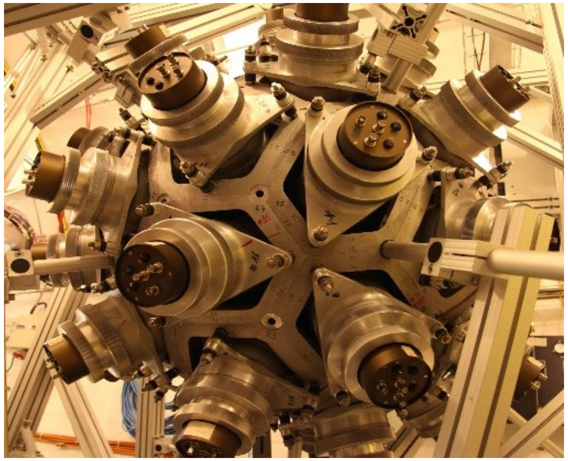


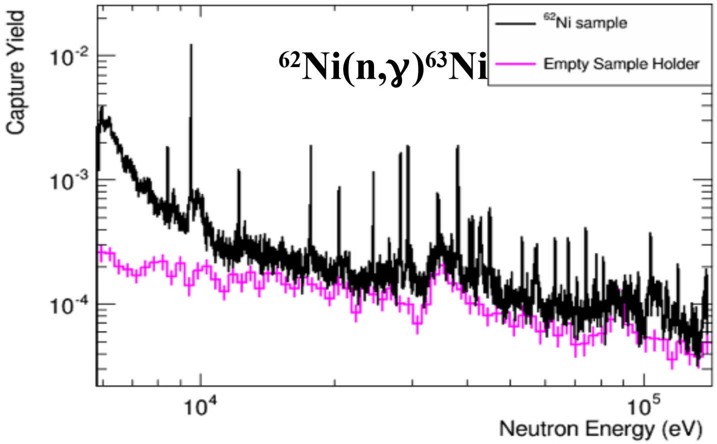
- Time-of-Flight = $\Delta t = t_{stop} - t_{start}$
- Energy of the neutron which caused the event: $v = \frac{L}{\Delta t} \quad \Rightarrow \quad E = \frac{1}{2}mv^2$

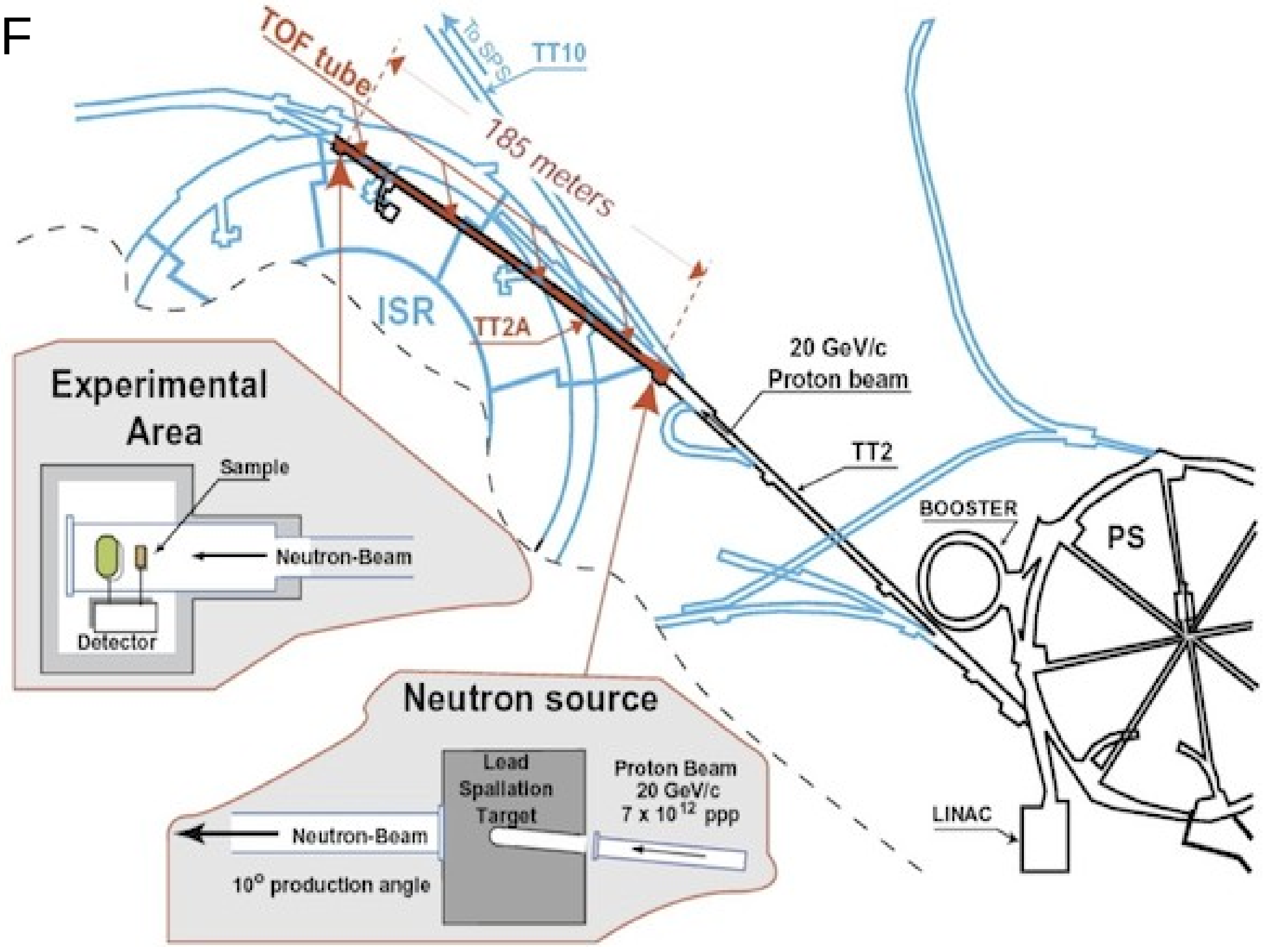
n-TOF @ CERN

- Pulsed neutron source coupled with 185 m flight path
- Neutron energy from few meV to several GeV determined by ToF

4π calorimeter (42 BaF_2)







Several (n,γ) measurements involved in *s*-process

4. Indirect measurements

Cross-section of astrophysical interest not measured directly

- Can be used to study quiescent and explosive nucleosynthesis processes
- Can use stable beams to study reactions involving radioactive nuclides not far from the valley of stability
- Radioacive ion beams can be used as well

✓

- Experiments with high energies (~ few 10's of MeV) implying higher cross sections
- Experimental conditions are relatively less constraining than for direct measurement (not necessarily true with RIB studies)

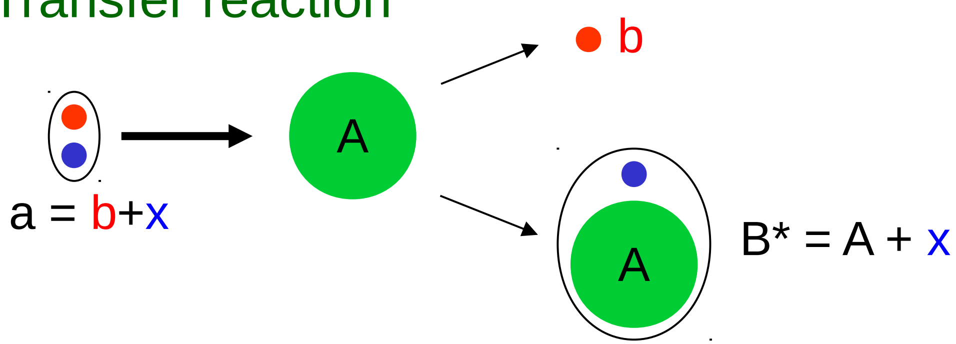
✗

- Results are model dependent
- Results depend on the uncertainties relative to the different model parameters

- Examples of indirect methods:
  - **Transfer reactions**, Asymptotic Normalization Coefficient (ANC) method, Trojan Horse Method (THM), surrogate method, Coulomb dissociation...

