Detection techniques for underground nuclear astrophysics experiments

XXX Giornate di studio sui rivelatori

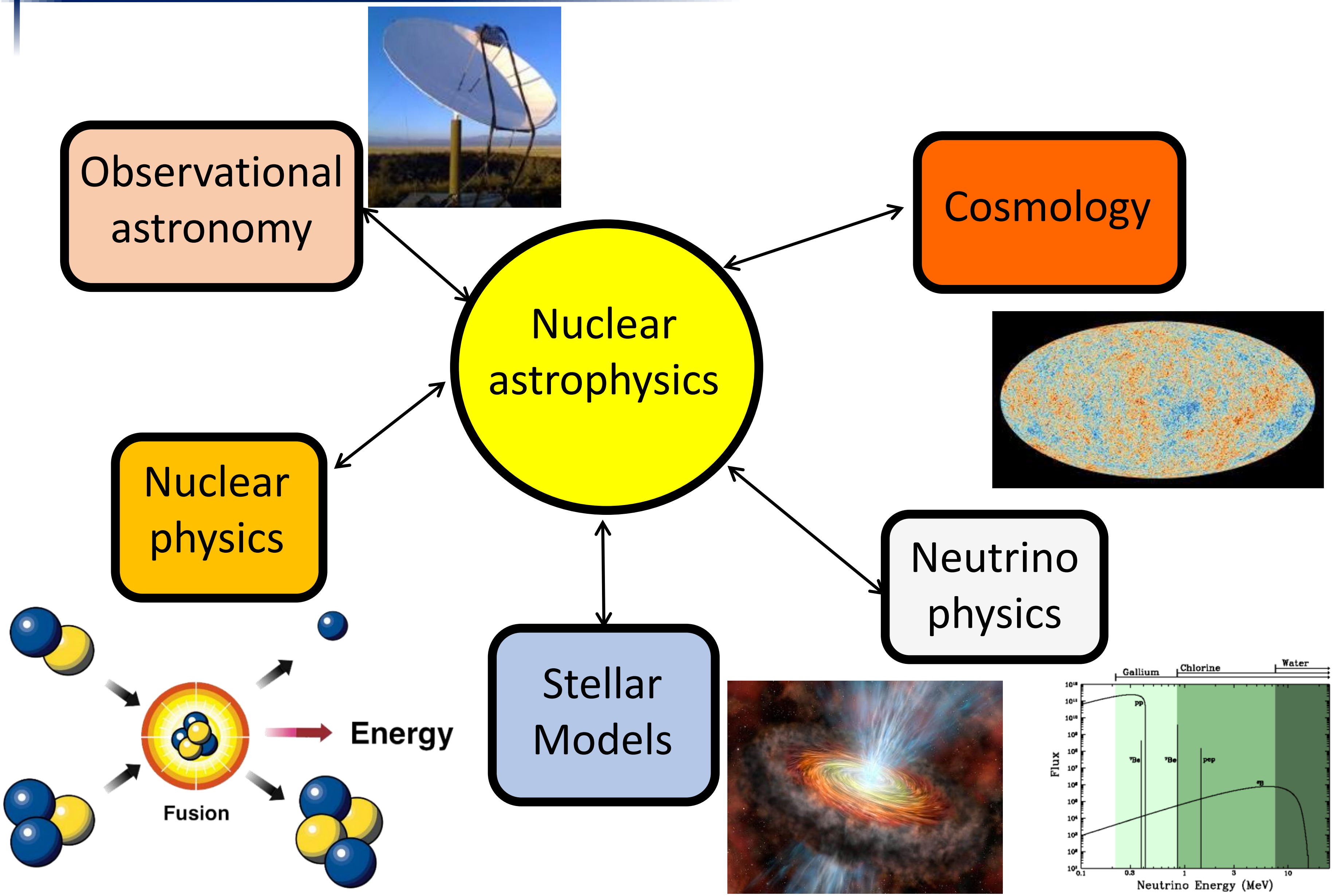
13 - 17 June 2022, Aosta-Cogne

Francesca Cavanna

LUNA Laboratory for Underground Nuclear Astrophysics

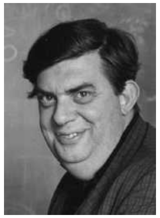
INFN Istituto Nazionale di Fisica Nucleare

Nuclear Astrophysics: an interdisciplinary field



The Origin of the Elements

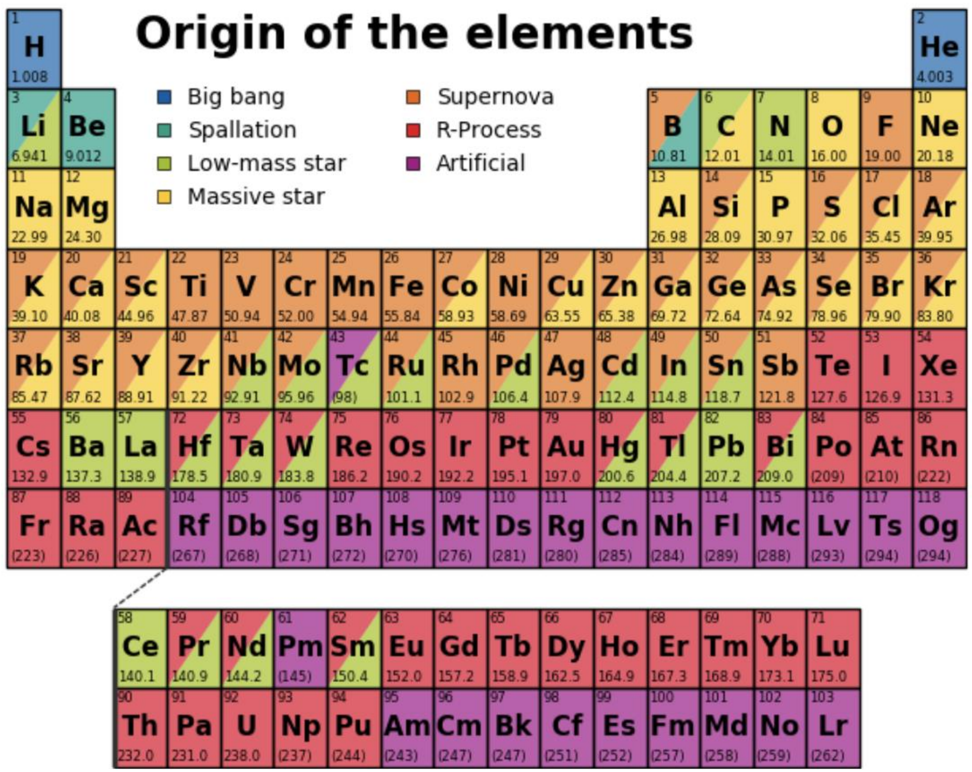
Burbidge, Burbidge, Fowler & Hoyle (B^2FH): Rev. Mod. Phys. 29 (1957) 547

Synthesis of the Elements in Stars*

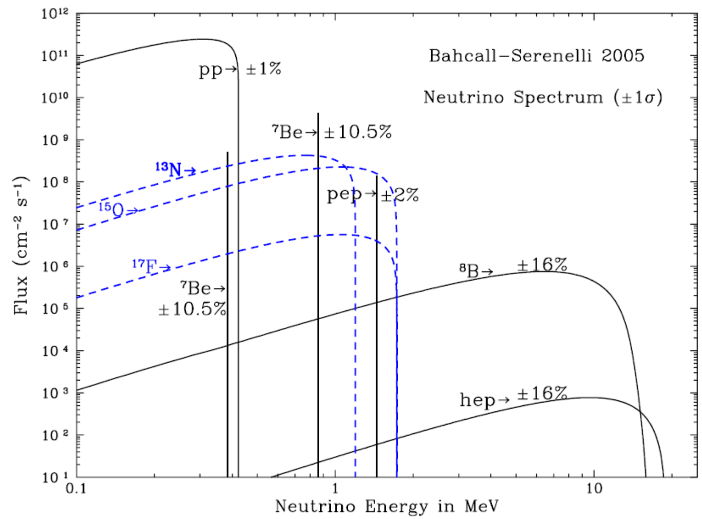
E. Margaret Burbidge, G. R. Burbidge, William A. Fowler, and F. Hoyle

Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California

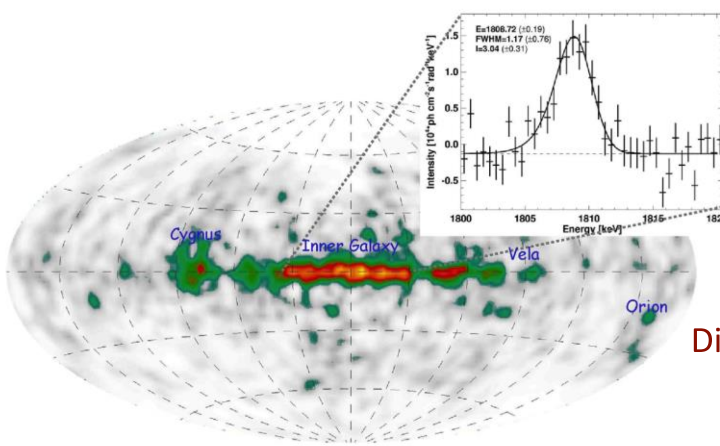


Direct evidence of nucleosynthesis in stars

- ✓ Solar Neutrino Detection at Homestake in 1960s



- ✓ 1982: discovery of 1.8 MeV γ-rays associated with ^{26}Al decay ($T_{½} = 7\times10^5$ y)



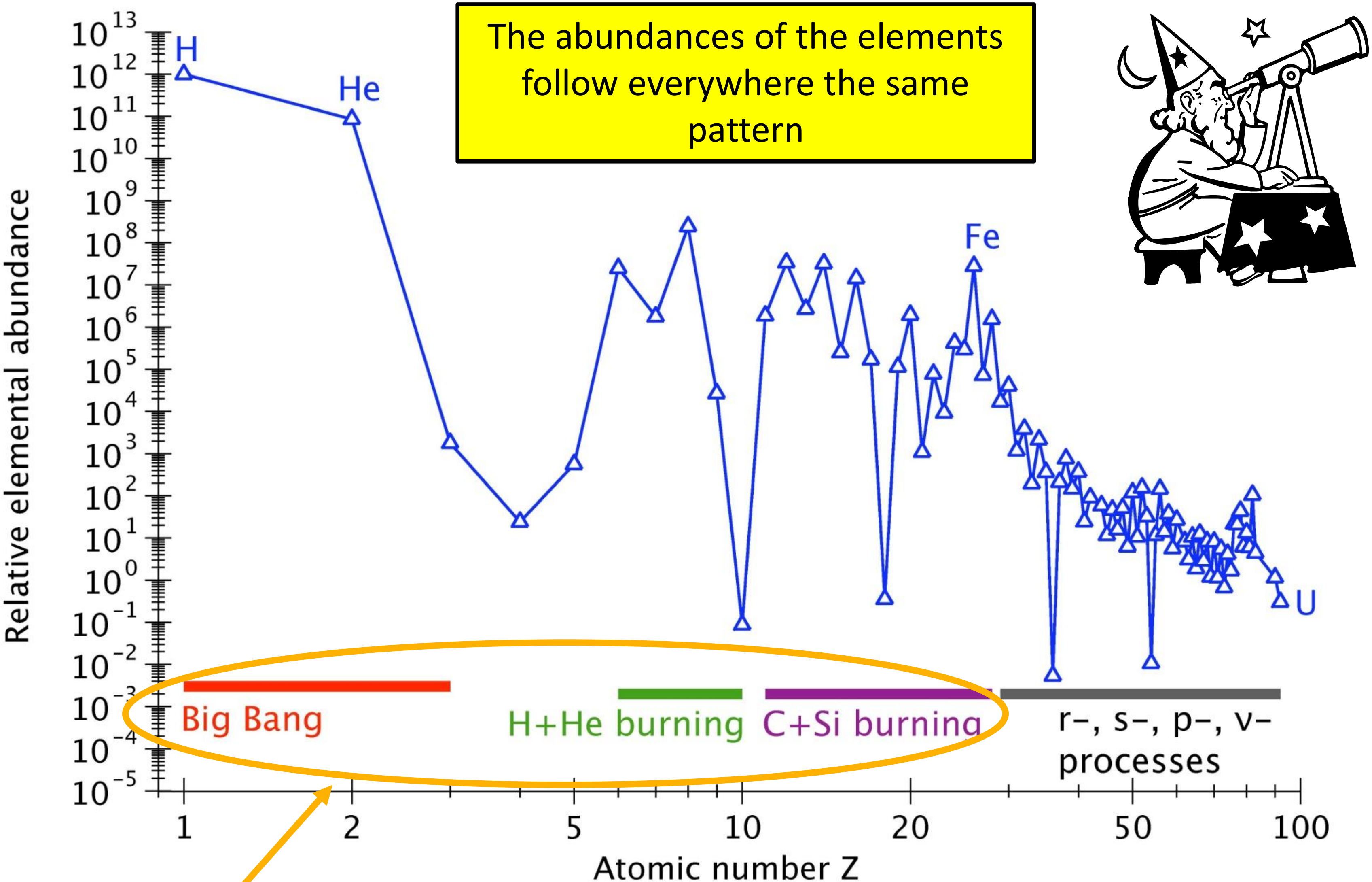
direct proof of ongoing nucleosynthesis in our Galaxy

Diehl et al., Nature 439 (2006) 45

Courtesy of M. Aliotta

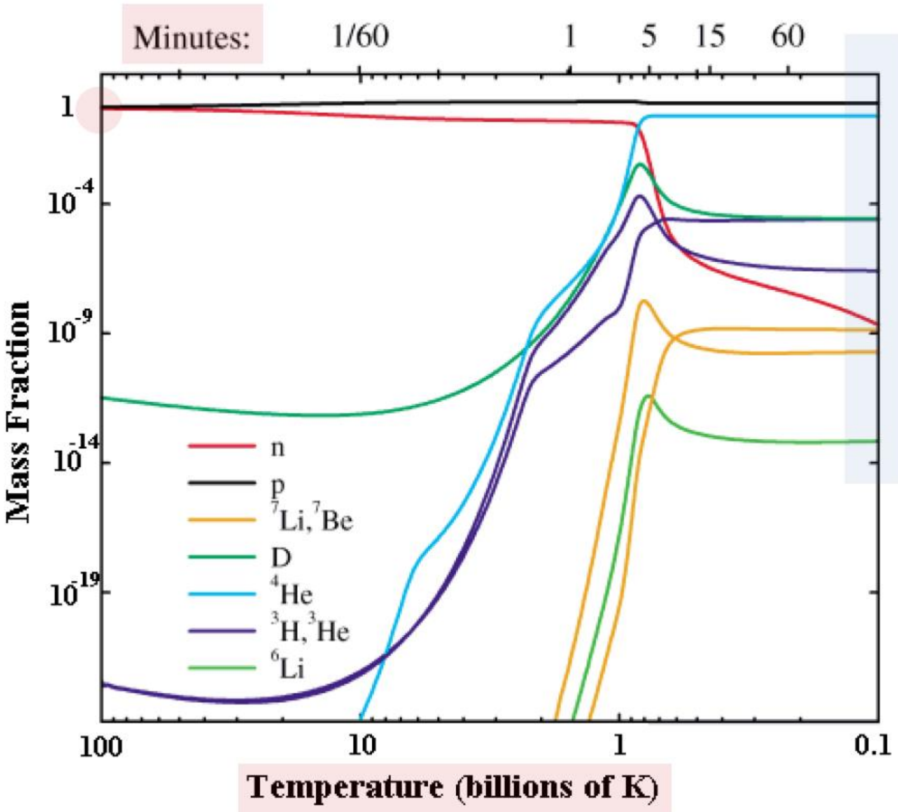
The Origin of the Elements

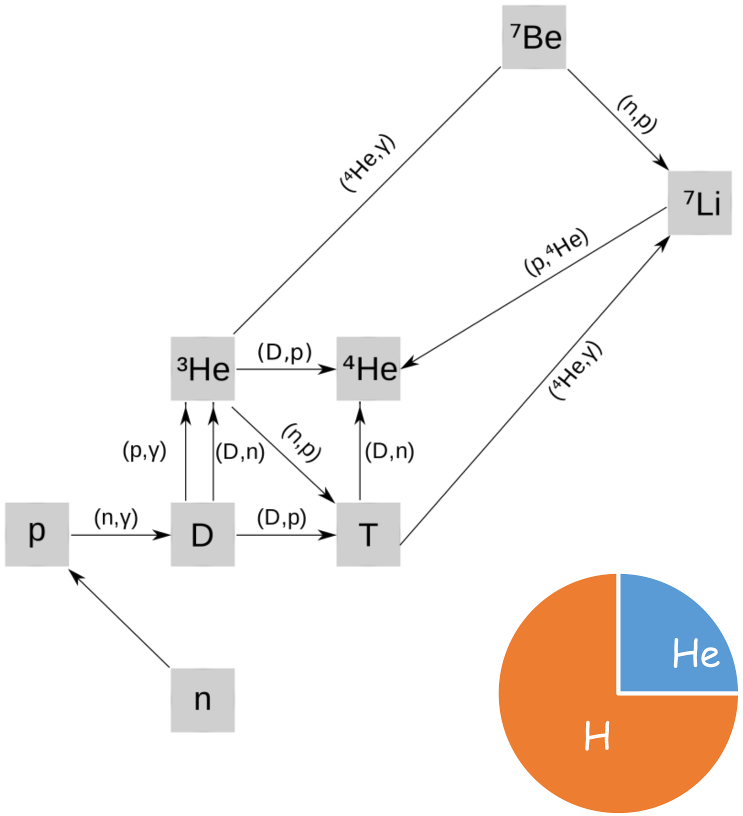
The abundances of the elements follow everywhere the same pattern



Charged-particle induced reactions

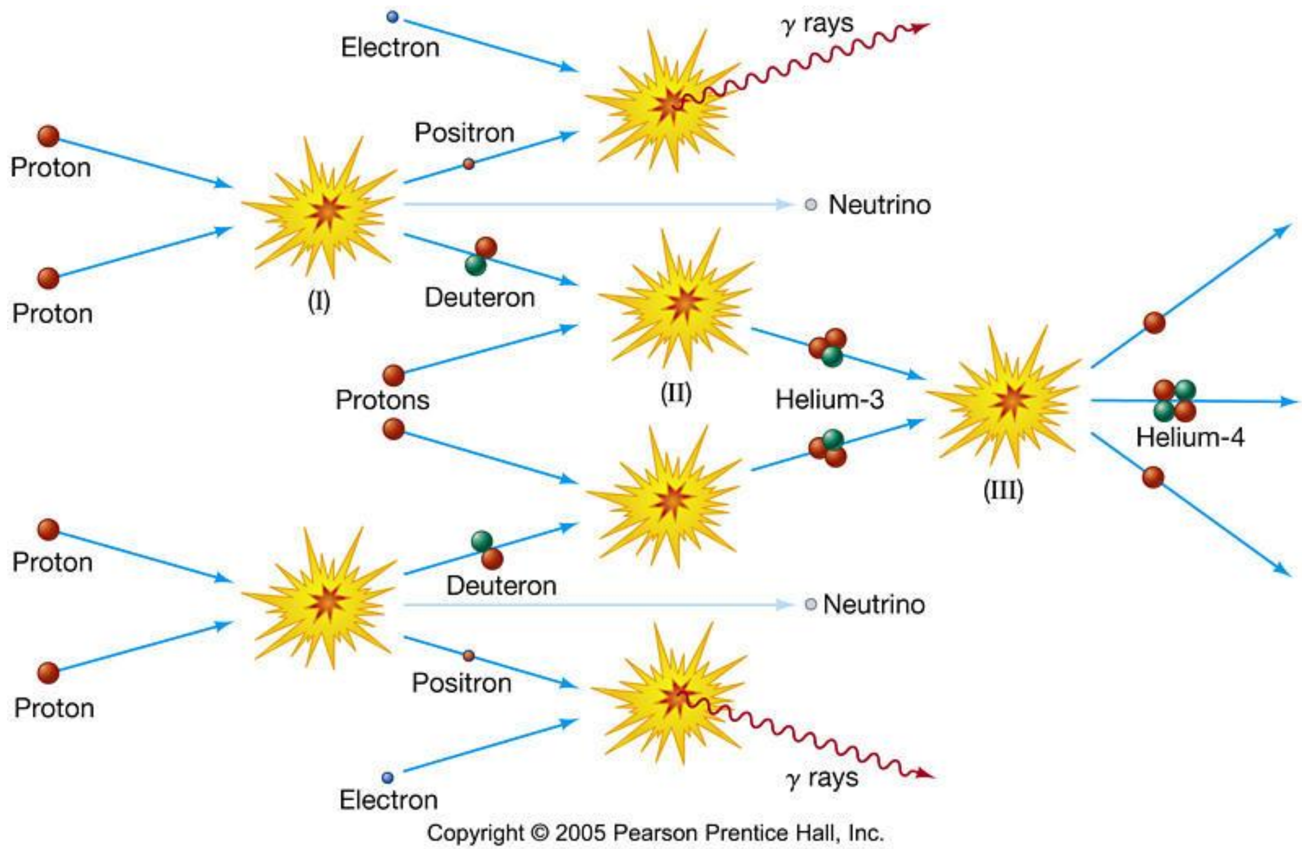
Big Bang Nucleosynthesis





- ✓ BBN occurs 3 minutes after Big Bang
- ✓ After BBN we have mainly H and ^{4}He plus small amounts of D, ^{3}He, ^{6}Li and ^{7}Li