Transfer reactions

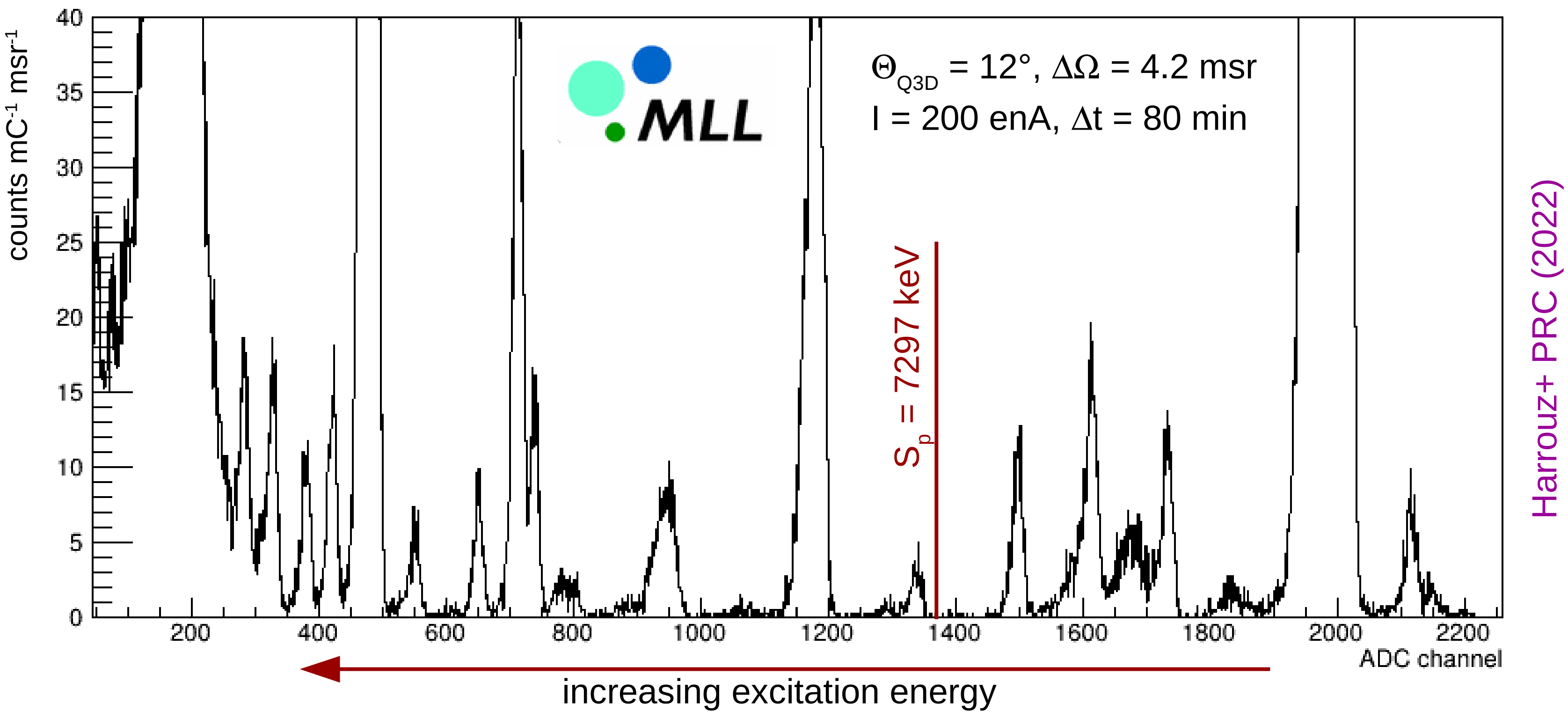
Transfer reaction



Two-body kinematics: A(a,b)B*

- Measured: E_b, θ_b
- Known: beam energy
- Determined:
  → excitation energies of B*
  → differential cross-section for each excited state

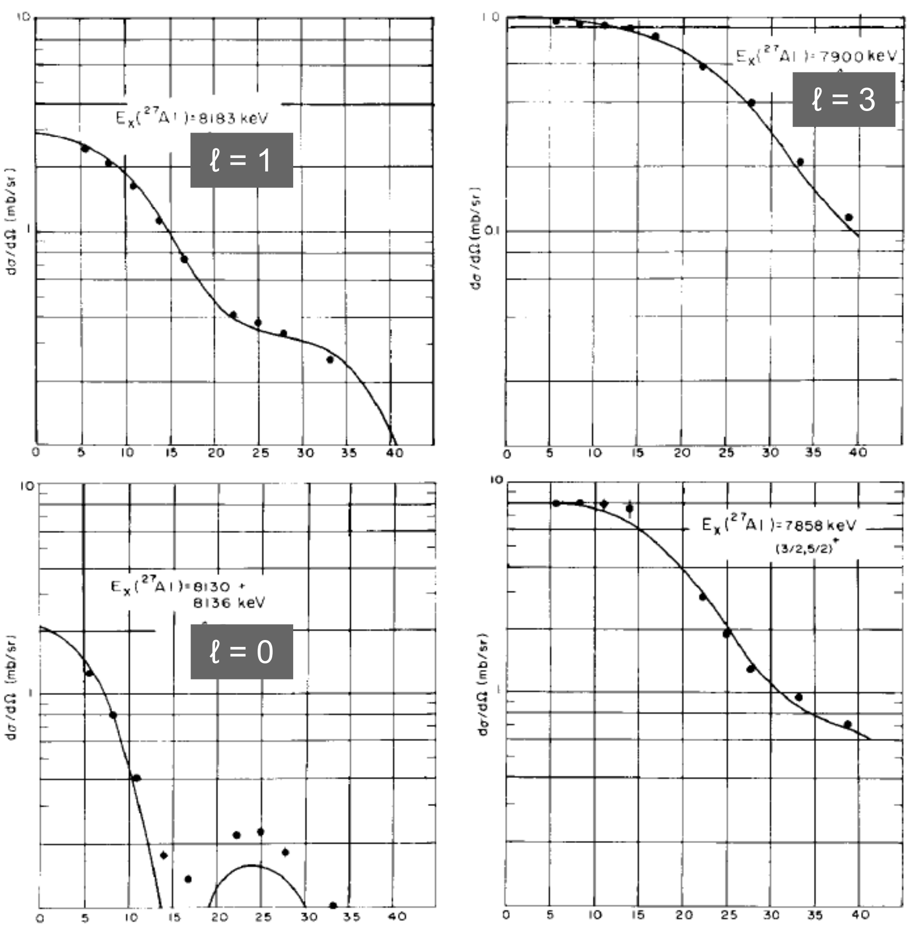
^{30}Si(^{3}He,d)^{31}P @ 25 MeV – one-proton transfer for studying ^{30}Si(p,γ)^{31}P



What can we learn from transfer reactions?