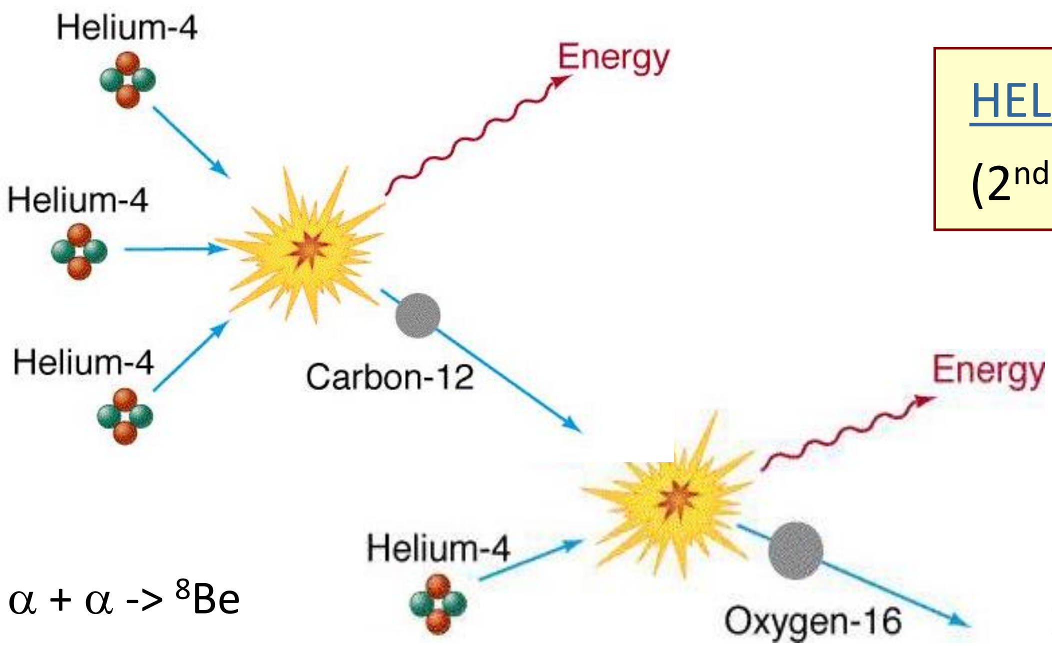
The Proton – Proton chain



HYDROGEN BURNING nucleosynthesis

(1st equilibrium) $4H \rightarrow {}^{4}He + 2\beta^{+} + 2\nu$

Helium burning



HELIUM BURNING $3\alpha \rightarrow {}^{12}C$

(2^{nd} equilibrium) ${}^{12}C(\alpha,\gamma){}^{16}O$

$\alpha + \alpha \rightarrow {}^{8}Be$

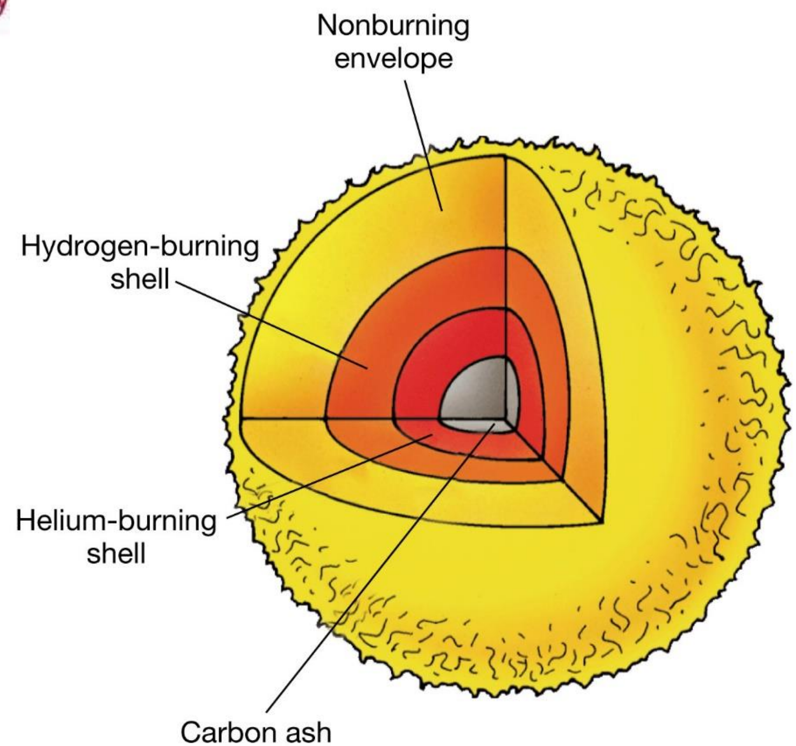
${}^{8}Be + \alpha \rightarrow {}^{12}C + \gamma$

${}^{12}C + \alpha \rightarrow {}^{16}O + \gamma$

$T_{1/2}({}^{8}Be) \approx 8.2\ 10^{-17}$ s

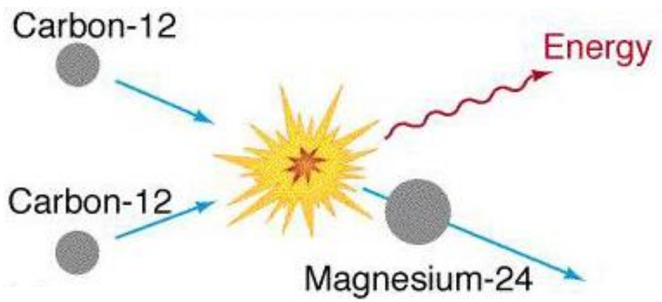
${}^{16}O + \alpha \rightarrow {}^{20}Ne + \gamma$

${}^{20}Ne + \alpha \rightarrow {}^{24}Mg + \gamma$



Mass gap can be bridged in stars!

Later Burning Stages



$^{12}C/^{16}O$ BURNING

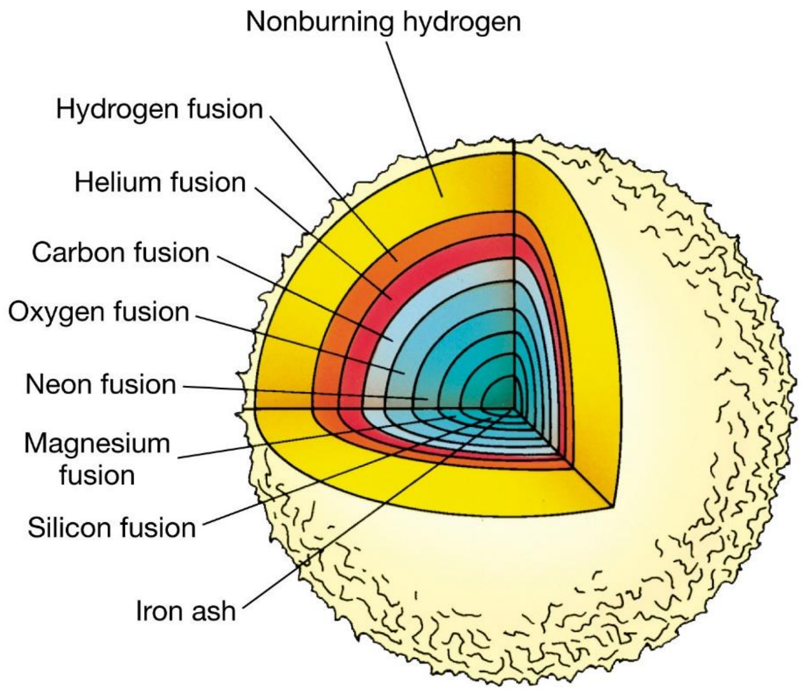
^{12}C ashes = Ne, Na, Mg

^{16}O ashes = Al, … Si

^{28}Si MELTING

major ash = ^{56}Fe

… A = 40-65



No further fusion reactions

↓

gravitational collapse

→ catastrophic explosion

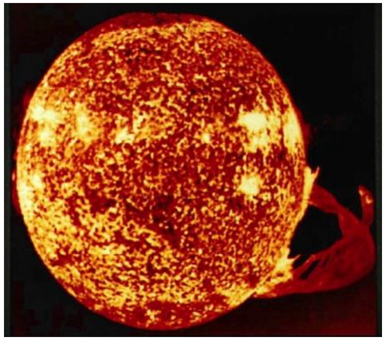
The Life Cycle of Stars

Interstellar medium

BIRTH

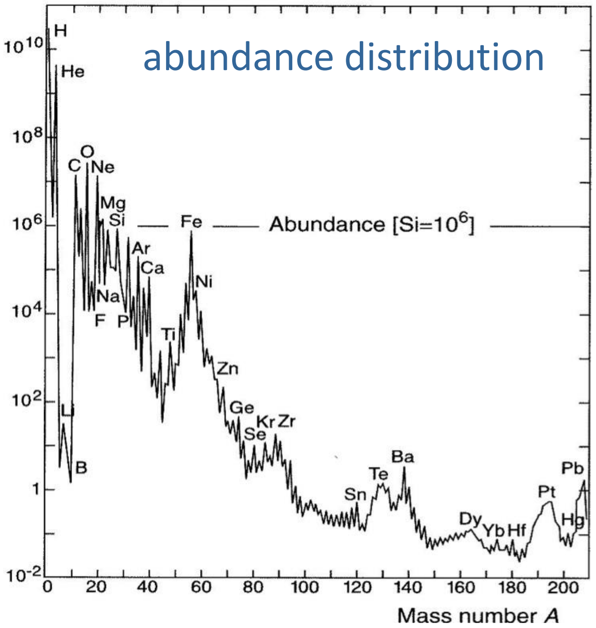
gravitational contraction

Stars



explosion ejection

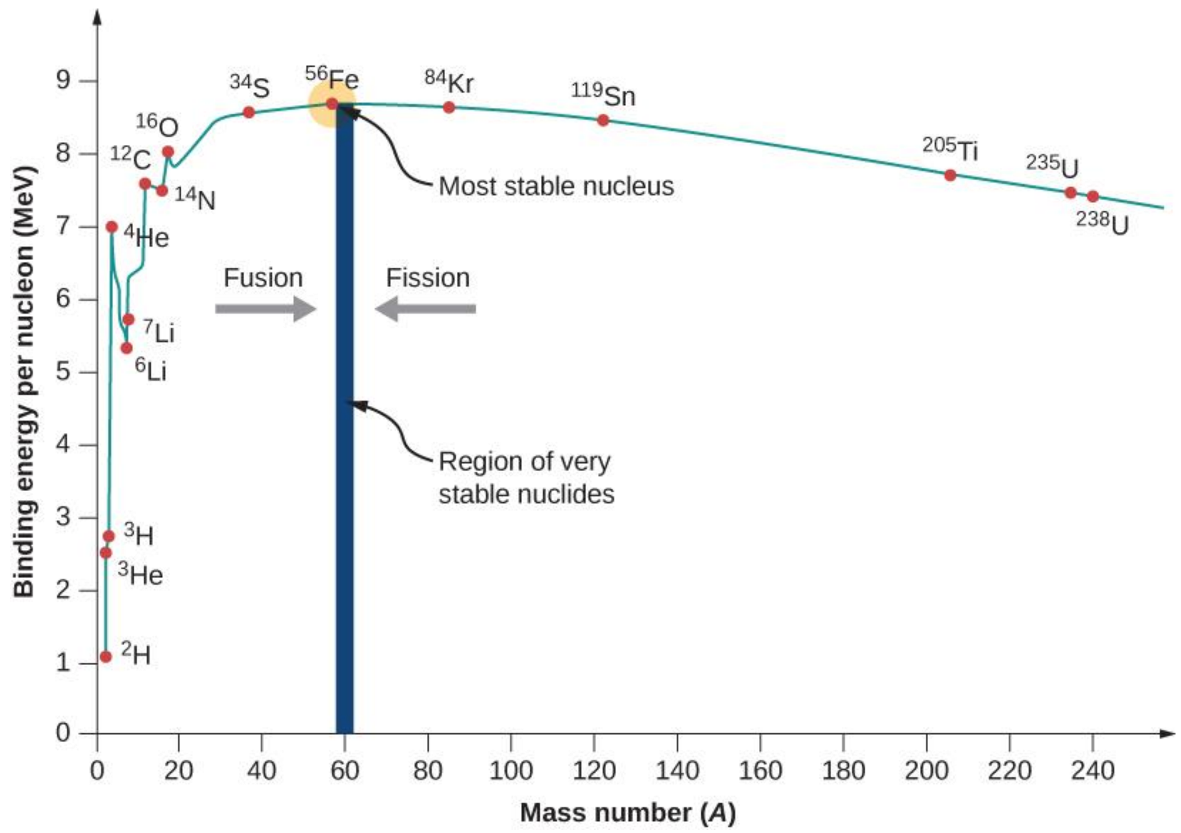
DEATH



- energy production
- stability against collapse
- synthesis of “metals”

Nucleosynthesis beyond Fe

- ✓ Nuclear fusion reactions are only responsible for the synthesis of the elements up to Fe



Nucleosynthesis beyond Fe

- ✓ The formation of nuclei with A > 60 occurs through neutron and proton captures

- ✓ The absorption of neutrons produces β^- unstable nuclei. They transform to stable isobar with higher Z:

$$(Z,A) + n \rightarrow (Z, A+1)$$

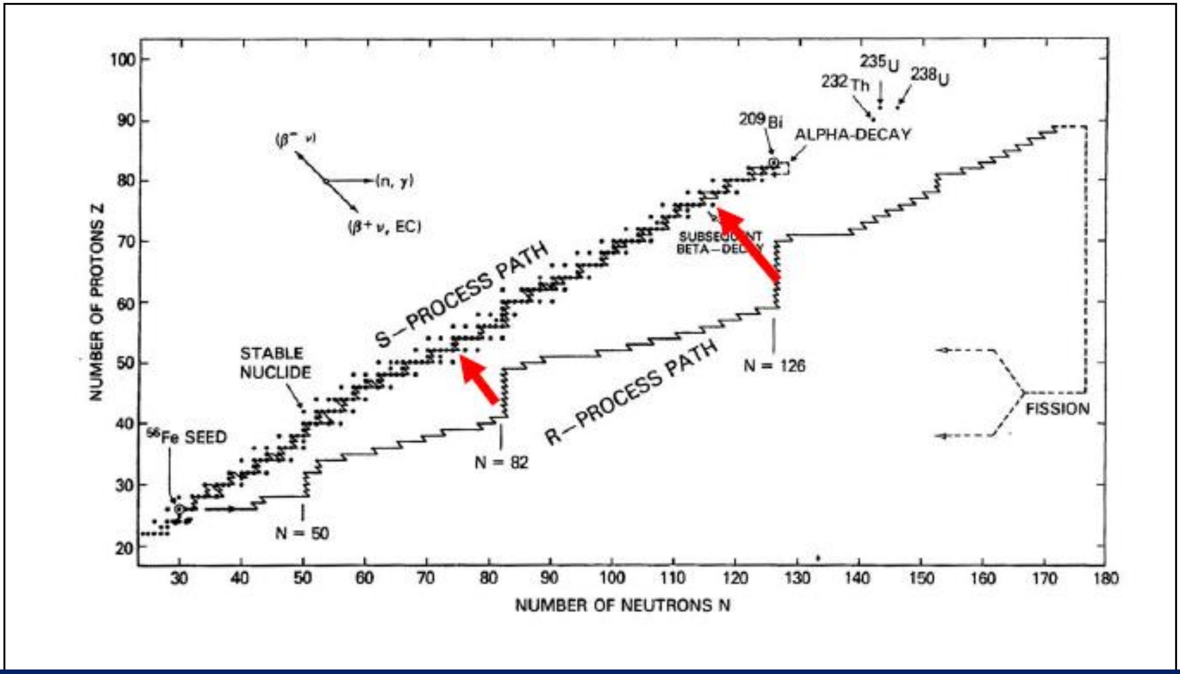
$$(Z, A+1) \rightarrow (Z+1,A) + e^- + \overline{\nu_e}$$

- ✓ These nuclei can again undergo neutron capture and β^- decay

- ✓ The stellar matter is hit by neutron fluxes of different intensities: «slow-s» or «rapid-r» neutron captures if the flux is high or weak respectively

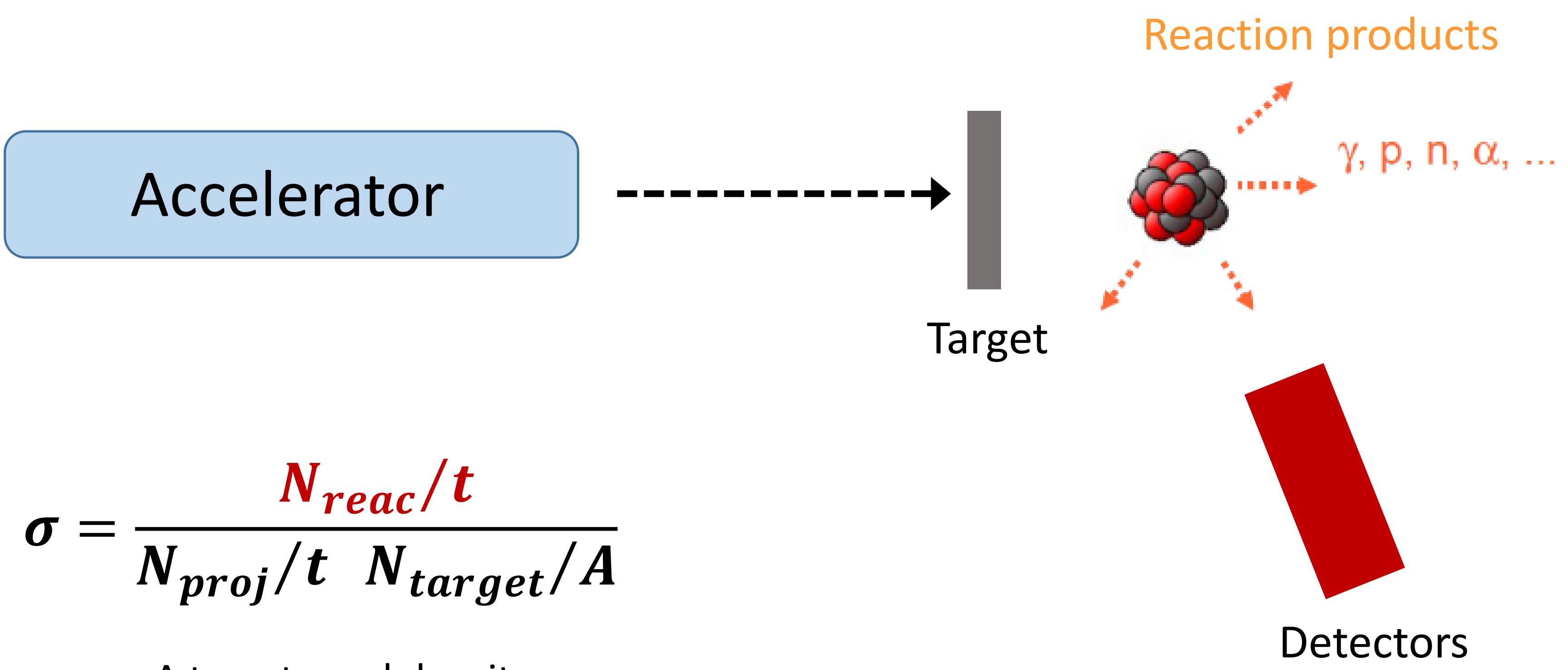
Nucleosynthesis beyond Fe

- In the s-process: $\tau_{n\gamma} >> \tau_{\beta}$. Un unstable (Z,N) nucleus captures 1-2 neutrons at maximum before the β^- decay and becomes a nucleus with Z' = Z + 1
- The s-process closely follows the valley of β^- stability. Neutron flux (10^8 n/cm^3)
- The process continues until a magic number of protons (Z) or neutrons (N) is reached
- In the r process ($\tau_{n\gamma} << \tau_{\beta}$) several neutrons are added to the initial nucleus (Z,N) producing a nucleus far from the stability line before β- decay



How do we measure these reactions in the laboratory?