^{26}Mg(^{3}He,d)^{27}Al, Q3D Princeton

Wang et al. NPA499 (1989) 546



$$\left(\frac{d\sigma}{d\Omega}\right)_{lab} = \frac{N(\theta)}{N_p N_t \Delta\Omega}$$

N(θ): number of detected particles at angle θ

N_p: number of incident particles, ΔΩ: solid angle

N_t: number of target atoms (cm^{-2})

Shape of angular distribution

- sensitivity to angular momentum ℓ of the transferred particle
  → constrain spin of populated state
  - $j = \ell \pm ½$ (one-nucleon transfer)

  → determination of parity

Normalization of angular distribution

- Spectroscopic factor determination

$$d\sigma/d\Omega_{exp} = C^2 S_p \, d\sigma/d\Omega_{DWBA}$$

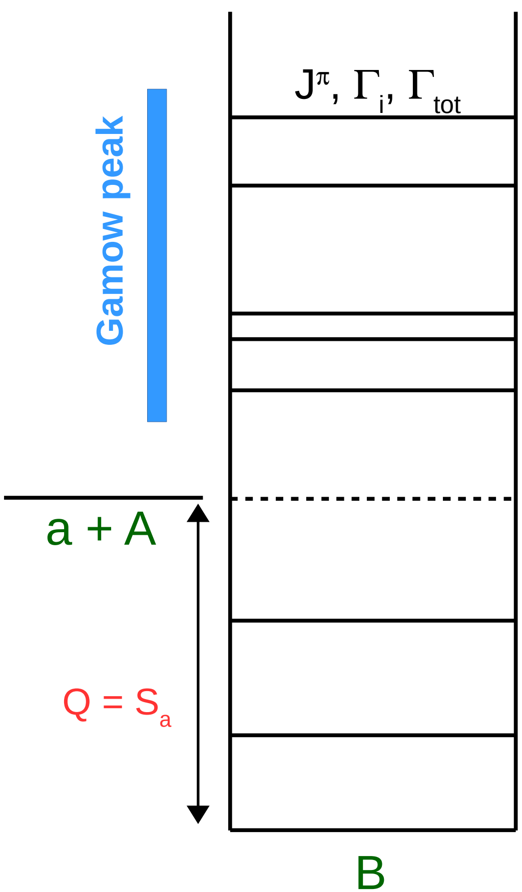
- The spectroscopic factor is related to the overlap between the ^{26}Mg+p configuration and the final ^{27}Al* state, e.g. how well a ^{27}Al excited state is described as a ^{26}Mg core and a proton

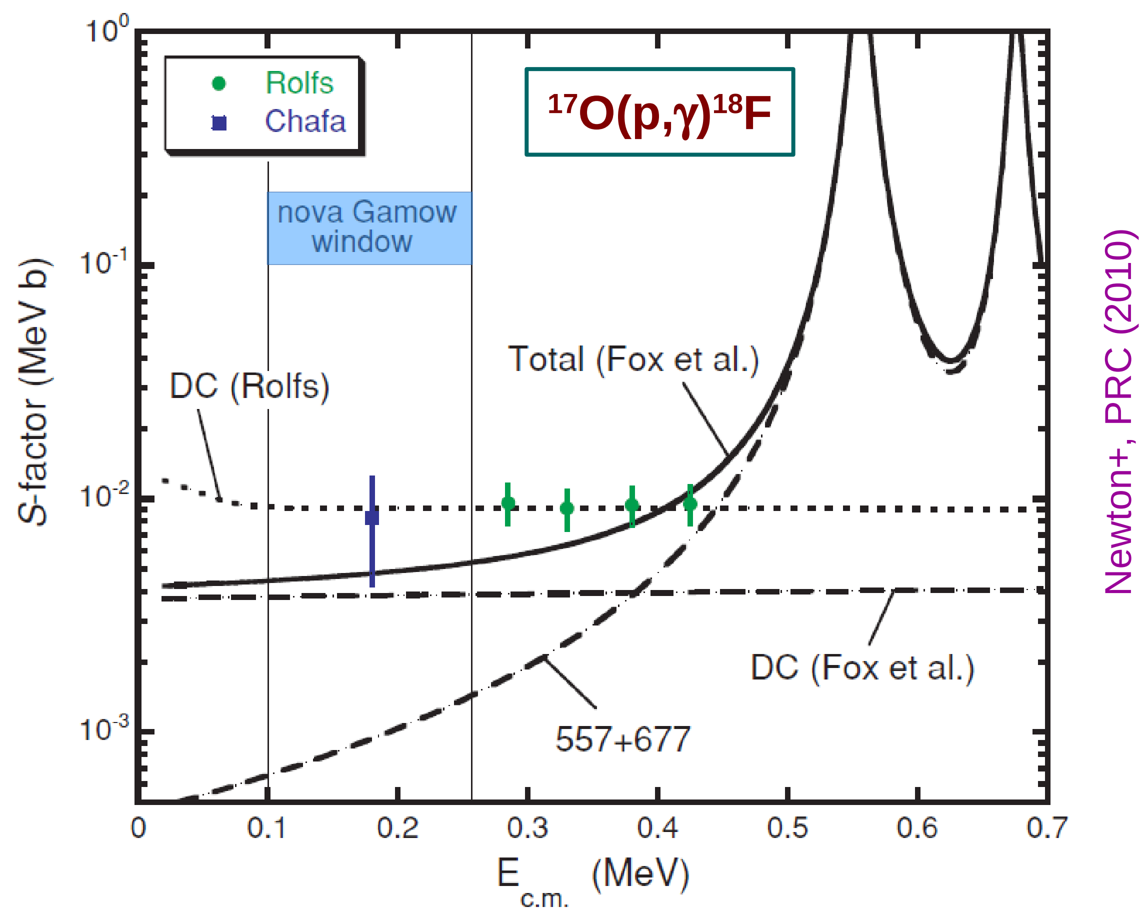
Transfer reactions are extremely powerful to:
- do spectroscopy
- probe single-particle nature of nuclear states

Why are transfer reactions useful in nuclear astrophysics?