A typical layout of a nuclear (astro)physics experiment



$$\sigma = \frac{N_{reac}/t}{N_{proj}/t \;\; N_{target}/A}$$

A target areal density

Cross section measured in barn
1 barn = 10^{-24} cm^2

Nuclear reactions with astrophysical impact

- $^{12}C + ^{12}C \rightarrow ^{20}Ne + \alpha$ $^{12}C(^{12}C,\alpha)^{20}Ne$
  - Relevant reaction in massive stars
- $D + p \rightarrow ^{3}He + \gamma$ $D(p,\gamma)^{3}He$
  - Relevant reaction during Big Bang Nucleosynthesis
- $^{13}C + \alpha \rightarrow ^{16}O + n$ $^{13}C(\alpha,n)^{16}O$
  - Relevant reaction for the production of neutrons responsible for the nucleosynthesis of the elements heavier than Fe
- In general:
  - $A + x \rightarrow B + w$ can be written as A(x,w)B and we can define the Q value as:

$$Q = (m_x + m_A - m_B - m_w)c^2$$

Source of radiation

The radiation originating in atomic or nuclear processes can be divided into three general types (charged and uncharged):

- ✓ **Charged particles**: all energetic charged particles (alpha particles, protons, fission products and electrons)
- ✓ **Electromagnetic radiation**: X-rays from atomic electron rearrangement and gamma-rays from transitions in the nucleus itself
- ✓ **Neutrons**: thermal or fast (e.g. emitted in nuclear reactions)

Charged particles

Interaction of charged particles with matter

✓ Charged particles interact with matter through:

1. inelastic collisions with atomic electrons of absorber atoms
2. elastic collisions with absorber nuclei

- process 1. is far more likely except at very low projectile energies
- cross sections for such collisions $\sigma \sim 10^7\text{-}10^8$ b
- energy transfer in collision results into excitation of electrons to higher orbits, or complete removal of electron (ionization)
- energy transfer per collision typically small, but very many collisions per path length
- almost continuous energy loss until charged particle is stopped
- *linear stopping power* S is defined as the energy loss per unit path length in a material

$$S = -\frac{dE}{dx}$$

Bethe-Bloch Formula

- Energy loss of a charged particle in an absorber material:

$$\frac{dE}{dx} = \frac{4\pi z^2 e^4 N_0}{m_e v^2} \rho \frac{Z}{A} B$$

$$B = \ln\left(\frac{2m_2\beta^2c^2}{I}\right) - \ln(1-\beta^2) - \beta^2$$

- with (v,z) the velocity and charge state of the incident particle; ρ and Z are the mass density and atomic number of absorber; m_e electron's rest mass; and *I* average ionisation and excitation energy of absorber. N_0 Avogadro number

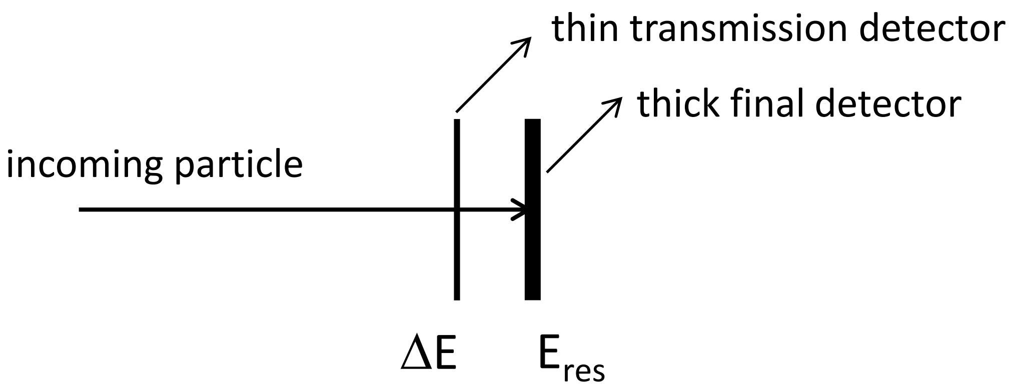
- Higher density materials have greater stopping power

$$\frac{dE}{dx} \propto \frac{z^2}{v^2} \propto \frac{Mz^2}{E}$$

Heavy particles lose energy faster

ΔE – E technique

✓ A ΔE-E telescope comprises two or more detectors which the particle traverses in sequence, usually being stopped in the last one



✓ ΔE = fraction of energy lost in thin detector

✓ E_{res} = residual energy deposited in thick detector

✓ $E = \Delta E + E_{res}$

✓ $\Delta E \sim Mz^2/E$ → $\Delta E x E \sim Mz^2$ → different hyperbolae for different Z

Photons

How do γ-rays Interact with Matter?

- Gamma-rays (photons) can interact with matter through three primary processes:
  - **Photo-electric absorption**
  - **Compton Scattering**
  - **Pair Production**
- Photon transfers part or all of its energy to an electron in absorber medium in a single interaction
- Photon either disappears or is significantly deflected from its original direction
- Photon intensity reduced as photons pass through matter
- The linear attenuation coefficient μ (= $N\sigma$) depends on the target material and gamma-ray energy E_γ

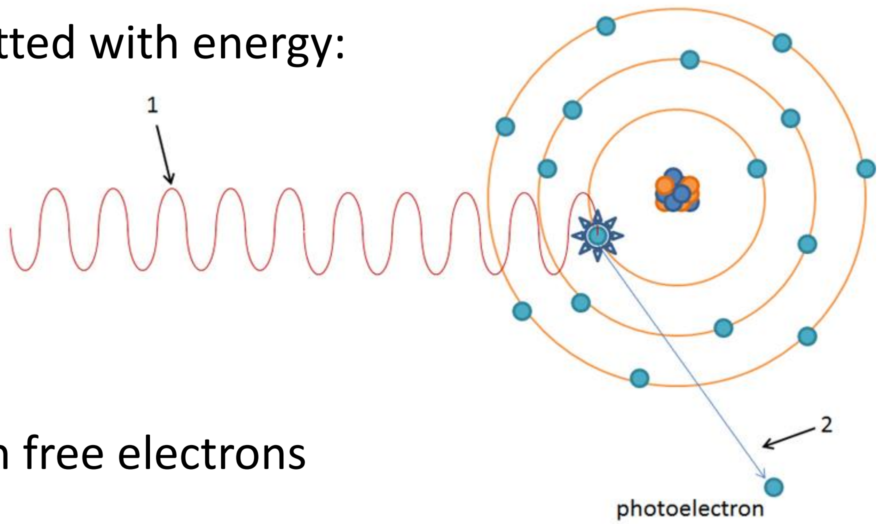
Photo-electric absorption

- Collision between a photon and a **bound** electron
- Photon disappears; (photo-)electron emitted with energy:

$$E_e = E_\gamma - E_b$$

E_γ = energy of incoming photon

E_b = binding energy of atomic electron

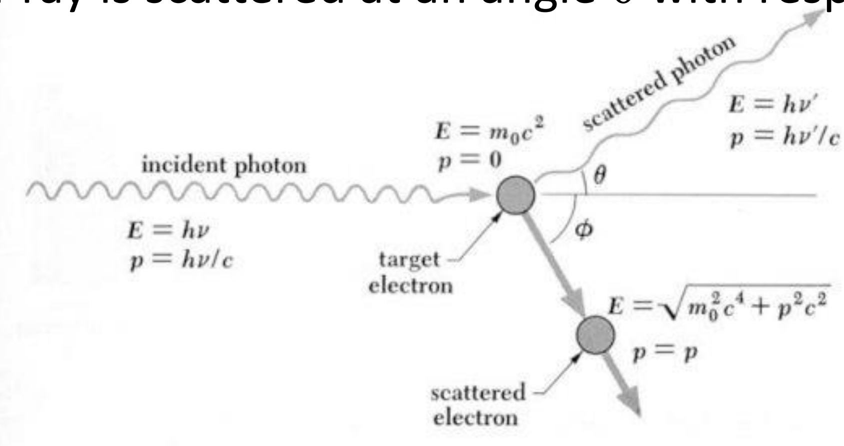


- Photo-electric effect cannot take place on free electrons (need to conserve energy and momentum)
- Most tightly bound electrons are more likely to contribute to PE effect
- Photo-electric cross section:

$$\sigma_{pe} \sim Z^5/E_\gamma^{3.5}$$

Compton scattering

- Collision between a photon and a **free (loosely bound)** electron
- The photon transfers part of its energy to a recoil electron
- Energy of electron depends on scattering angle
- Incoming gamma-ray is scattered at an angle θ with respect to its original direction

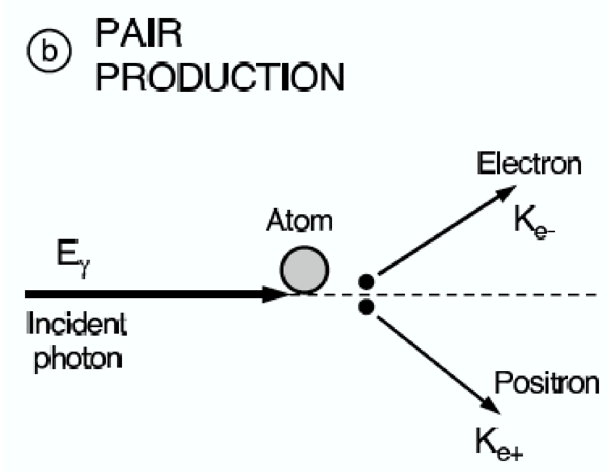


- Energy of the scattered photon after collision:

$$E'_g = \frac{E_g}{1 + \frac{E_g}{m_0 c^2}(1 - \cos q)}$$

- Compton-scattering cross section: σ_{comp} ~ Z/Eγ

Pair production



- ✓ For gamma rays with energies $E_\gamma \geq 1.022$ MeV, pair production becomes possible
- ✓ A gamma ray disappears in the Coulomb field of the nucleus and is replaced by an electron-positron pair
- ✓ The excess energy above 1.02MeV goes to the kinetic energy of the electron and the positron:

$$K_- + K_+ = E_\gamma - 2m_ec^2$$

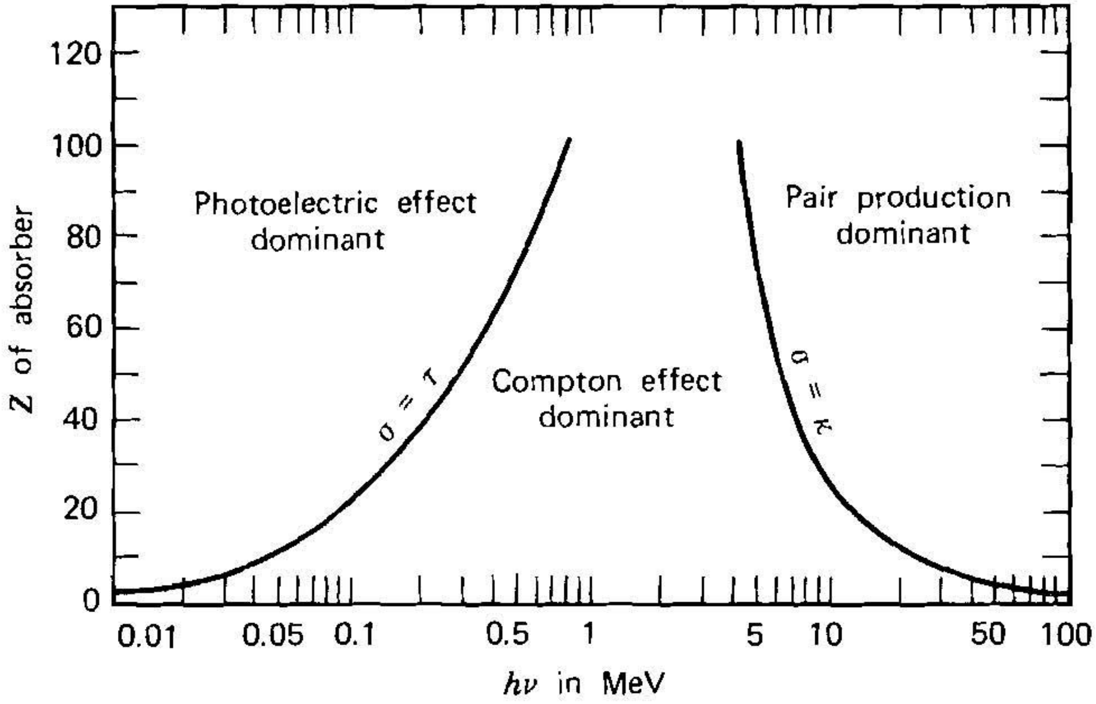
- ✓ After slowing down in the absorbing medium, positron annihilates producing two annihilation photons (511 keV each) emitted in opposite directions
- ✓ Pair-production cross section:

$$\sigma_{pair} \sim Z^2 \ln(E_\gamma)$$

Relative importance of all contributions

- ✓ The total cross section for photon-matter interaction has contributions from all three processes

$$\sigma = \sigma_{pe} + \sigma_{comp} + \sigma_{pair}$$



- ✓ The lines show the values of Z and hν for which the two neighboring effects are just equal

Gamma-rays attenuation

- For a well-collimated photon beam, all three processes can take place, leading to attenuation of beam intensity as it passes through matter
- Photons undergoing photo-electric absorption or pair- production disappear altogether; those which are Compton scattered are deflected from incident direction
- Beam intensity is reduced exponentially as:

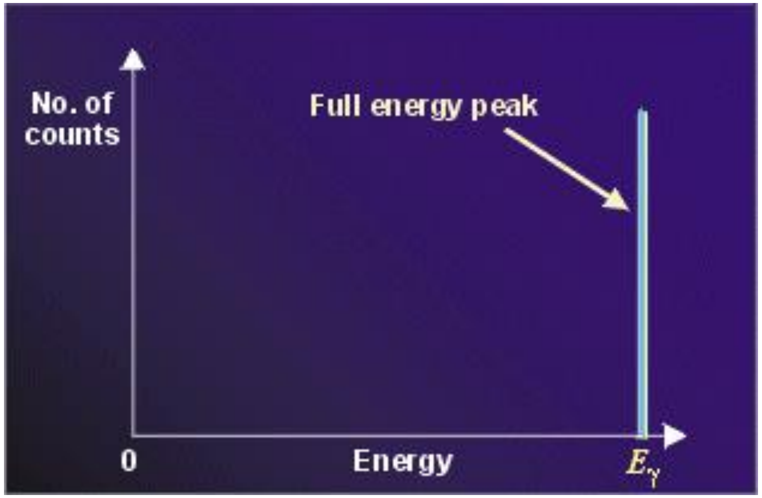
$$I = I_0 \exp(-\mu x)$$

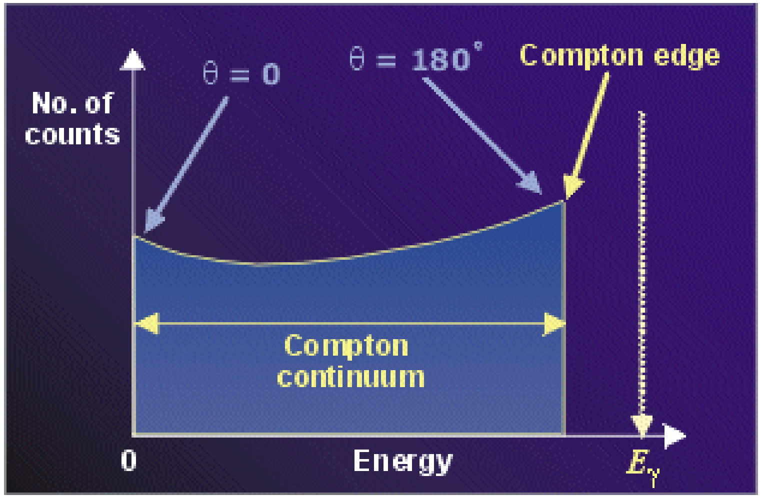
with μ (=$N\sigma$) linear attenuation coefficient (length^{-1})
being N the number of targets per unit volume e σ the cross section

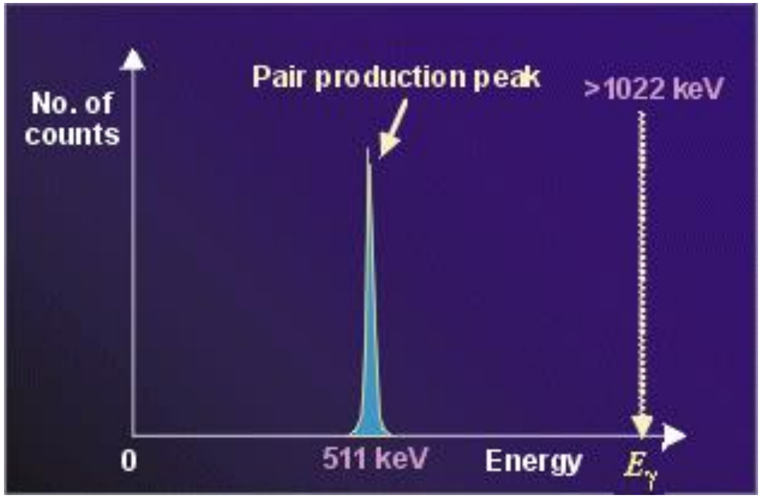
Gamma-ray spectrum and Detector response

- ✓ High-Z materials are typically chosen for gamma-ray detection

- ✓ Each of the three interaction processes will leave an electron with finite energy in semiconductor material

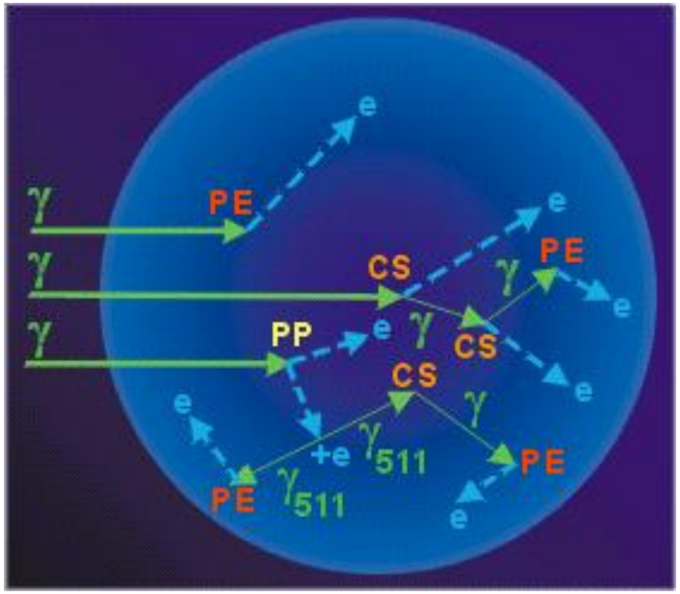


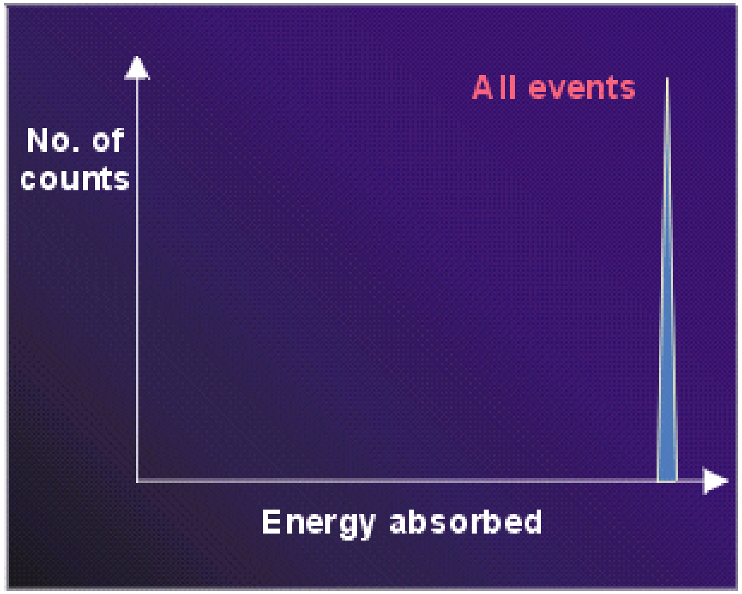




Interaction in large detectors

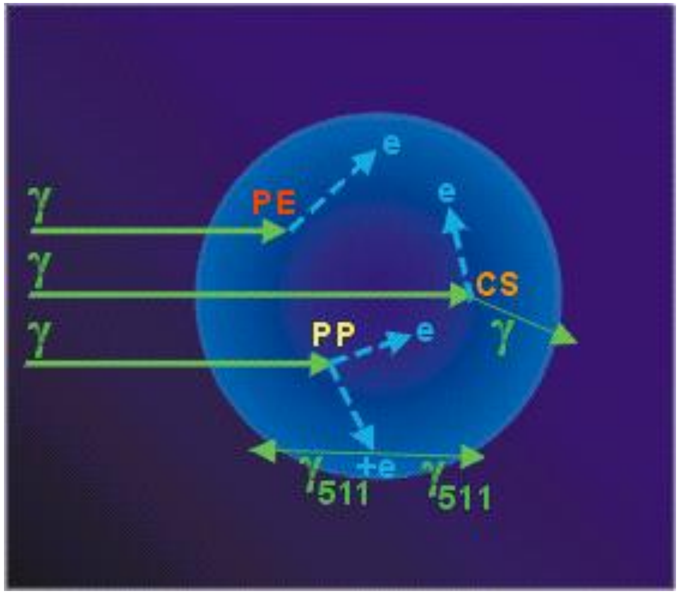
- ✓ A **large detector** is one in which we can ignore the surface of the detector
- ✓ Various successive photoelectric absorption, Compton scattering and pair production interactions will occur
- ✓ The result is complete absorption of the gamma-ray and a single gamma-ray peak, referred to as the full energy peak

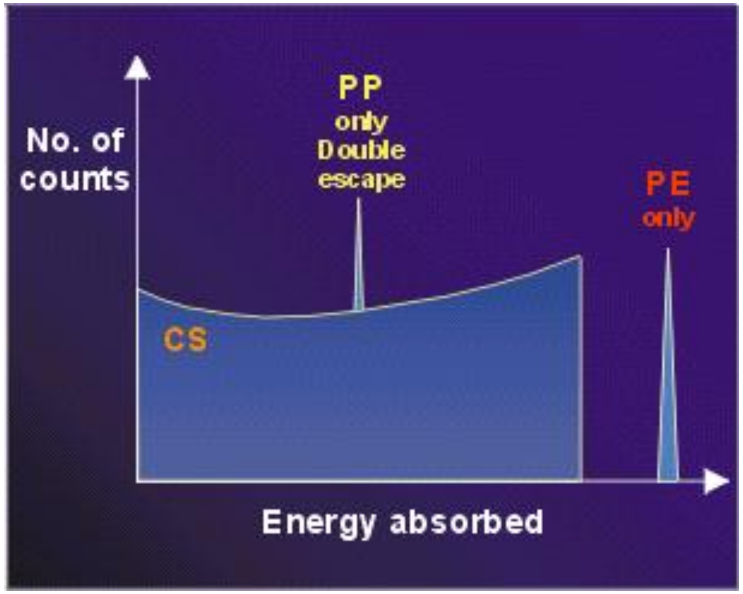




Interaction in a small detector

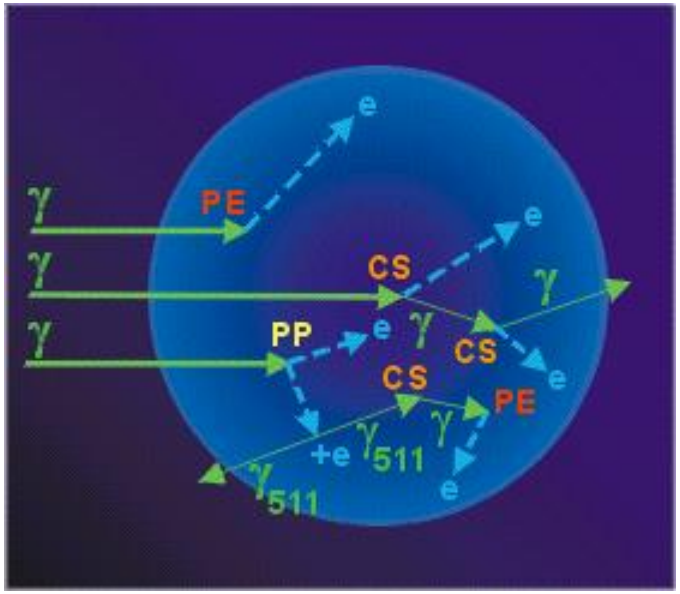
- ✓ A **small detector** is one so small that only one interaction can take place within it (small compared to mean free path of secondary radiation)
- ✓ Only the photoelectric effect will produce full energy absorption
- ✓ Compton scattering events will produce the Compton continuum
- ✓ Pair production will give rise to the double escape peak due to both gamma-rays escaping

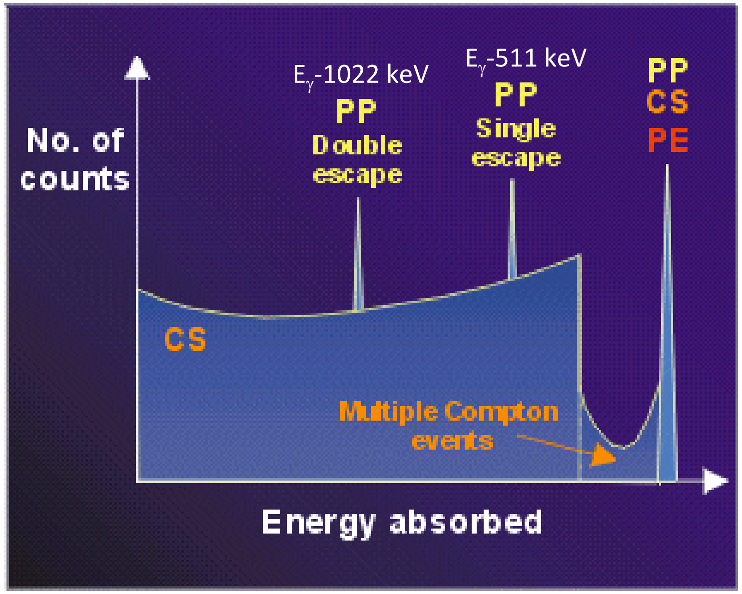




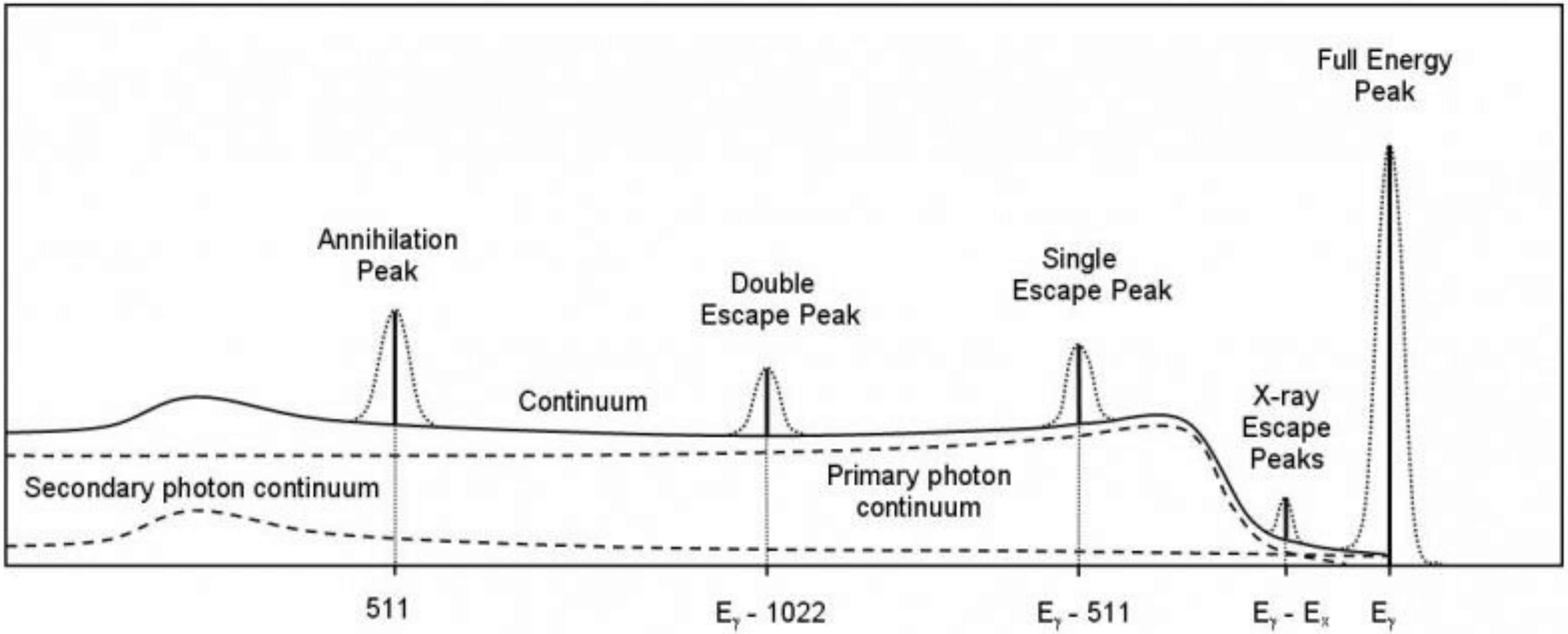
Interaction in a real detector

- ✓ Within a **real detector** the interaction outcome is not as simple to predict as the small or large detector cases
- ✓ Compton scattering may be followed by other Compton scatterings before the gamma-ray photon escapes from the detector
- ✓ Also, pair production may be followed by the loss of only one annihilation gamma-ray, resulting in a single escape peak as well as a double escape peak





Gamma-ray spectrum



Neutrons

Neutron Detection

- Like γ rays, neutrons cannot be detected directly, but through secondary radiation produced in interaction of neutrons with matter

- In contrast to γ rays, secondary radiation from neutrons interactions is almost always heavy charged particles

- Neutron interaction probabilities depend on neutron energy

- Fast neutrons ($E_n > 0.5$ eV)
  - low capture cross sections ($\sigma \sim 1/v$)
  - lose energy via collisions, mostly with nuclei in absorbing material until they become *moderated*
  - most efficient moderator is hydrogen because of its comparable mass with n

$$\mathbf{E'_{n-min}} = \mathbf{E_n}\left(\frac{\mathbf{A-1}}{\mathbf{A+1}}\right)^{\mathbf{2}}$$

Neutron Detection

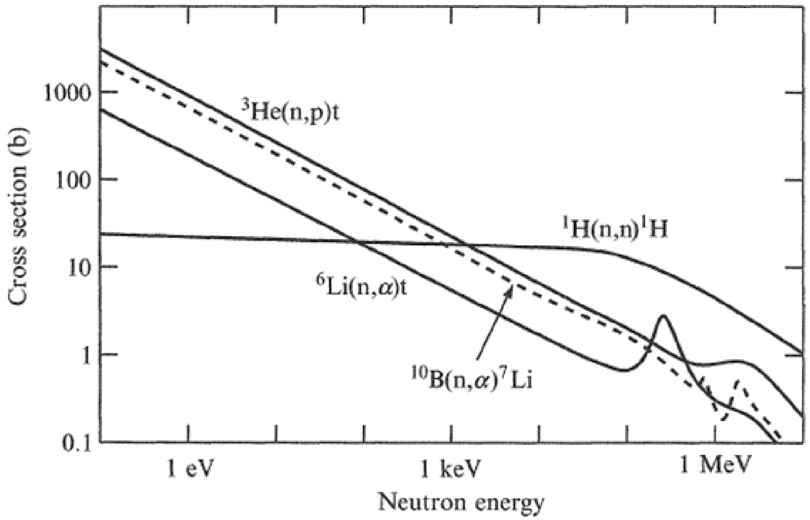
✓ Slow neutron to thermal neutron ($0.025\ eV < E_n < 0.5\ eV$)

- main interaction through (n,γ) (n,p) (n,α) and (n,fission) reactions
- typically large Q-value reactions preferred
- typically reactions producing charged particles preferred

$n + {}^{6}Li \rightarrow \alpha + {}^{3}H$ (Q=4.782 MeV)

$n + {}^{10}B \rightarrow \alpha + {}^{7}Li$ (Q=2.790 MeV)

$n + {}^{3}He \rightarrow p + {}^{3}H$ (Q=0.763 MeV)



Neutron detection

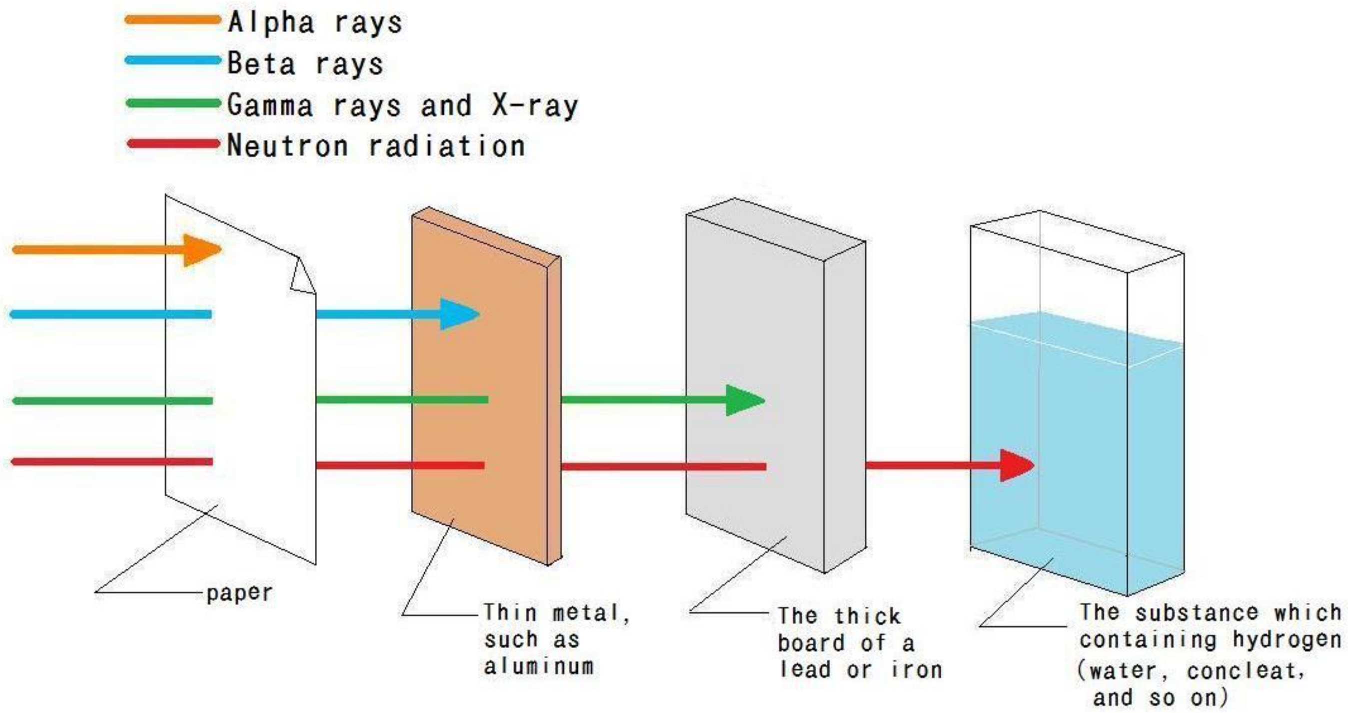
Table 7: Some Reactions Useful for Slow-Neutron Detection

reaction*	Q-value (MeV)	cross section (in barns) for thermal (0.025 eV) neutrons
$^{10}B + n \rightarrow {}^{7}Li + \alpha$	2.31	3,840
$^{6}Li + n \rightarrow {}^{3}H + \alpha$	4.78	940
$^{3}He + n \rightarrow {}^{3}H + p$	0.764	5,330
$^{235}U + n \rightarrow X + Y$ (fission fragments)	~200	575

*n represents a neutron, p a proton, and α an alpha particle.

Penetration power for different radiation

- ✓ Range of Radiation
  - Alpha: Small: shield with a piece of paper
  - Beta: Small-"ish": shield with a few cm or so of Pb
  - Gamma: Long shield with a several cm of Pb
  - Neutron: Very long shield with many cm of paraffin



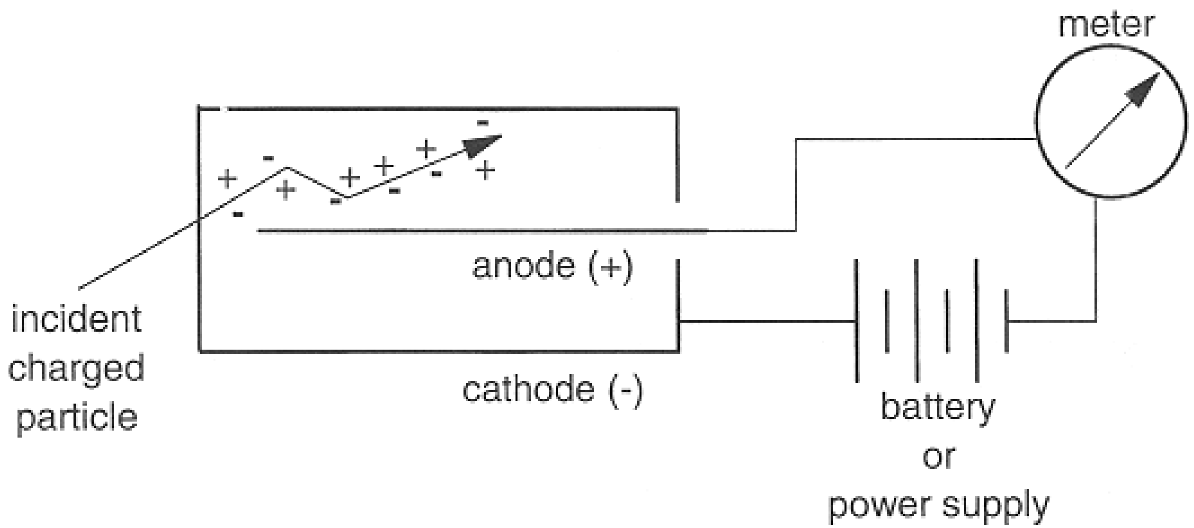
Type of detectors

- ✓ Gas-filled detectors
- ✓ Solid state (semi-conductor) detectors
- ✓ Organic scintillators (liquid & plastic)
- ✓ Inorganic scintillators

Note: scintillators operate with photo-sensor (i.e. another detector)

Gas filled detectors

- Consist in volume of gas between two electrodes, with potential difference (voltage) applied between them
- Ionizing radiation produces ion pairs in gas
- Positive ions (cations) attracted to negative electrode (cathode); electrons (anions) attracted to positive electrode (anode)
- Typically, cathode is the wall of the container; anode is a wire inside