Thermonuclear reaction rate: $N_A < \sigma v > = \sqrt{\frac{8}{\pi\mu}} \frac{N_A}{(kT)^{3/2}} \int_0^\infty \sigma(E) E e^{(-E/k_B T)} dE$

Case of a radiative capture: A(a,γ)B





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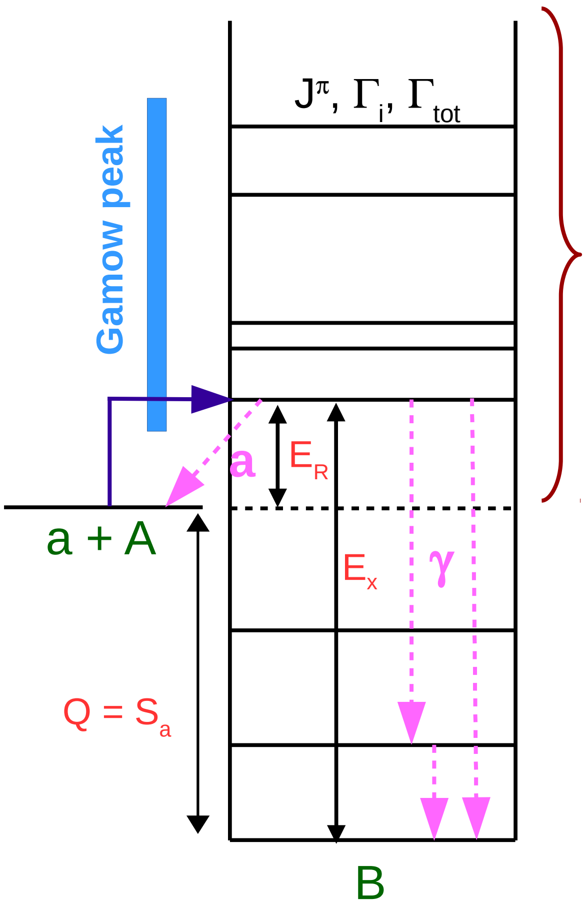

Resonant capture

- Only possible for $E_{c.m.} = E_R$ (= E_x -Q)
- $\sigma(E) = \pi^2 \frac{2J_R + 1}{(2J_A + 1)(2J_a + 1)} \frac{\Gamma_a(E)\Gamma_\gamma(E+Q)}{(E - E_R)^2 + \Gamma_{tot}{}^2(E)/4}$
- Partial particle width → $\Gamma_a = C^2 S_a \Gamma_a^{s.p.}$

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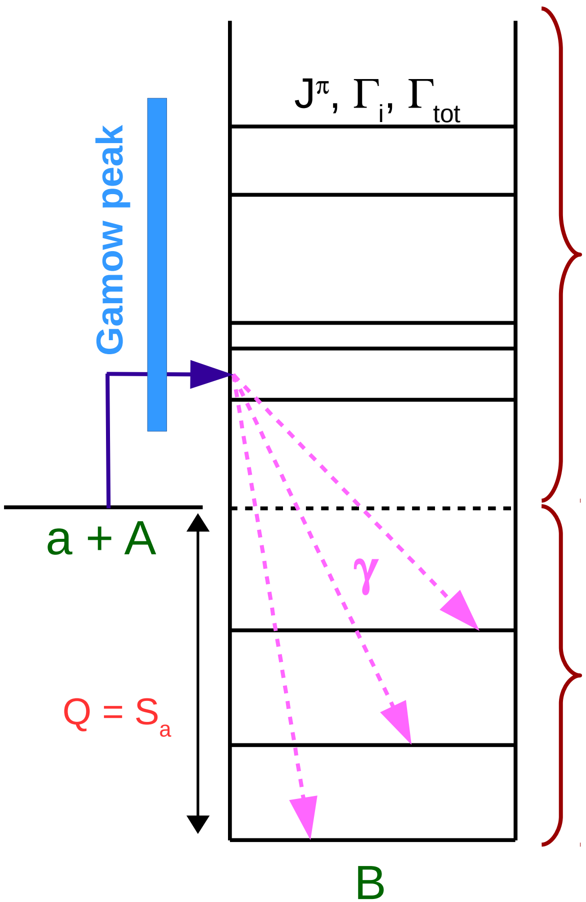

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- $\sigma(E) = \pi^2 \frac{2J_R + 1}{(2J_A + 1)(2J_a + 1)} \frac{\Gamma_a(E)\Gamma_\gamma(E + Q)}{(E - E_R)^2 + \Gamma_{tot}{}^2(E)/4}$
- Partial particle width → $\Gamma_a = C^2 S_a \Gamma_a^{s.p.}$

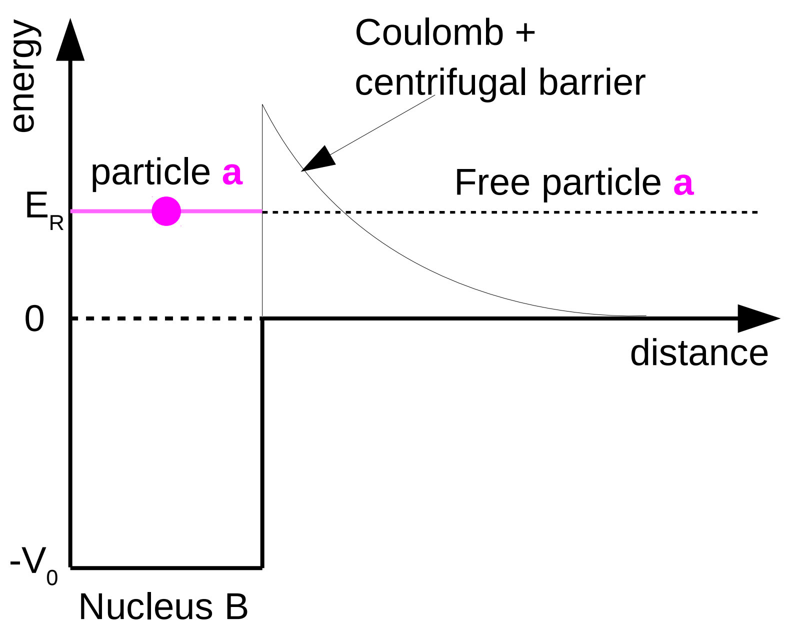
Direct capture

- Possible for all incident energies
- Capture on bound states of final nucleus
- $\sigma^{DC}(E) = \sum_f C_f^2 S_f \sigma_f^{DC}(E)$

Particle partial width determination

Single particle decay width

- For an excited state of nucleus B with a pure core (A) – particle (a) configuration
  $\rightarrow |B^*\rangle = 1 \times |A \otimes a\rangle$



- The single particle decay width of excited state B* in the a+A channel is:

$$\Gamma_a^{s.p.} = \frac{\hbar^2 s}{\mu} |\mathcal{R}(s)|^2 P_l(E_r, s)$$

Iliadis, Nuclear Physics of Stars (2015)

- Product of two probabilities:
  - Probability that the single nucleon will appear at the nuclear boundary $|R(s)|^2$
  - Probability that the single nucleon will penetrate Coulomb and centrifugal barrier $P_l(E_r,s)$

General case

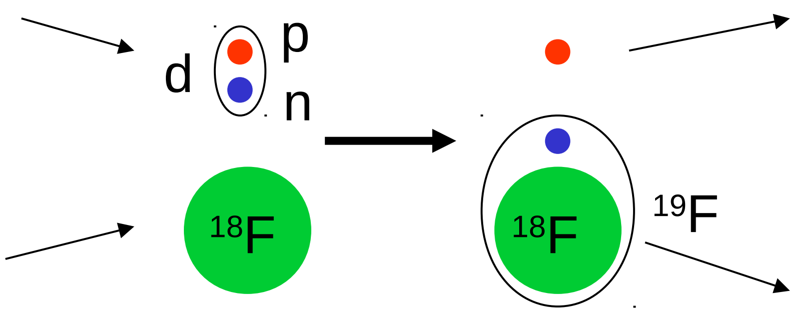
- The excited state of nucleus B is a mixture of configurations
  $\rightarrow |B^*\rangle = \langle a \otimes A|B^*\rangle \times |A \otimes a\rangle + \ldots$
  where $\langle a \otimes A|B^*\rangle \propto \sqrt{C^2 S_a}$ is the overlap between the final and initial state