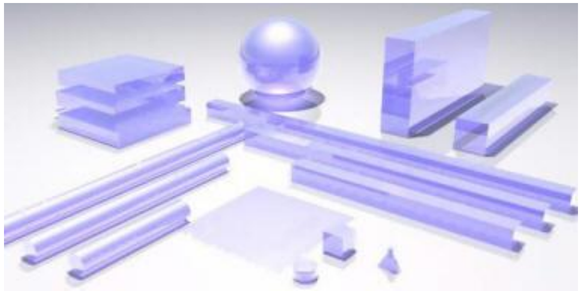


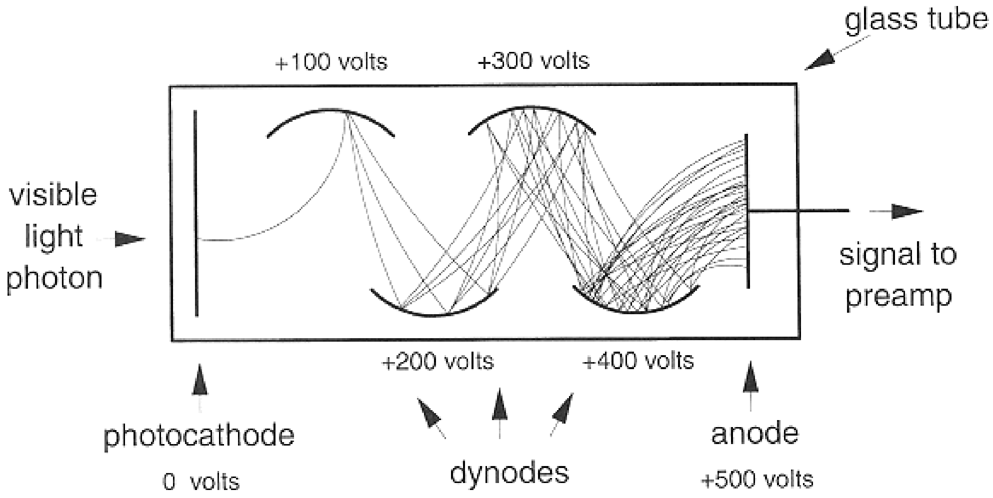
Semicondutor detectors

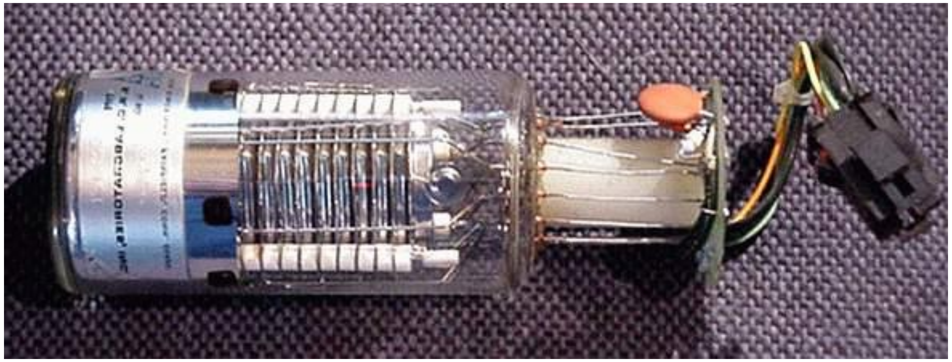
- ✓ Single crystal of semiconductor
  - ❖ p-n junction (typically, Si)
  - ❖ intrinsic detector (typically, Ge)
- ✓ High Z → better material for γ-ray detection
- ✓ Large crystals needed for high efficiency
- ✓ Ge detectors have better resolution than scintillators
- ✓ Must be cooled to LN_2 temperatures
- ✓ Prone to radiation damage

Scintillators

- ✓ Scintillator = organic or inorganic material transparent to its own fluorescent light
- ✓ Incoming radiation excites electrons in scintillator
- ✓ De-excitation leads to emission of light, collected by photo-multiplier tubes (PMT) which converts light into electric signals



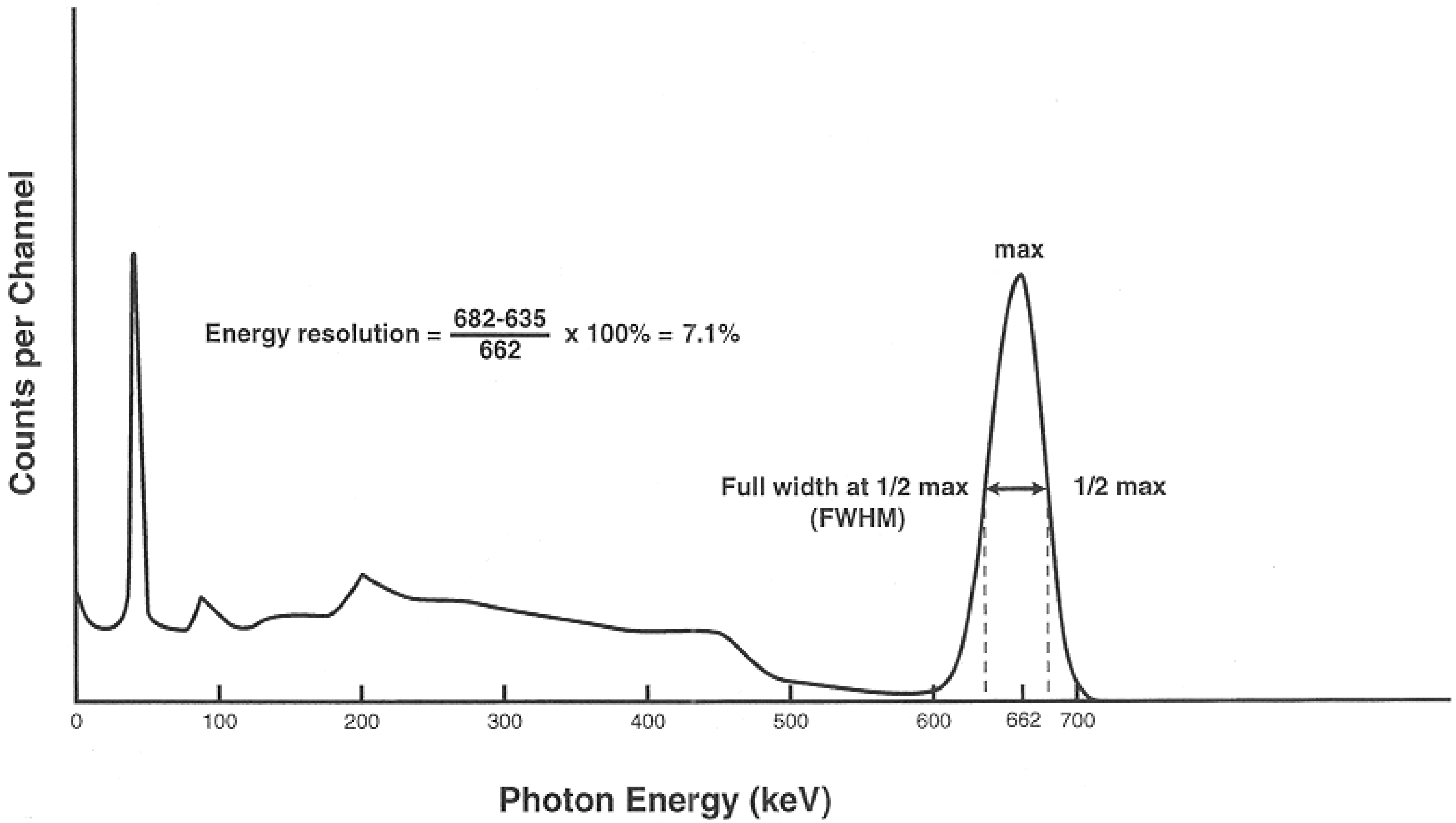




Key features for detectors

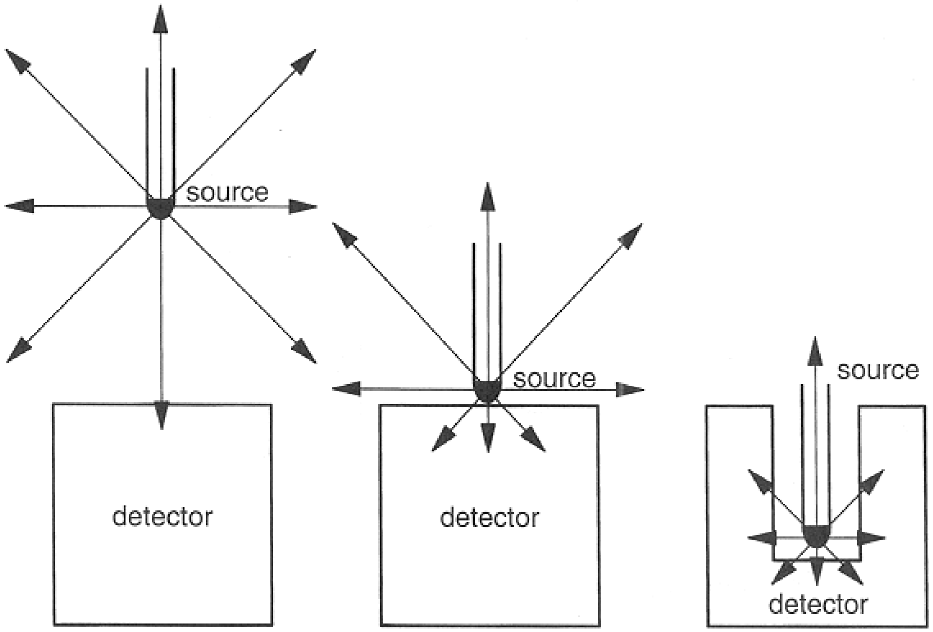
Detector resolution

- ✓ Resolution
  - ❖ in energy (FWHM/peak position)*100%
  - ❖ in angle/position (depends on setup)



Detection efficiency

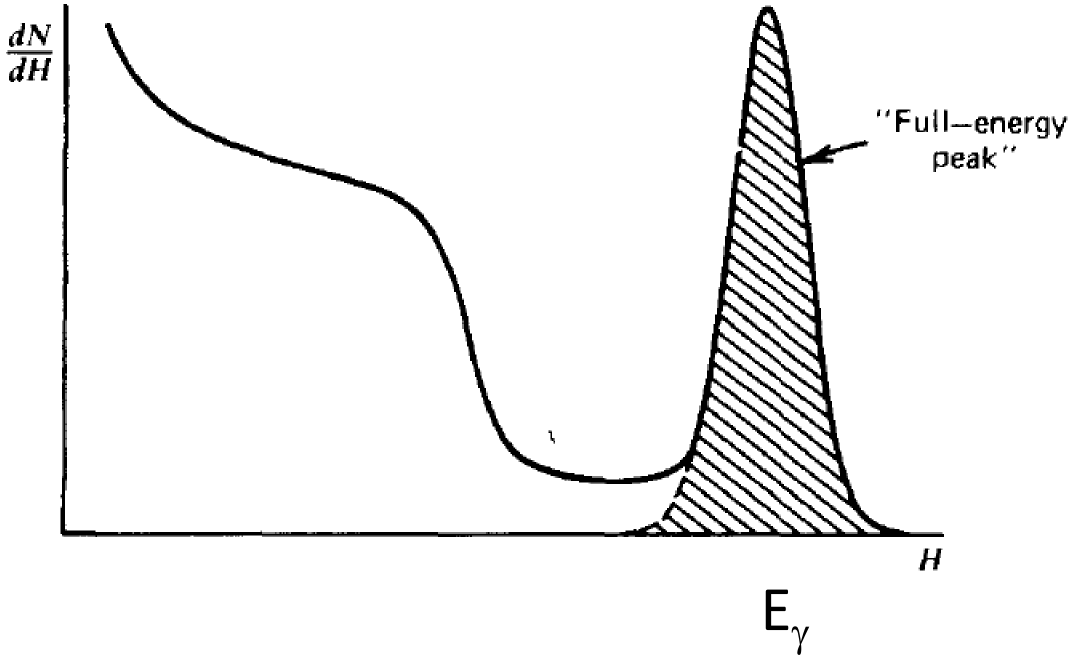
- ✓ Efficiency
  - ❖ intrinsic (100% for charged particles; few % for γ rays)
  - ❖ geometrical (depends on the setup)



$$\varepsilon = \frac{\text{number of pulses recorded}}{\text{number of radiation quanta emitted by the source}}$$

Efficiency in the case of γ spectroscopy

✓ The most common type of efficiency used for γ-ray detectors is the *peak efficiency*



Experimental challenges of nuclear astrophysics experiments

Relevant energies to measure cross sections

Stellar reaction rate at a given temperature

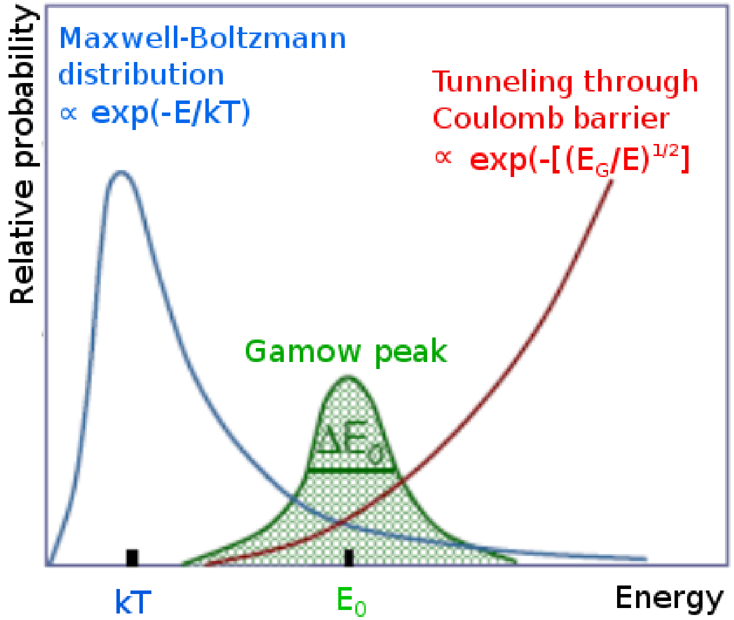
$$r = \frac{N_r}{Vt} = \rho_a \rho_A \int_0^\infty \sigma(v) v \phi(v) d(v) = \rho_a \rho_A < \sigma v >$$

Density of interacting nuclei

Relative velocity

Maxwell – Boltzmann distribution

Cross section



Experimental Challenges of Direct Measurement

Reaction Rate = N_p x N_t x cross section x detection efficiency

10^{14} pps (~100 μA q=1+) typical stable beam intensities

10^{19} atoms/cm^2 typical solid state targets

10^{-12} barn (often even smaller)

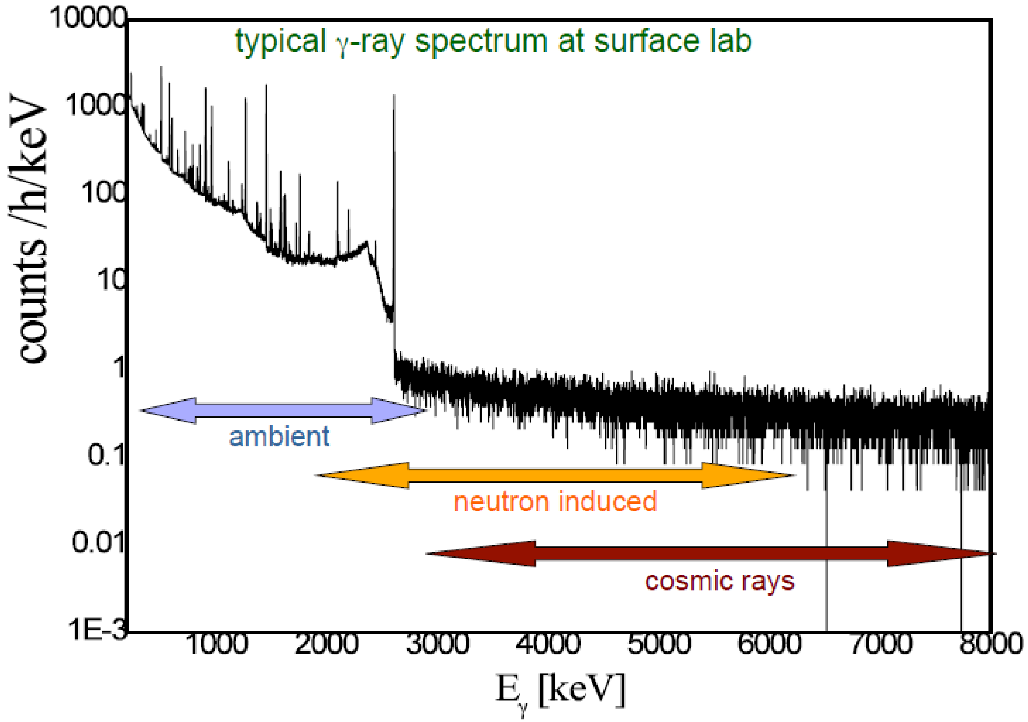
~1-10% for gamma rays (HPGe detectors)

R_{lab} = 1-10 counts/day

Rate and background

The rate R has to be compared with background B:

- ✓ $B_{beam\ induced}$: reactions with impurities in the target, collimators,… secondary processes
- ✓ B_{env} : natural radioactivity mainly from U and Th chains
- ✓ B_{cosmic} : mainly muons

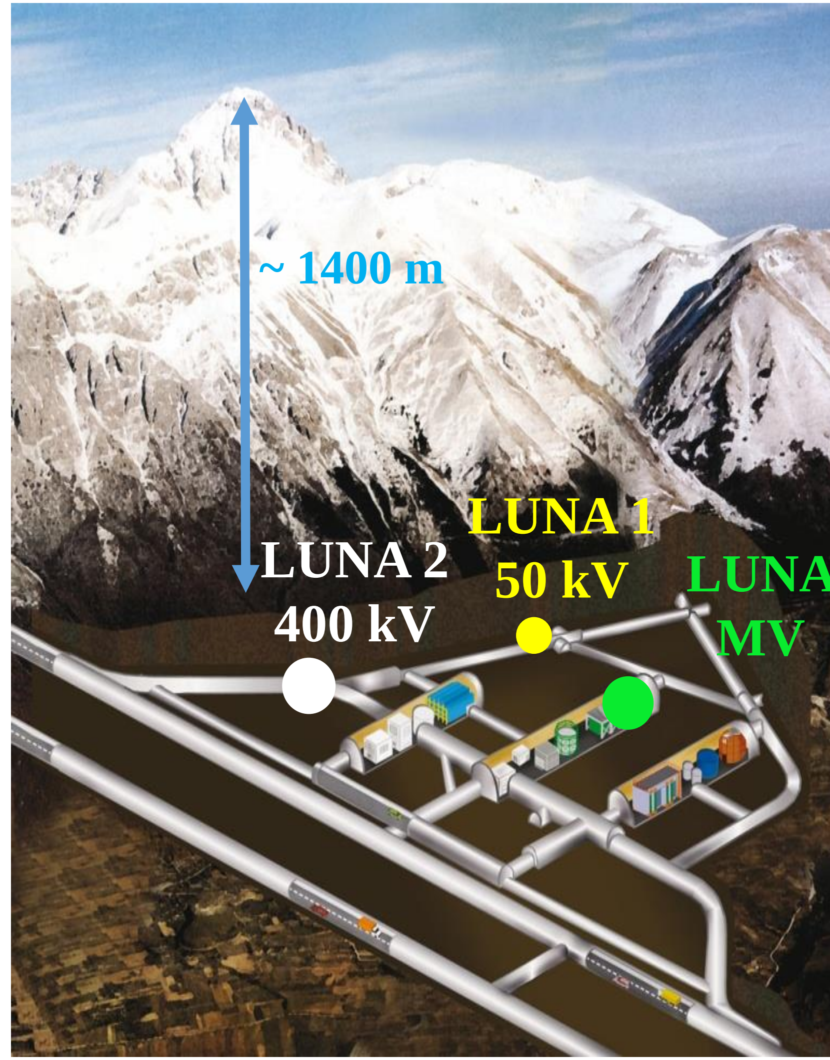


low cross sections → poor signal-to-noise ratios

How to improve the signal-to-noise ratio?