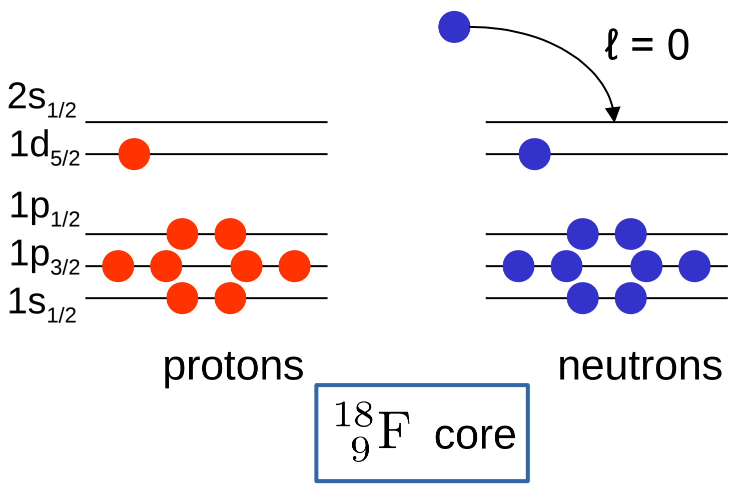
$$\Gamma_a = C^2 S_a \Gamma_a^{s.p.}$$

Transfer reactions: the DWBA model

The simplest theoretical model to describe a transfer reaction: A + a(=b+x) → b + B*(=A+x)
DWBA: Distorted Wave Born Approximation

Example of the $^{18}F(d,p)^{19}F$ transfer reaction



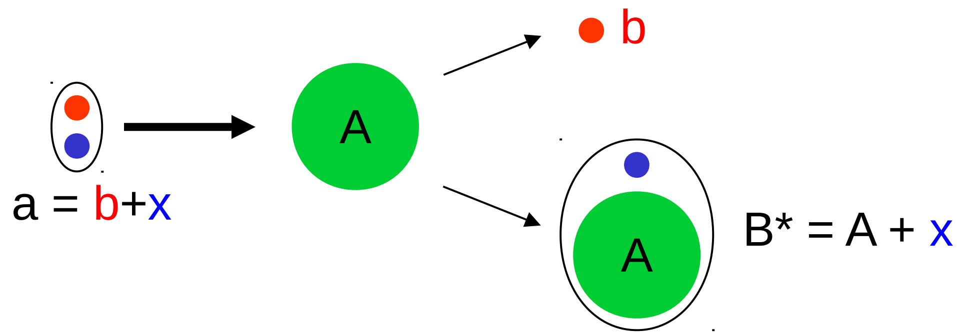


DWBA main assumptions

- The transferred nucleon/cluster is directly deposited on its orbital
  → no nucleon rearrangment in the final nucleus (B)
- The entrance and exit channels are dominated by elastic scattering
  → Distorted Wave
- The transfer process is weak enough to be treated as a first order perturbation
  → Born Approximation

Transfer reactions: the DWBA model

Transfer of particle *x* on core *A*



Transition amplitudes

- Cross section is proportional to the square of transition amplitudes $T_{i \to f}$
- DWBA amplitude $$T_{i\to f}^{DWBA} = \iint \chi_f^{(-)}(\vec{k}_f, \vec{r}_f)^* \langle b, B|V_{bx}|a, A\rangle \chi_i^{(+)}(\vec{k}_i, \vec{r}_i) d\vec{r}_i d\vec{r}_f$$

Austern (1970)

Ingredients

- $\chi_{i,f}$ are the distorted wave functions describing elastic scattering in the entrance (*i*) and exit (*f*) channels
- $\langle b, B|V_{bx}|a, A\rangle$ is the nuclear matrix element which contains all the information concerning
  - angular momenta selecting rules
  - nuclear structure: overlap between the final state |B*> and the |A+x> configuration

$$\langle x \otimes A|B^*\rangle \propto \sqrt{C^2 S_x^B} \mathcal{R}(r)$$ $\mathcal{R}(r)$: radial part of the A+x wavefunction

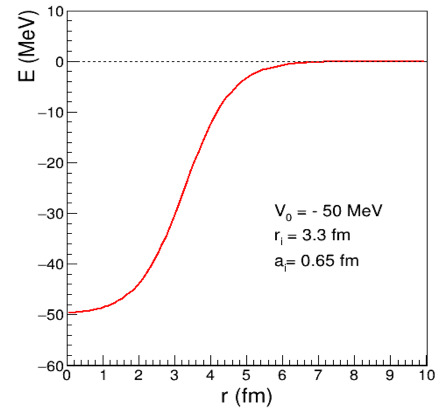
$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} \propto S_x^B S_x^a \left(\frac{d\sigma}{d\Omega}\right)_{DWBA}$$ $S_x^a \approx 1$ (in most cases)

DWBA ingredients

Woods-Saxon → most common shape of optical potential

$$V(r) = -\frac{V_0}{1+\exp(\frac{r-r_i}{a_i})}$$

V_0: potential depth (MeV)
r_i: radius (fm)
a_i: diffusivity (fm)



- Entrance and exit channels potentials → distorded waves
  - Components: volumic, surfacic and spin-orbit (if non zero spins are involved)
  - Complex potential: attractive (real part) and absorptive (imaginary part)
    → elastic scattering from entrance/exit channel: A(a,a)A and B(b,b)B
    → global optical potential paratremization for given energy and mass range
    (see Thompson & Nunes, p. 132-133)

- Binding potential → interaction of the transferred nucleon(s) with the core in the final nucleus
  - Depth of volumic potential is adjusted to reproduced binding energy of bound state
  - Geometry of potential (r_i, a_i) → uncertainty on spectroscopic factors

- Software → FRESCO, DWUCK, TWOFNR, etc….
  https://people.nscl.msu.edu/~brown/reaction-codes/

Transfer reactions: your turn!

What kind of transfer reactions can you use to determine the spectroscopic properties (E_R, ℓ, parity, spectroscopic factors) for the following reactions?

- A(p,γ)C reactions

- A(n,γ)C reactions

- A(α,γ)C and A(α,p)B and A(α,n)D reactions

Transfer reactions: your turn!

What kind of transfer reactions can you use to determine the spectroscopic properties (E_R, ℓ, parity, spectroscopic factors) for the following reactions?

- A(p,γ)C reactions
  → proton transfer reaction: (d,n) & (^{3}He,d)

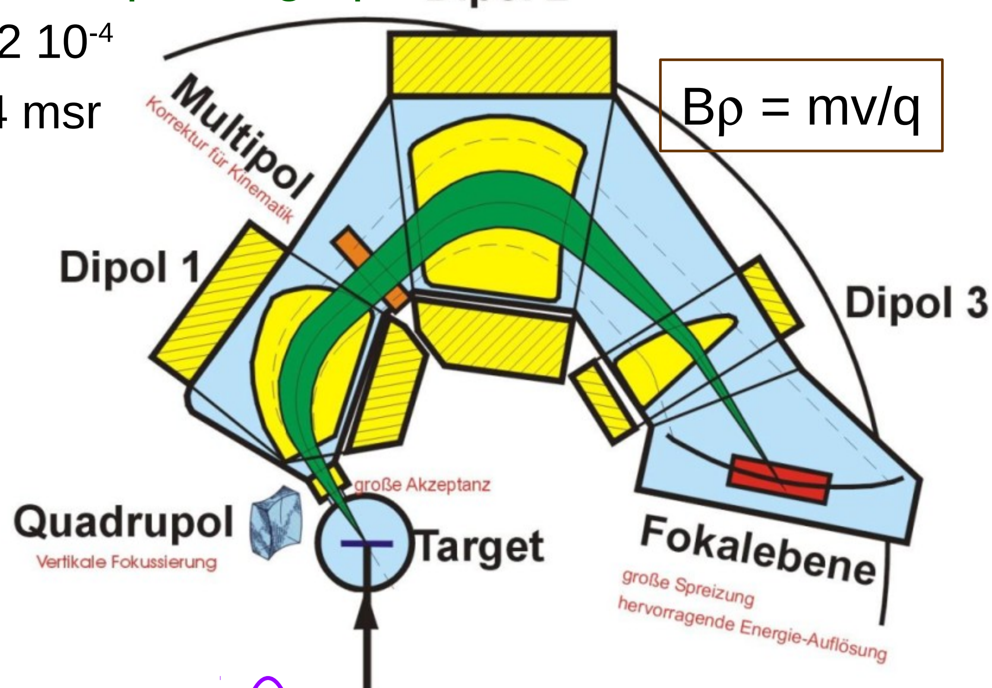
- A(n,γ)C reactions
  → neutron transfer reaction: (d,p)

- A(α,γ)C and A(α,p)B and A(α,n)D reactions
  → alpha-particle transfer reaction → (^{7}Li,t) & (^{6}Li,d)

$^{30}Si(^{3}He,d)^{31}P$ experimental study

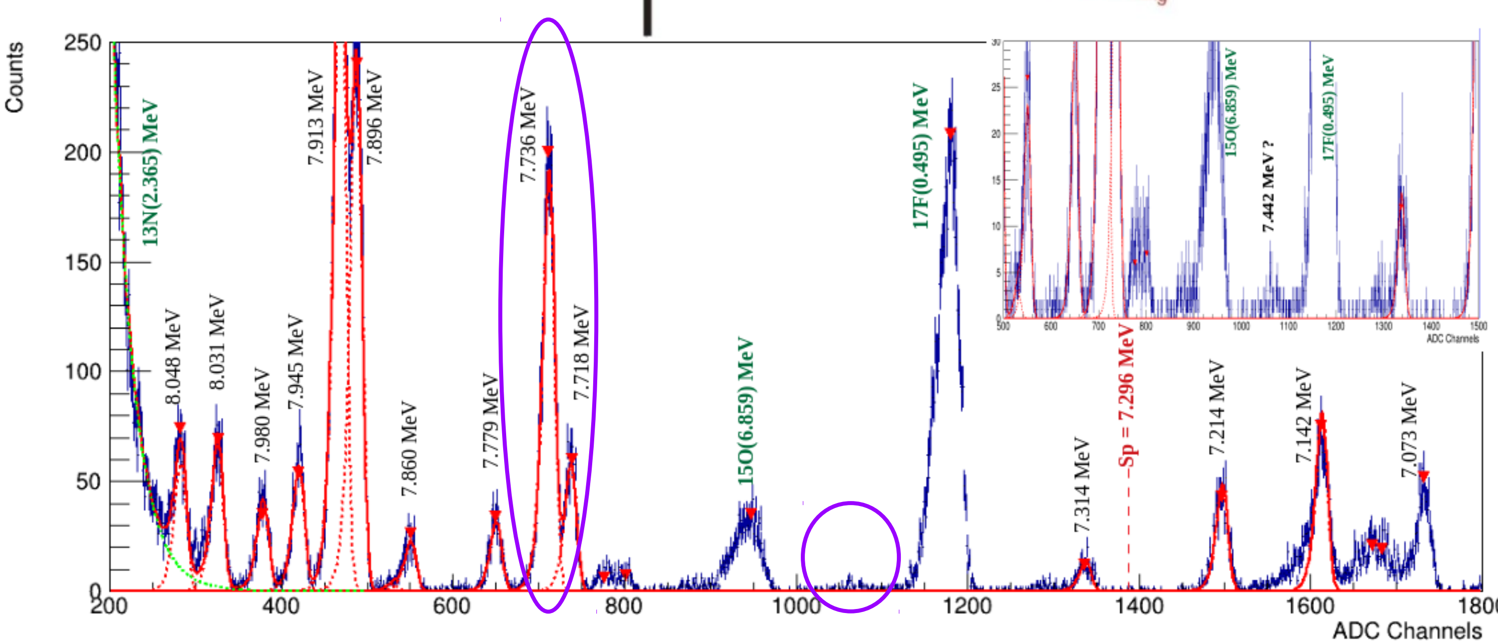
Q3D magnetic spectrograph

- $\Delta E/E = 2\ 10^{-4}$
- $\Delta\Omega = 14$ msr



Experimental conditions

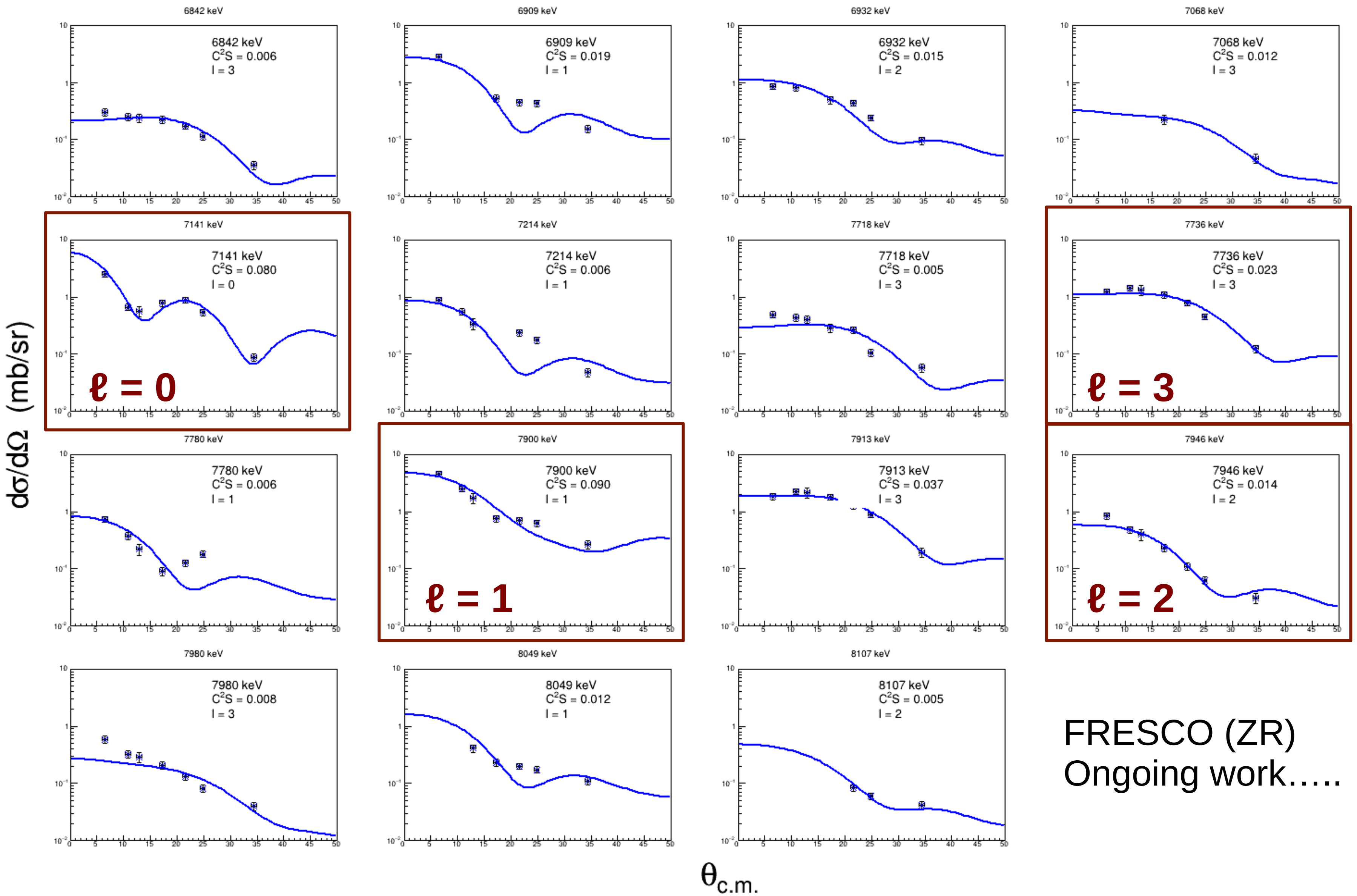
- ^{3}He beam @ 25 MeV, 200 enA
- Targets $^{30}SiO_2$ (17 μg/cm^2) + ^{nat}C (40 μg/cm^2)
- 7 detection angles between Θ_{lab} = 6° and 32°
- 6.5 keV resolution (FWHM) at 12°