Laboratory for Underground Nuclear Astrophysics

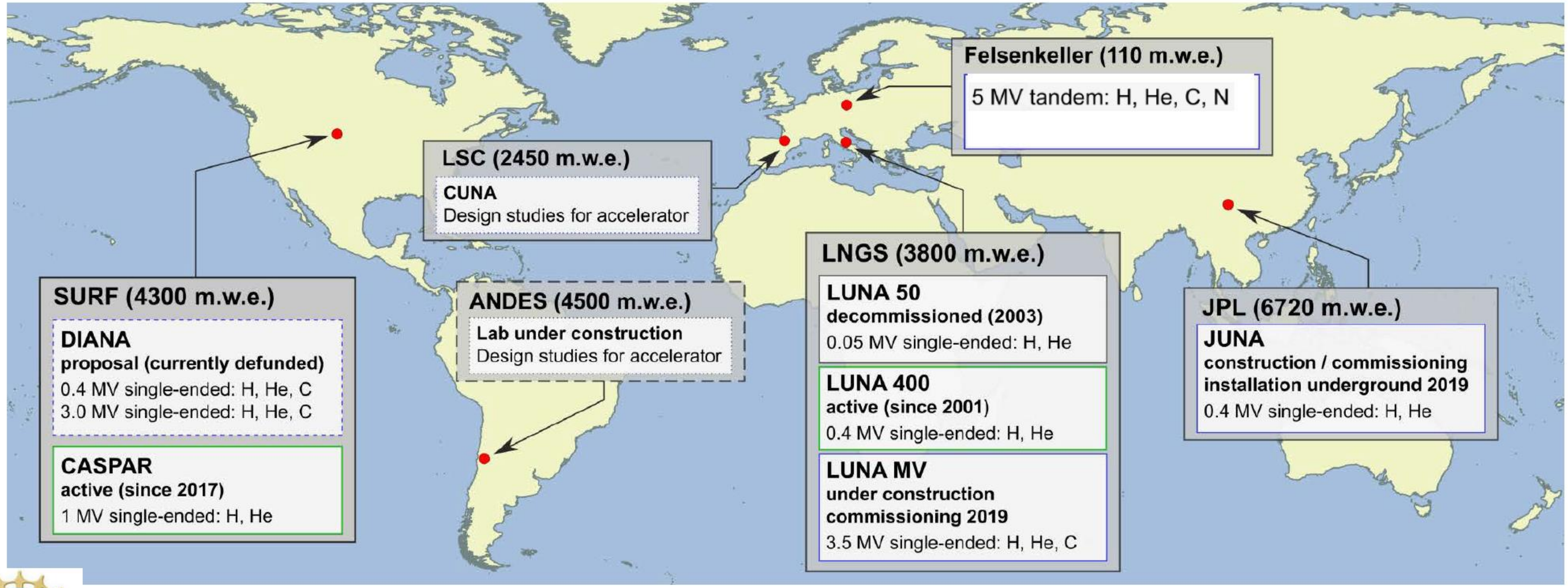
Radiation	LNGS/surface
Muons	10^{-6}
Neutrons	10^{-3}



LNGS (1400 m rock shielding ≡ 4000 m w.e.)

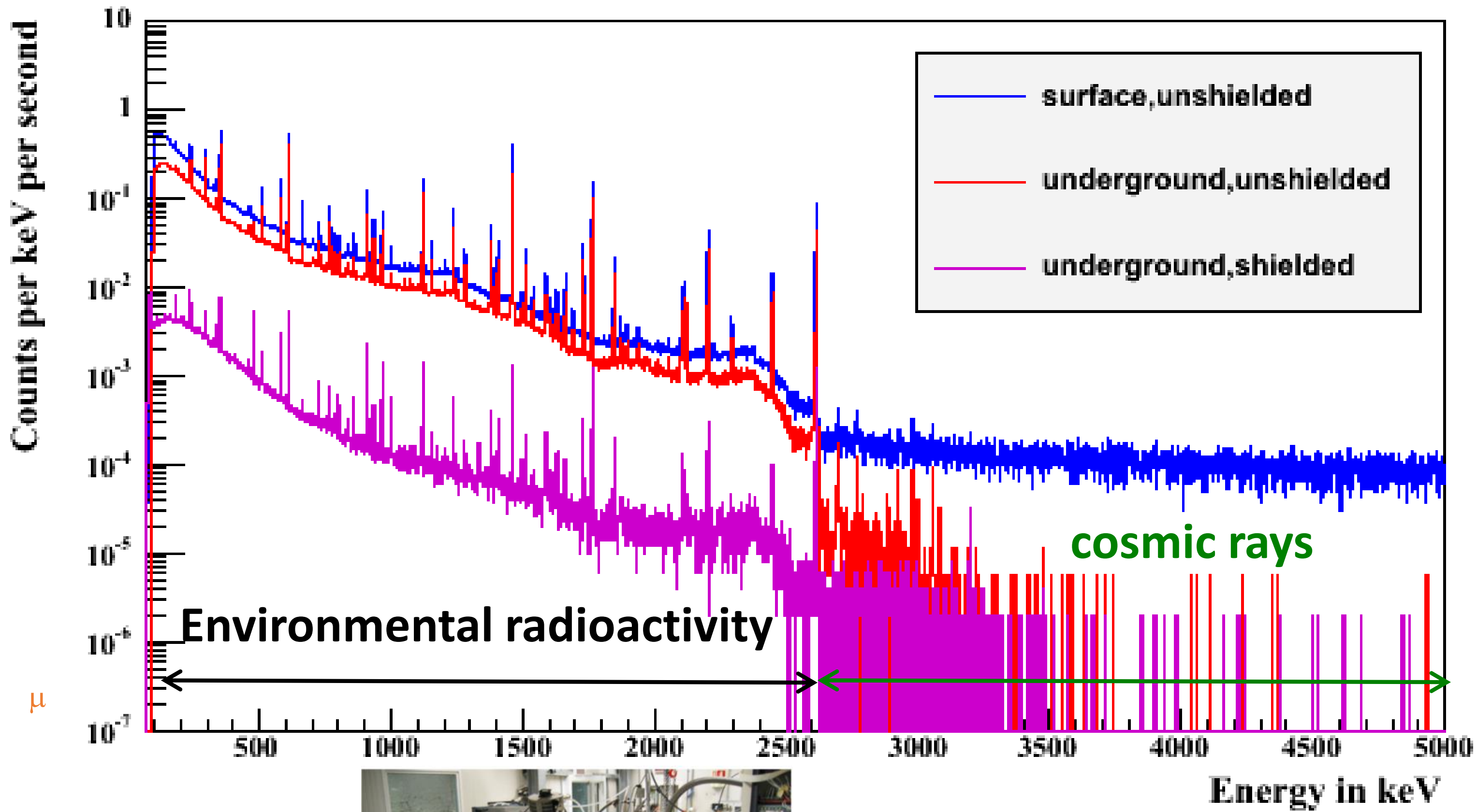
Nuclear Astrophysics Underground Laboratories

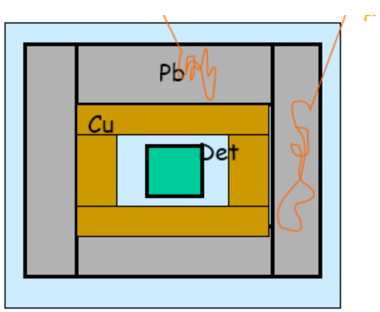
Nuclear Astrophysics Underground Laboratories



courtesy: A. Boeltzig

Gamma background reduction at LNGS





Key elements for a low counting rate experiment

To study nuclear reactions with astrophysical impact we need:

- ✓ High beam currents
- ✓ Prolonged run times
- ✓ High target density and purity
- ✓ High detection efficiency
- ✓ Large solid angle coverage
- ✓ Need to identify reaction channels for proper background subtraction

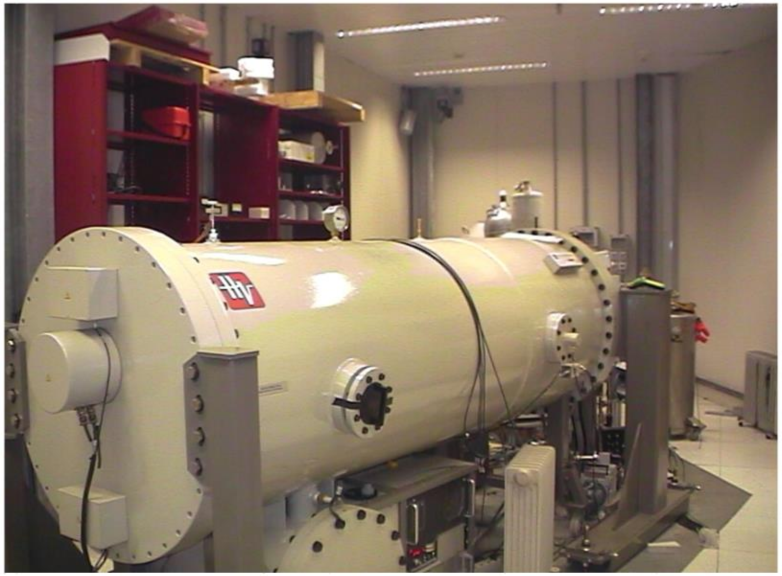
⬇

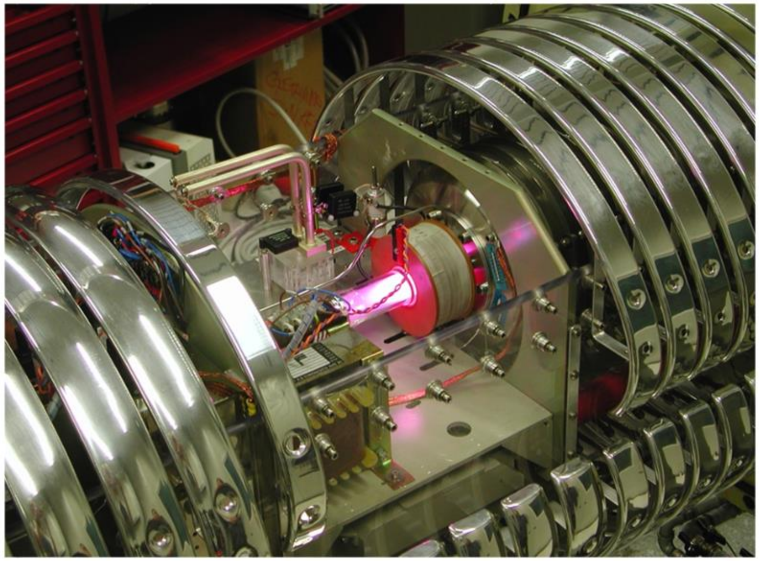
Related to detectors

LUNA experimental setup

The accelerator

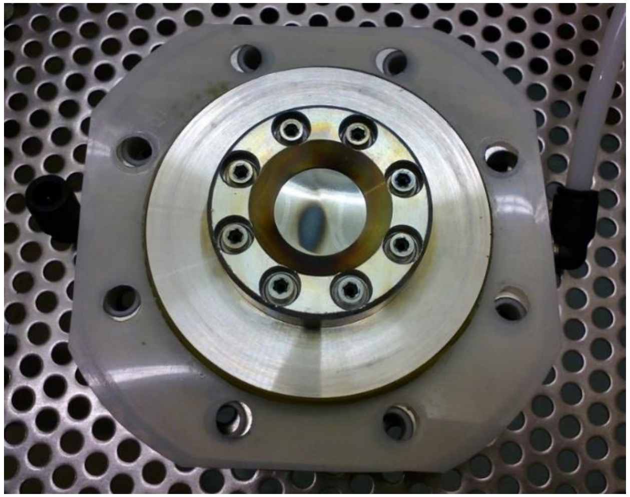
- $E_{p-\alpha}$ = 50 - 400 keV
- I_{beam} = 300-400 μA





Most common targets

✓ Solid targets:



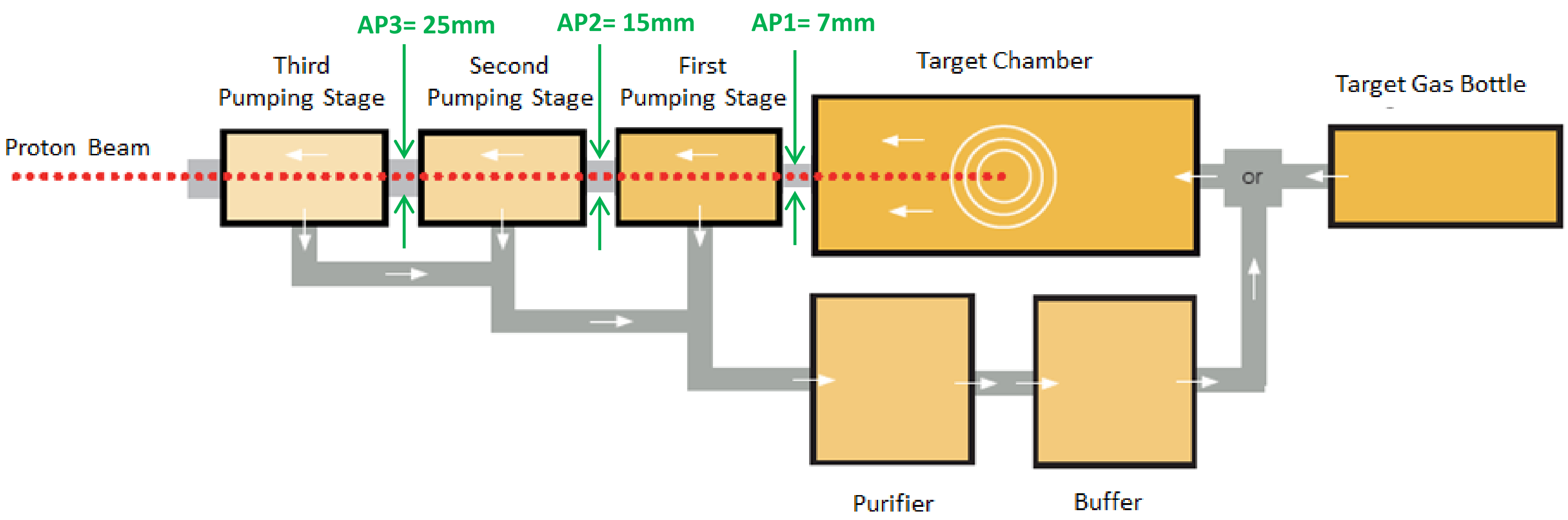
❖ Solid target can be produced by evaporation, implantation…

❖ Typically the target consists of a chemical compound containing active (N_a) and inert (N_i) atoms

Most common targets

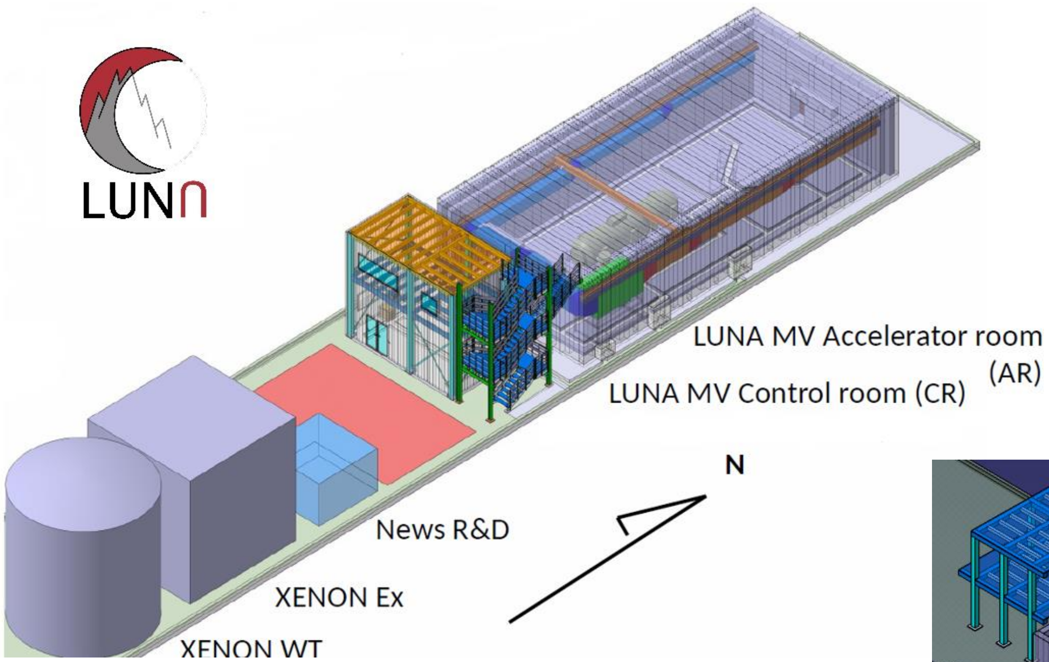
✓ Gas targets:

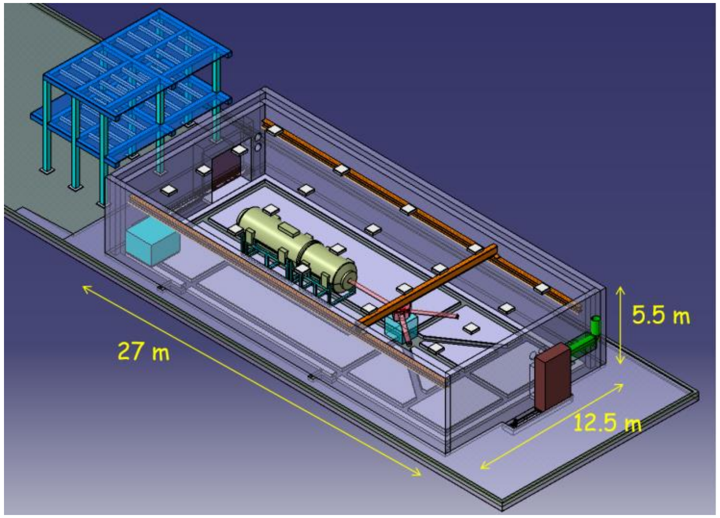
Windowless gas target:
- 3 differential pumping stages
- Gas recirculation and purification system



The future

LUNA MV: A 3.5 MV accelerator





$^{1}H^{+}$ (TV: 0.3 – 3.5 MV): 500-1000 μA

$^{4}He^{+}$ (TV: 0.3 – 3.5 MV): 300-500 μA

$^{12}C^{+}$ (TV: 0.3 – 3.5 MV): 150 μA

$^{12}C^{++}$ (TV: 0.5 – 3.5 MV): 100 μA

LUNA MV: next steps

H, He, C+, C++ beams with high intensity

3.5 MV terminal voltage

Commissioning summer 2022

Final authorizations end of 2022

First scientific beam planned in 2023

Age of Globular Clusters and AGB nucleosynthesis: **$^{14}N(p,\gamma)^{15}O$** -> WG Leader G. Gyurky, Atomki, HU.

Main neutron sources: **$^{13}C(\alpha,n)^{16}O$** -> WG Leader A. Formicola, INFN Roma

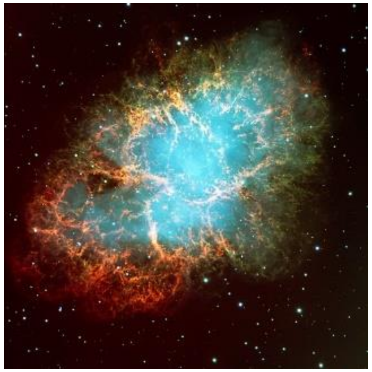
$^{22}Ne(\alpha,n)^{25}Mg$ -> WG Leader A. Best (SHADES ERC project), UniNa, Napoli

Advaced burnings: **$^{12}C(^{12}C, p)^{23}Na$, $^{12}C(^{12}C,\alpha)^{20}Ne$** -> WG Leader A. Guglielmetti, UniMi, Milano

Charged particle detectors

$^{12}C+^{12}C$: the scientific case

- ✓ $^{12}C+^{12}C$ rate determines which stars explode as Supernovae and which die as White Dwarfs
- ✓ Energy of α and p ≈ 1 - 2.5 MeV



$^{12}C+^{12}C \rightarrow {}^{20}Ne + \alpha_i + \gamma_i$ $\quad E_\gamma = 1634$ keV

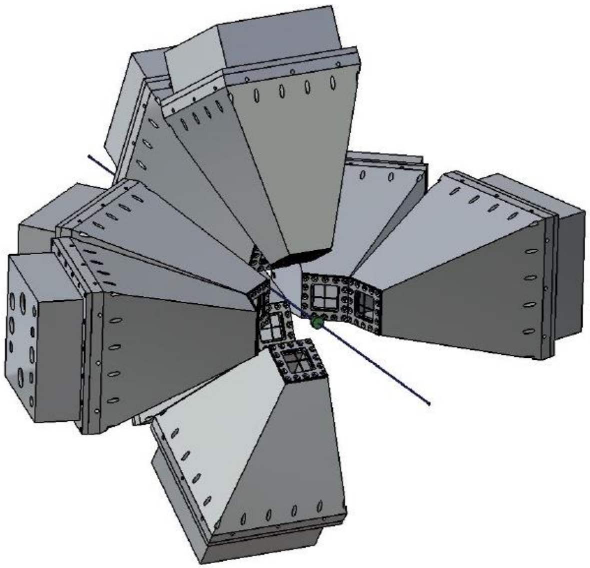
$^{12}C+^{12}C \rightarrow {}^{23}Na + p_i + \gamma_i$ $\quad E_\gamma = 440$ keV

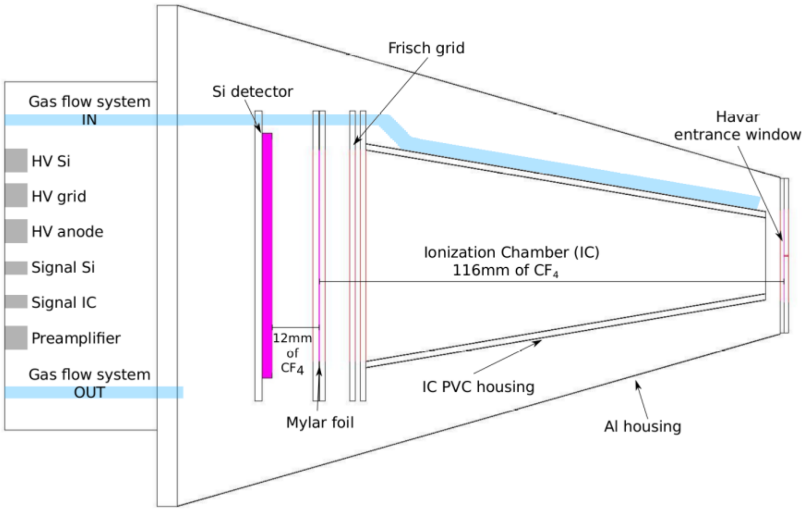
Particle yield

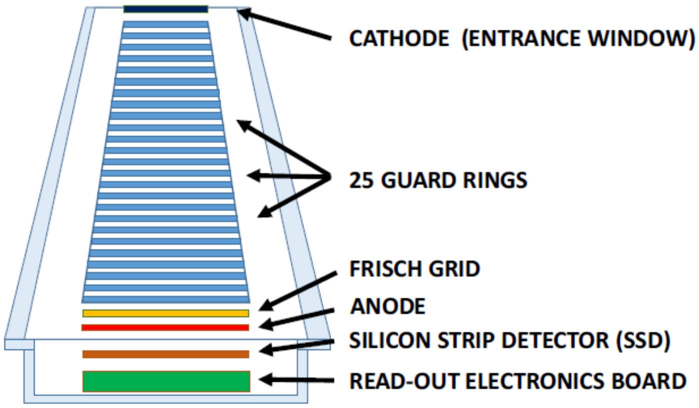
Gamma yield

GAs Silicon Two-Layer sYstem (GASTLY)

- ✓ The array consists of a two stage detection system:
  - ❖ Ionisation chambers (ΔE stage)
  - ❖ Large area (6x6 cm^2) silicon strips detectors (E stage)
- ✓ Up to 8 individual modules
- ✓ Detectors provided by the CIRCE group in Caserta



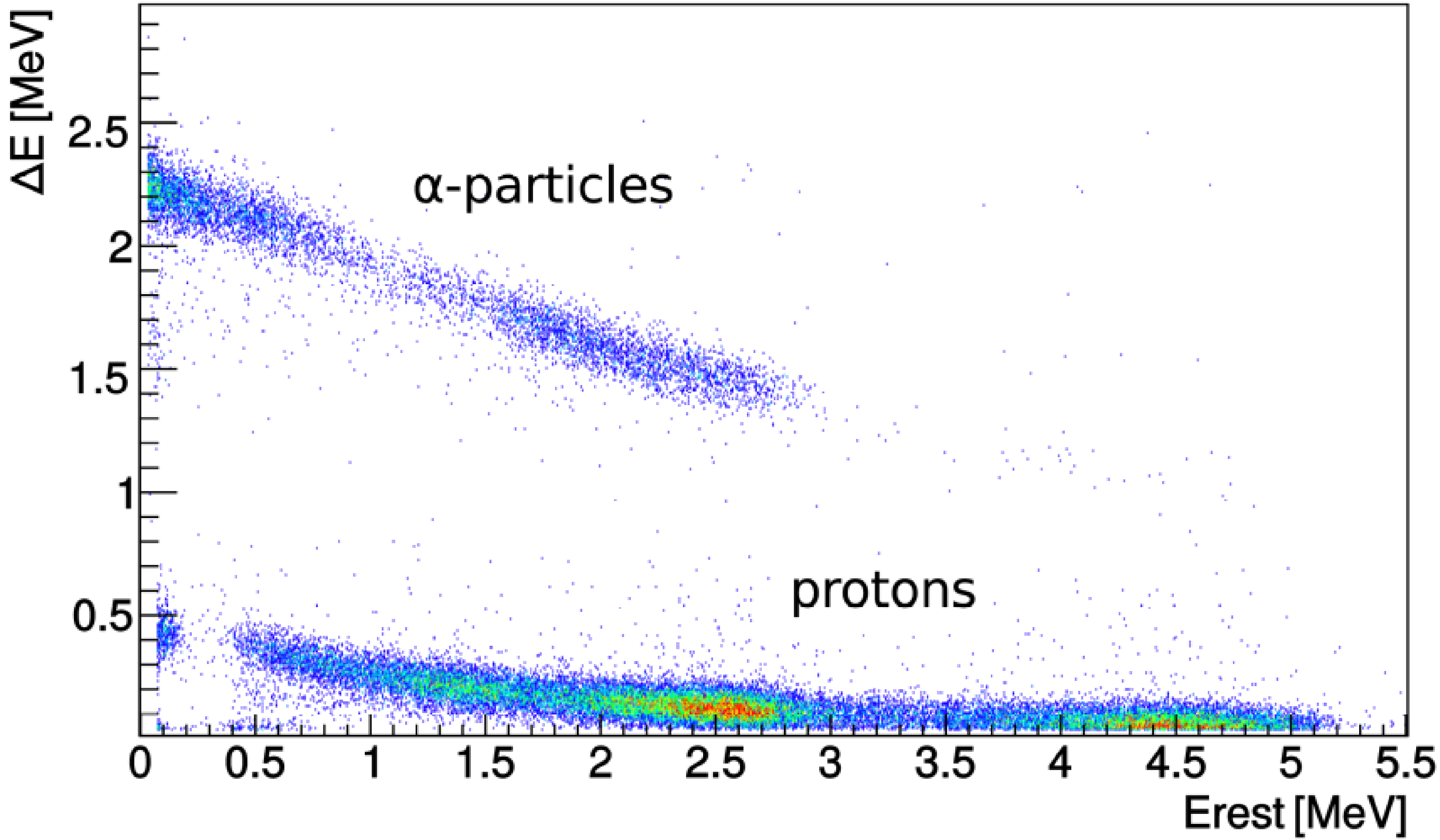




Courtesy of L. Morales

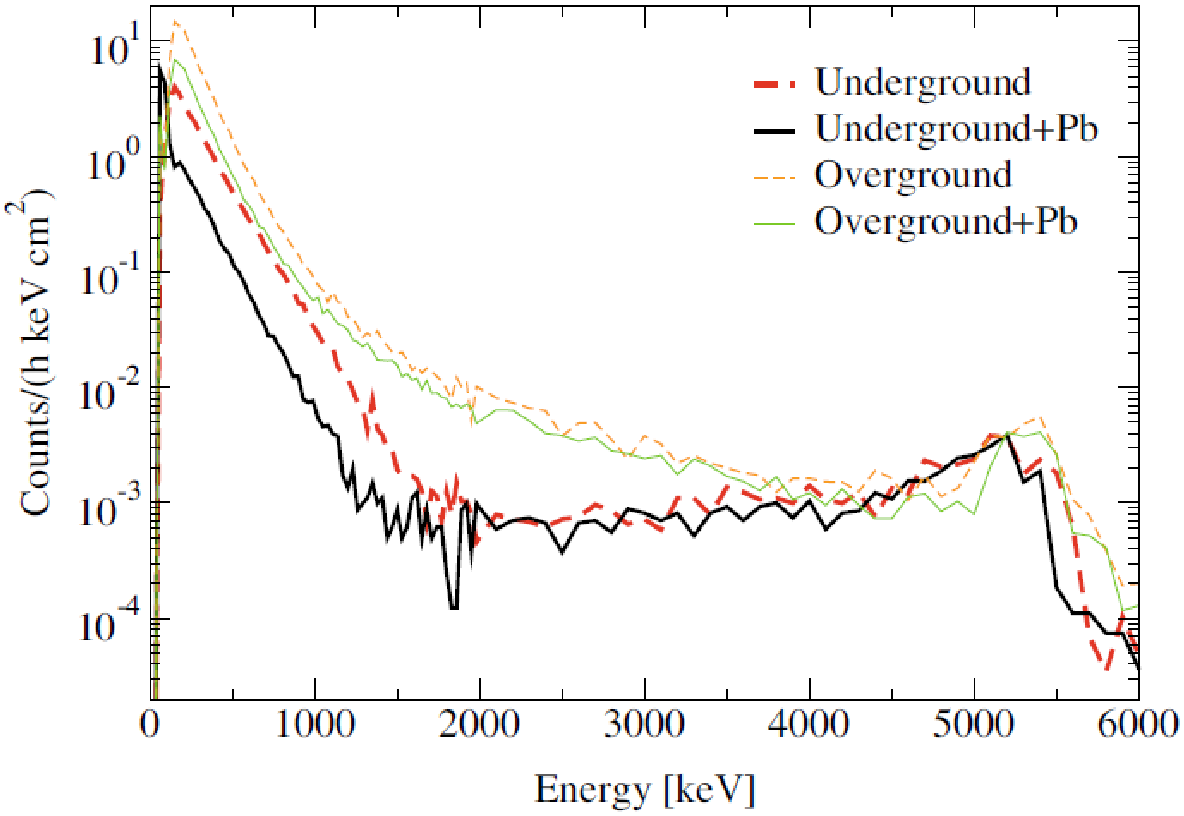
Energy spectra

- ✓ ΔE-E matrix obtained with a ^{12}C beam on a graphite target



Courtesy of L. Morales

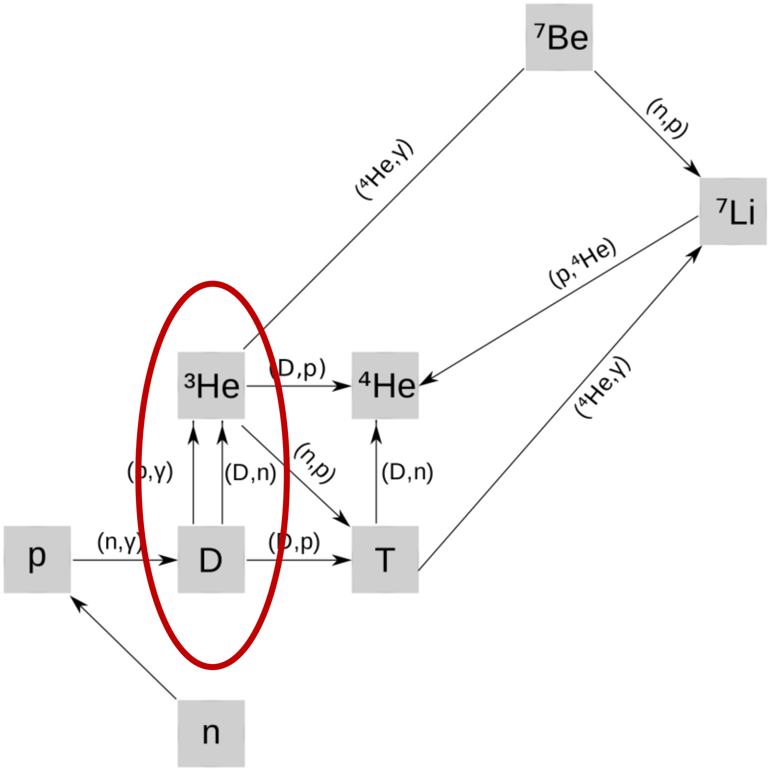
Background spectra



Gamma detectors

$D(p,\gamma)^3He$: the scientific case

- ✓ It occurs during Big Bang Nucleosynthesis



- ✓ A crucial reaction for the determination of the primordial abundance of deuterium
- ✓ Poorly known cross section in the relevant energy range for astrophysics (30-300 keV)

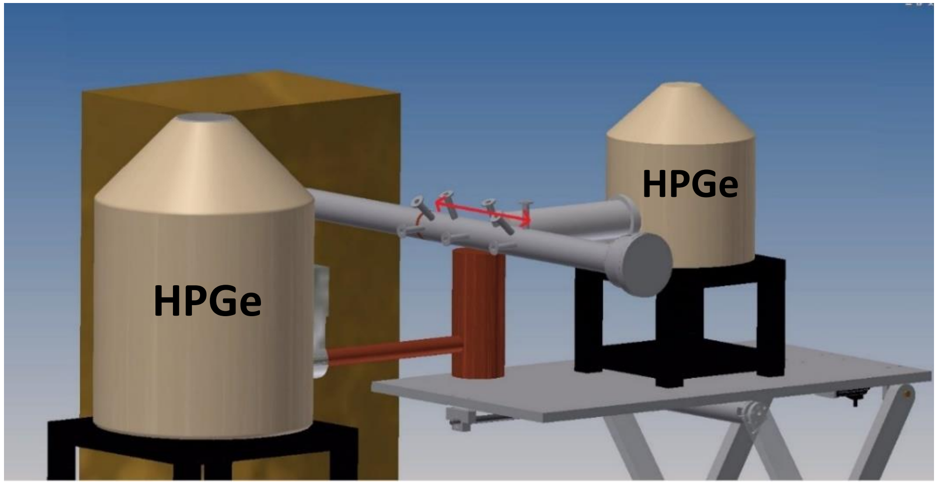
D(p,γ)^{3}He: experimental setup

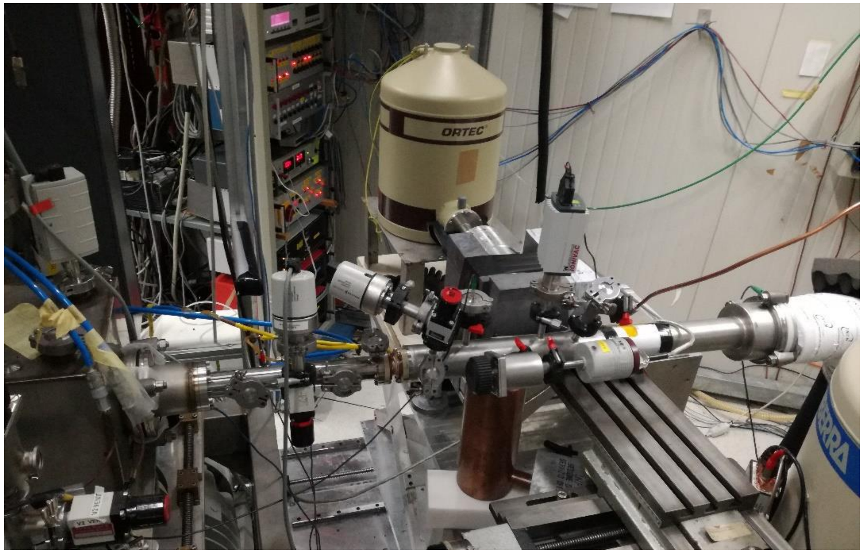
Measurement goal:

- ✓ Cross section measurement with ~3% accuracy
- ✓ E_{cm}= 30-300 keV

Experimental setup:

- ✓ Proton beam
- ✓ D_2 windowless gas target (P=0.3 mbar)
- ✓ HPGe detectors for γ-rays
- ✓ E_γ = 5500 – 5800 keV (Q≈5500 keV)





D(p,γ)³He: determination of the cross section

Number of reactions (gamma rays)

$$\sigma(E) = \frac{N_\gamma(E)}{N_p \int_0^L \rho(z)\,\varepsilon(z, E_\gamma)\,W(z)\,dz}$$