- Doublet at 7718 keV and 7736 keV is now resolved
- Observation of the key 7442 keV state (E_R = 144 keV), main remaining uncertainty

Indirect measurement

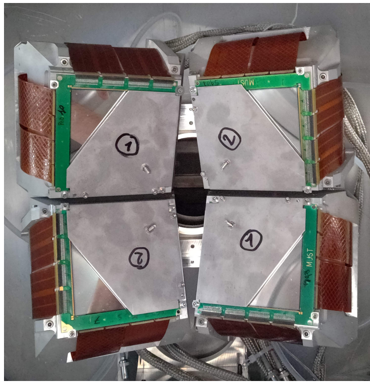
Angular distributions



FRESCO (ZR)
Ongoing work…..

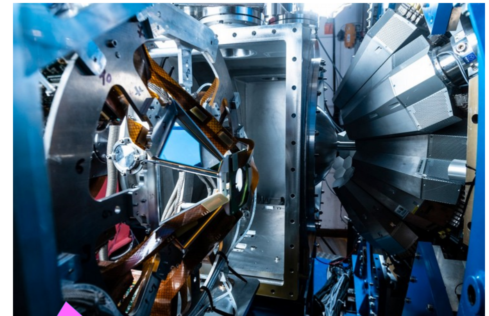
Strong sensitivity to transferred angular momentum (one-nucleon transfer)

$^{7}Li(^{15}O,t\gamma)^{19}Ne$: MUGAST + VAMOS + AGATA



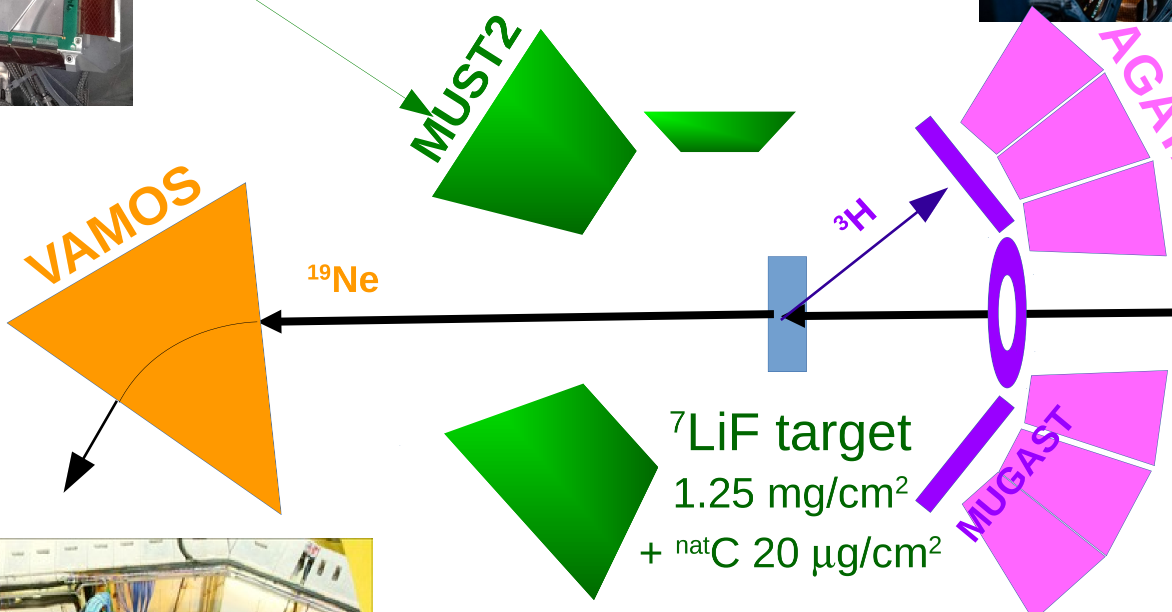
MUST2:

- DSSSD 300 μm + CsI
- 128+128 strips



AGATA @ 18 cm

- 37 crystals
- ε(1 MeV) ~ 8% w/ add-back

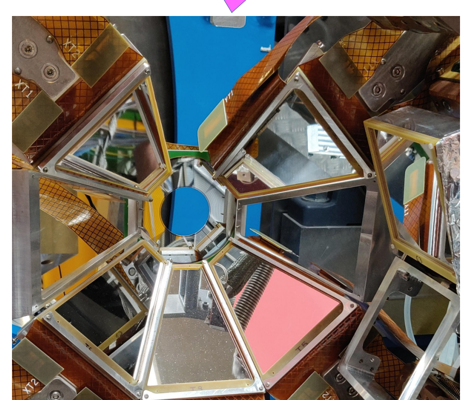


^{15}O @ 4.7 MeV/u

- ~ 2×10^{7} pps
- SPIRAL1 beam
- ^{15}N contaminant < 0.5 %

VAMOS @ 0°

- ΔΘ ± 7°
- ΔBρ ± 10° (~)



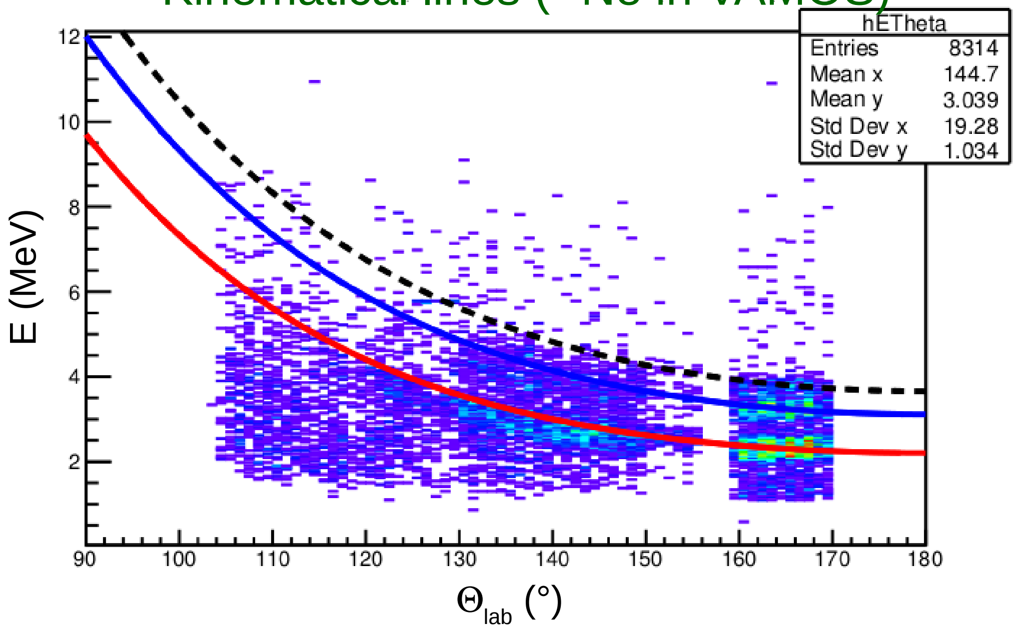
MUGAST

- DSSSD 500 μm
- Trapezoid (x5), annular (x1) and square (x2) shapes
- 128+128 strips

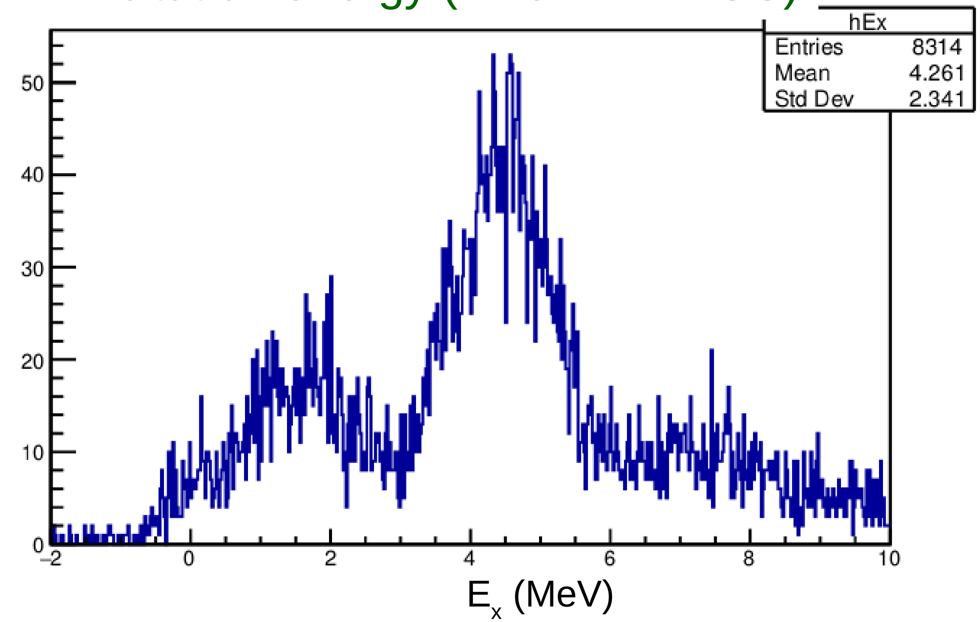
Indirect measurement

Online spectra

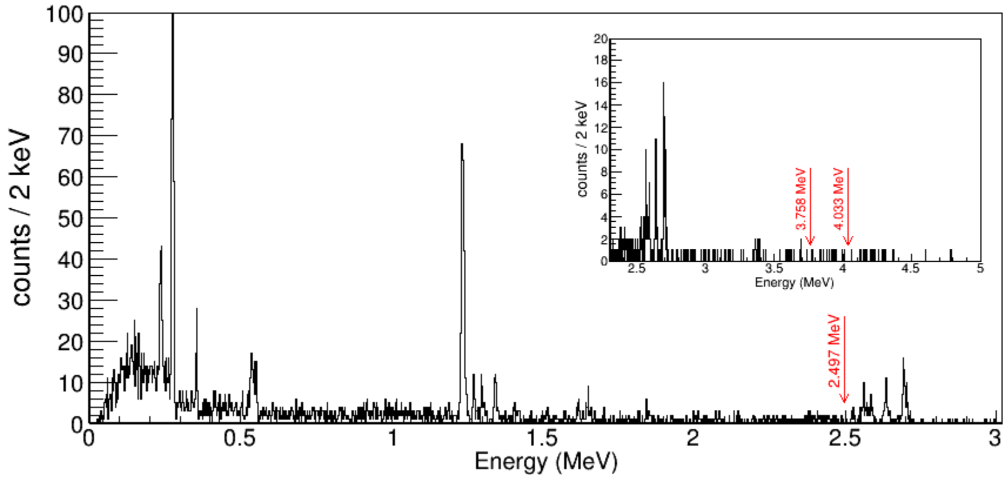
Kinematical lines (^{19}Ne in VAMOS)



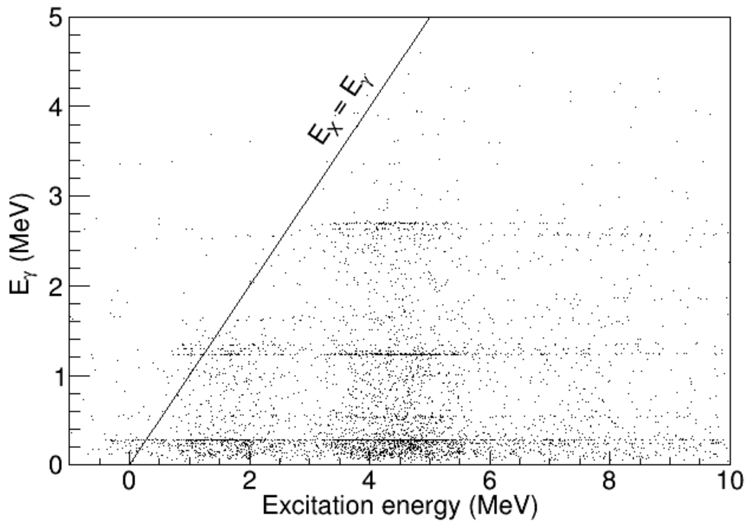
Excitation energy (^{19}Ne in VAMOS)



γ-ray spectrum (triple coincidence)



γ-ray energy vs excitation energy



Very clean spectrum → "no" background

Transfer reaction summary

- Advantages
  - High cross sections
  - Allows to determine excitation energies, angular momenta, parity, partial widths (useful for resonant reactions)

- Limitations and warnings
  - 20% – 30% uncertainty on spectroscopic factors related to optical potential parameters
  - Other reaction mechanisms are possible
    - Multi-step transfer
    - Projectile breakup
    - Compound nucleus (statistical model)

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