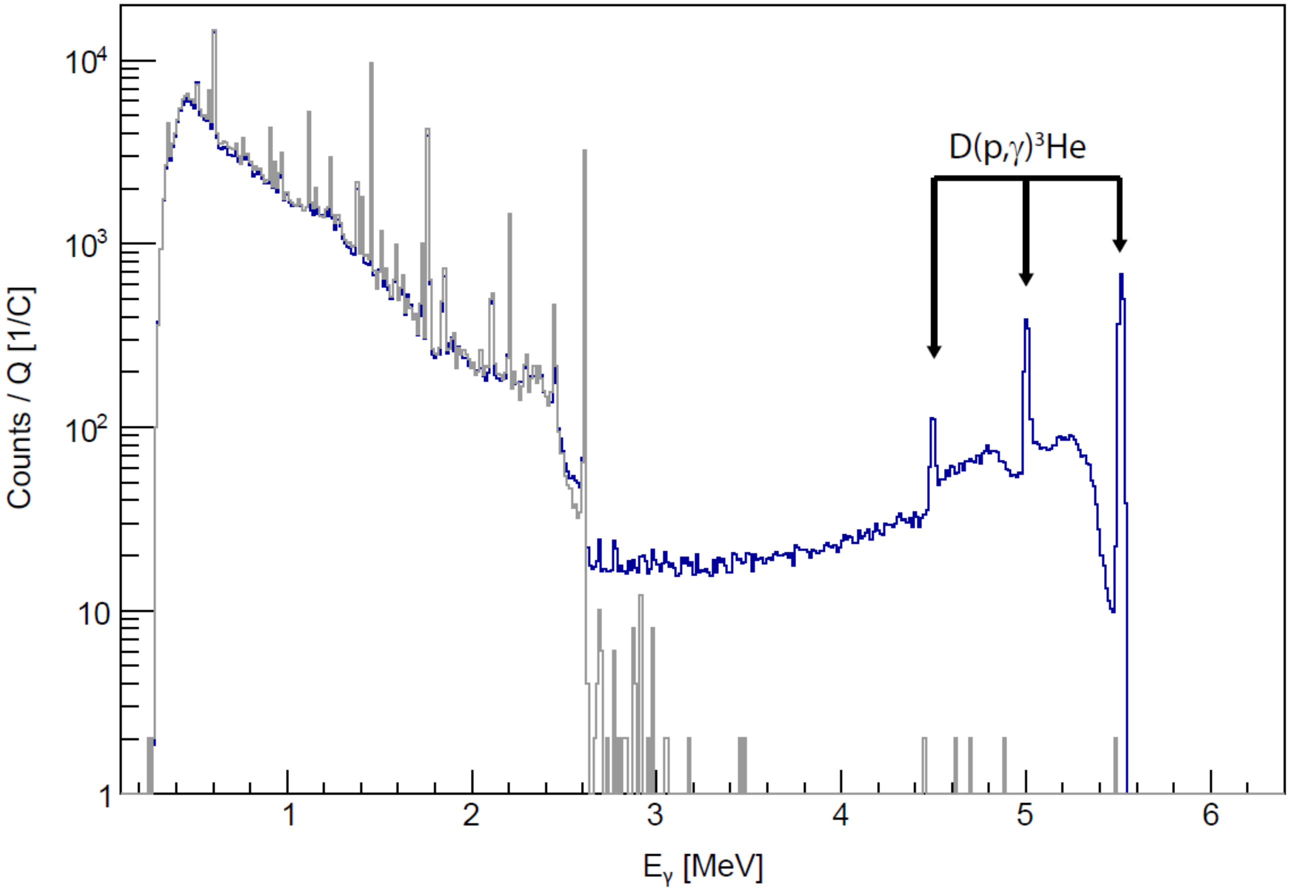
Number of projectiles

Target density

Gamma detection efficiency

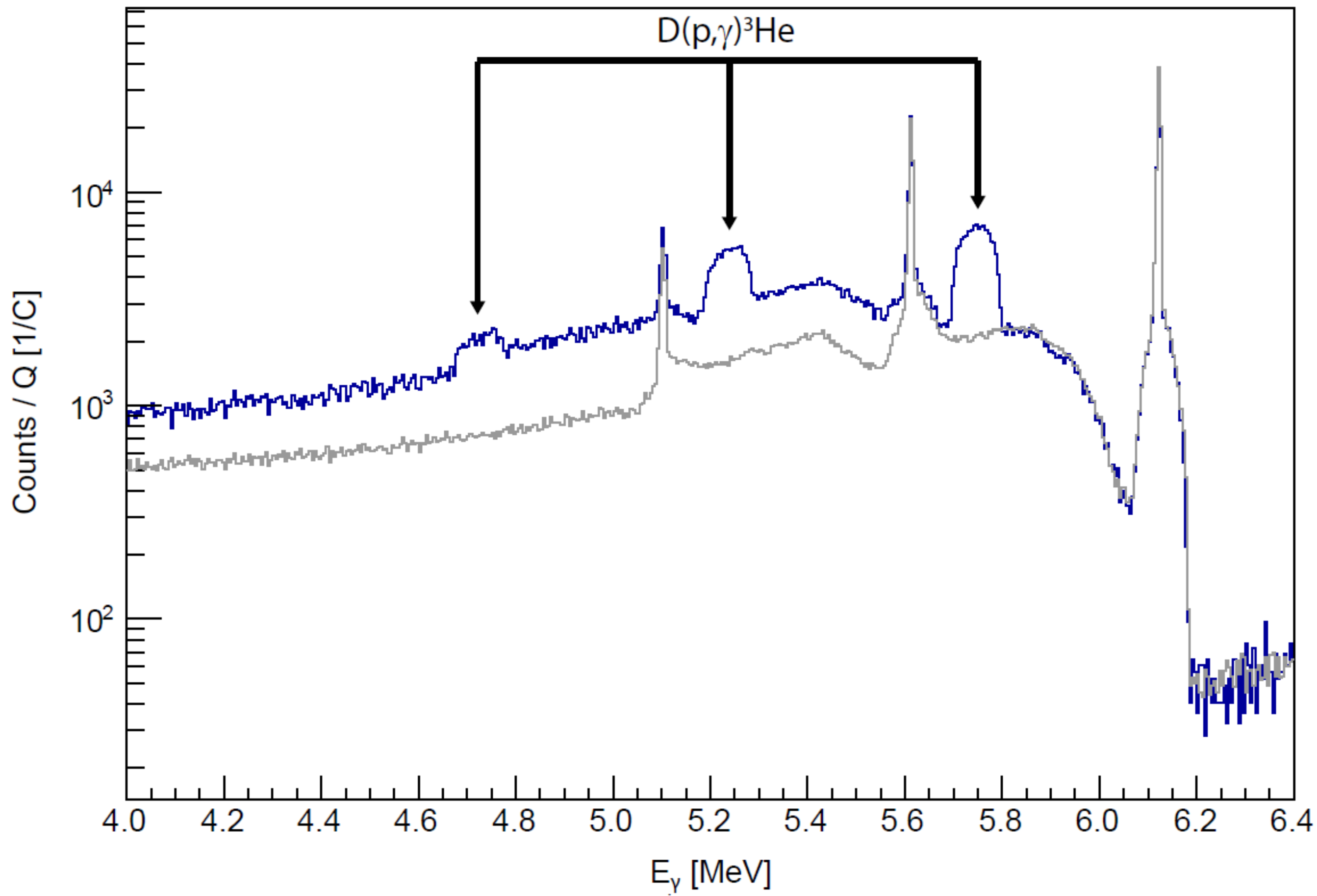
Parameter related to the angular distribution

$D(p,\gamma)^3He$: typical spectrum



- ✓ Spectrum obtained @ E_p = 50 keV with D_2 gas target (P=0.3 mbar)
- ✓ Spectrum obtained @ E_p = 50 keV with ^4He gas target (P=0.4 mbar)

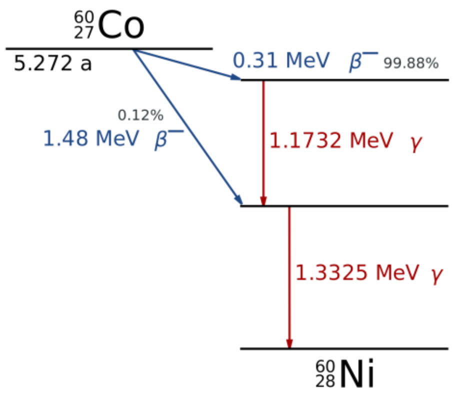
D(p,γ)³He: typical spectrum

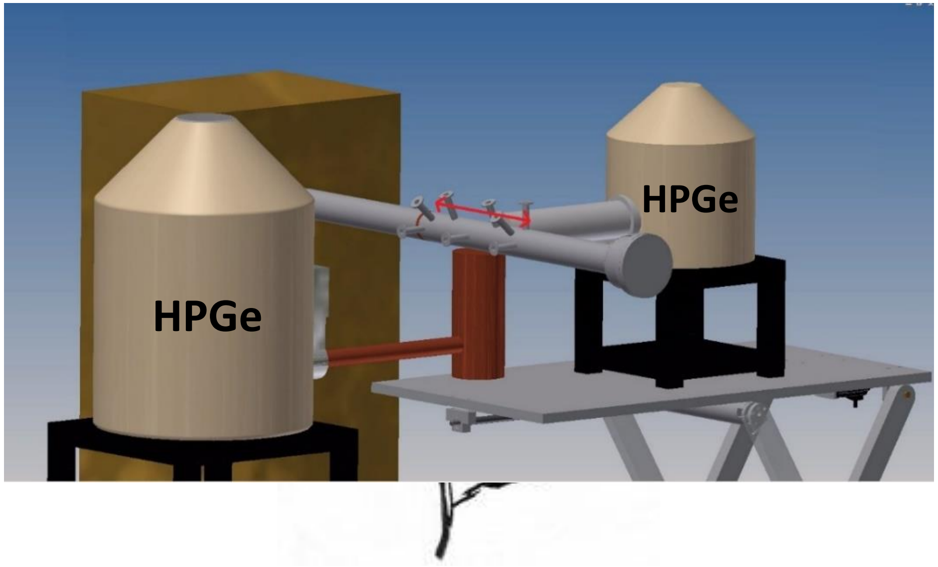


- ✓ Spectrum obtained @ E_p = 395 keV with D_2 gas target (P=0.3 mbar)
- ✓ Spectrum obtained @ E_p = 395 keV with ^4He gas target (P=0.3 mbar)

D(p,γ)^{3}He: Gamma detection efficiency

- ✓ The photons emitted by the reaction have an energy far away from the commonly used radioactive sources (E_γ = 5500 – 5800 keV)
- ✓ Having an extended gas target the efficiency should be measured also as a function of the position z along the beam axis
- ✓ How do we perform this measurement?





$$\varepsilon = \frac{N_{\gamma-\text{detected}}}{N_{\text{decays}}}$$

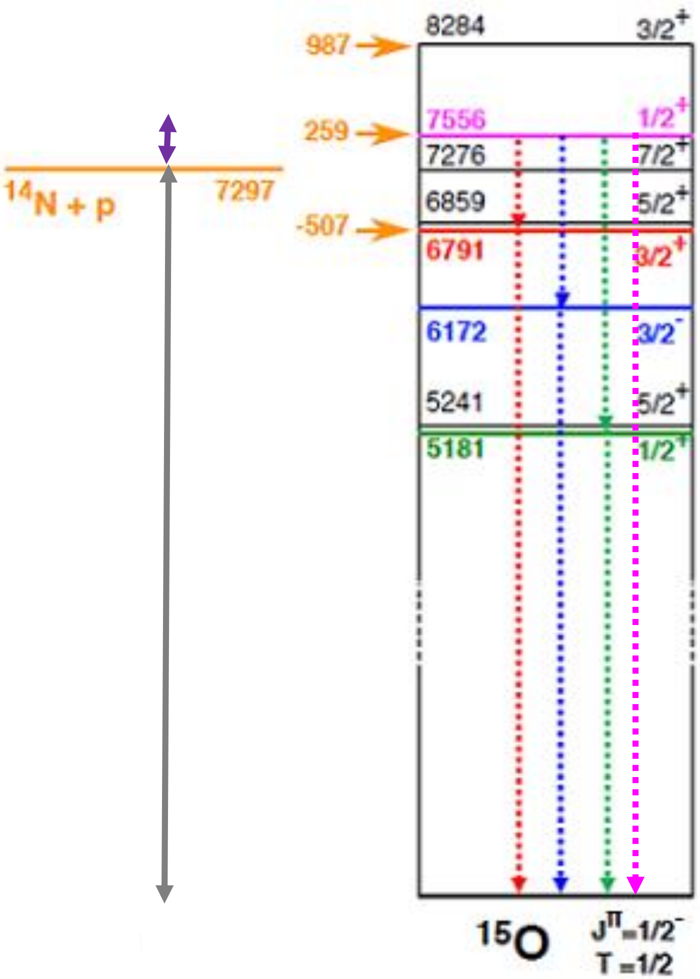
Solution: we use a very well known resonance emitting γ rays in the desired energy range to determine the efficiency

What is a resonance?

- A resonance is excited when:
  - $E_{level} = Q + E_{cm}$

$$^{14}N + p \rightarrow {}^{15}O + \gamma$$

Q = 7297 keV

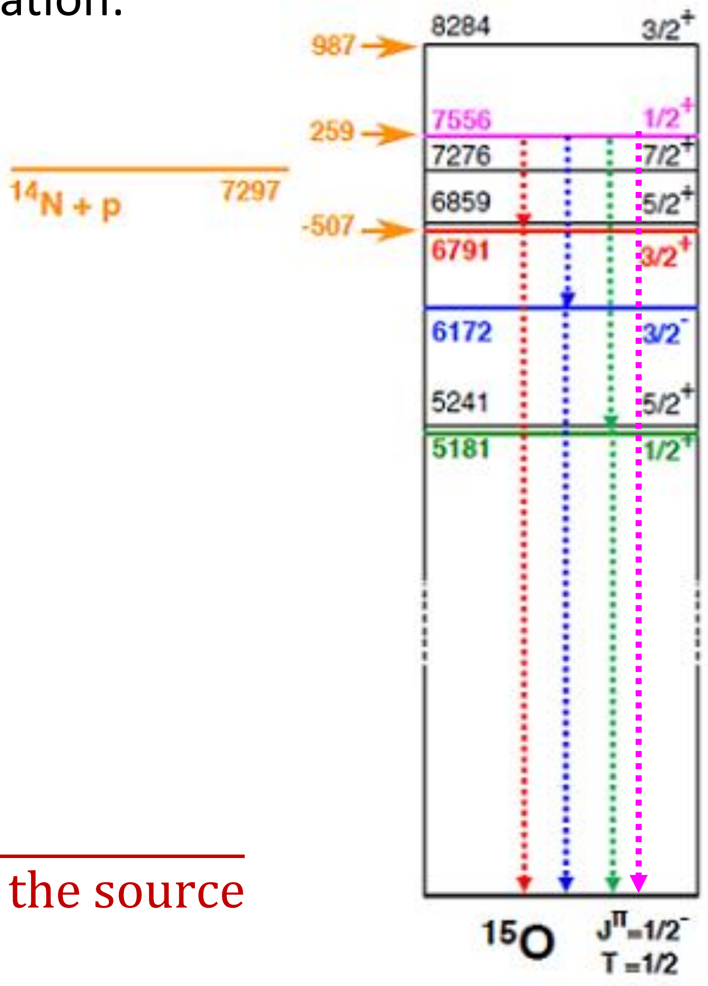


$D(p,\gamma)^3He$: Gamma detection efficiency

$E_\gamma = E_\gamma$ = 5500 – 5800 keV → efficiency calibration:

✓ E_R = 259 keV resonance of $^{14}N(p,\gamma)^{15}O$

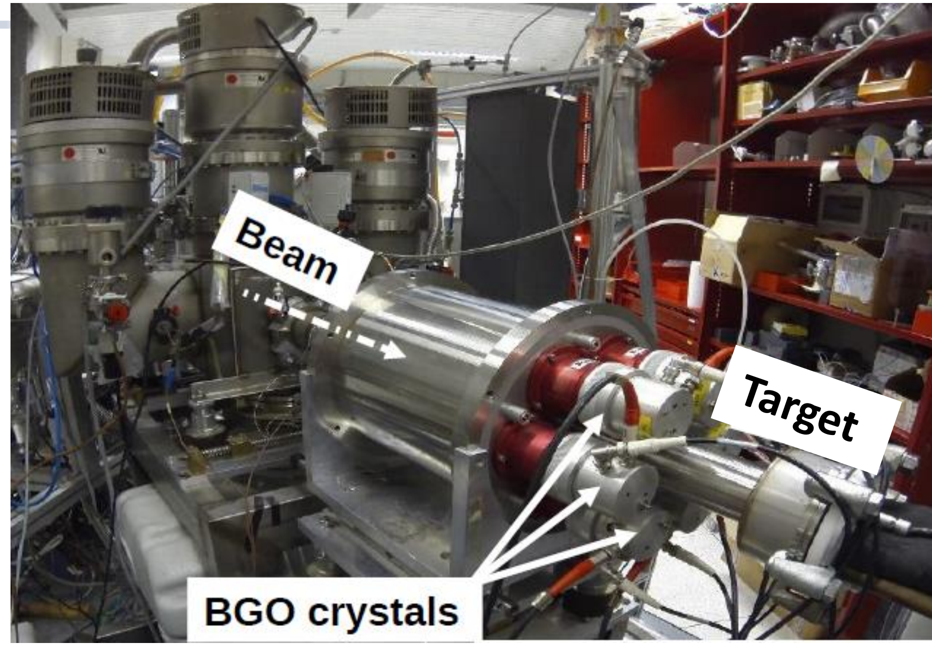
E_γ [keV]	Branching %
6172 + 1384	58.3
6792 + 764	23
5181 + 2375	16.9
7556 + 0	1.5

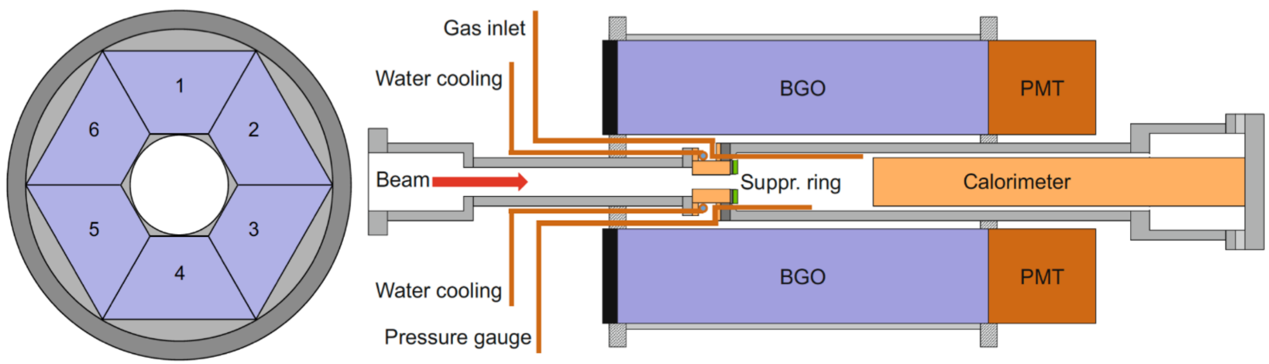


$$\varepsilon = \frac{\text{number of pulses recorded}}{\text{number of radiation quanta emitted by the source}}$$

A segmented BGO detector

- ✓ For very low counting rate reaction a high-efficiency detector is needed
- ✓ 4π-BGO ($Bi_4Ge_3O_{12}$) detector an inorganic scintillator with very large γ-absorption efficiency ($Z(Bi)=83$, $\rho=7.13$ g/cm^3)
- ✓ Array of 6 optically independent segments (prismatic crystals)



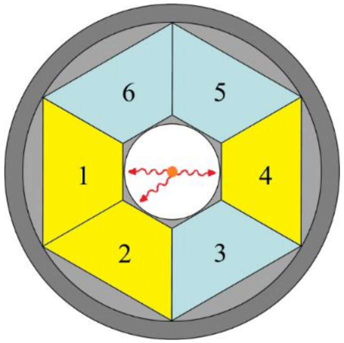


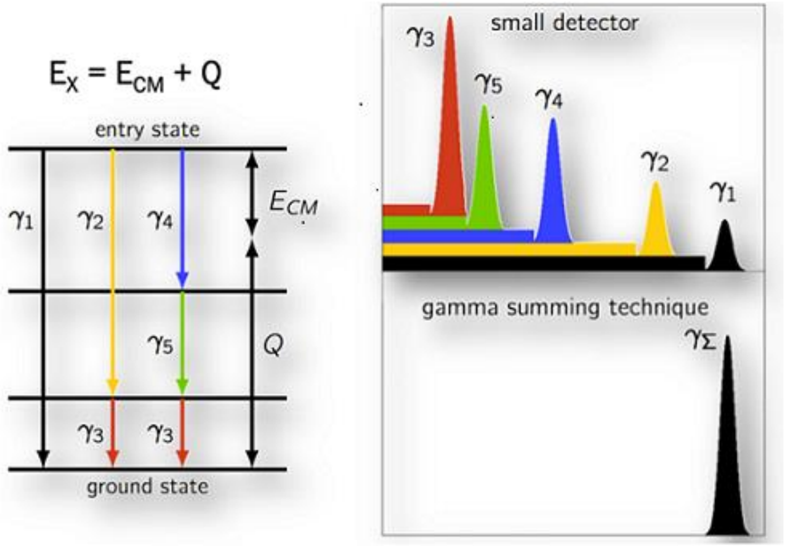
A segmented BGO detector

- ✓ Used as γ-ray calorimeter to derive the total cross section: when two gammas are detected in coincidence, their energy is summed

- ✓ A peak is formed in the γ-ray spectrum at an energy corresponding to the total excitation energy:

$$E_\gamma = Q + E_{cm}$$





Neutron detectors

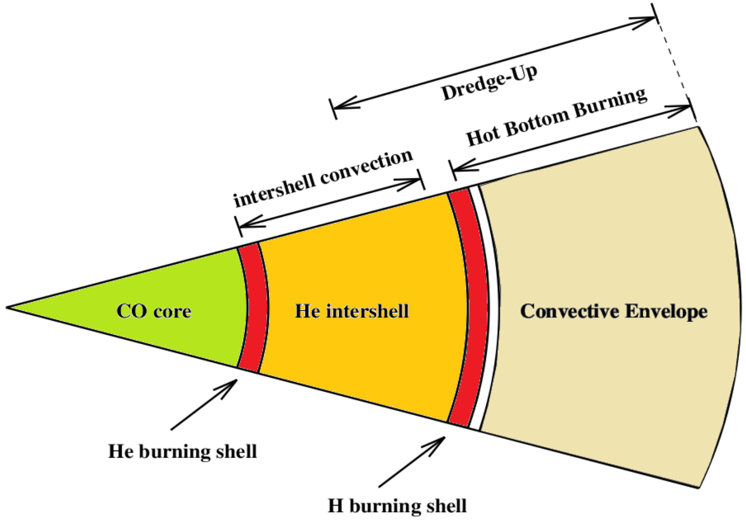
s process nucleosynthesis

Main s-process 90≲A<210

TP-AGB stars 1-3 $M_{\odot}$

shell H-burning
$T_9 \sim 0.1$ K
10^7-10^8 cm^{-3}
$^{13}C(\alpha,n)^{16}O$

He-flash
$0.25 \leq T_9 \lesssim 0.4$ K
10^{10}-10^{11} cm^{-3}
$^{22}Ne(\alpha,n)^{25}Mg$



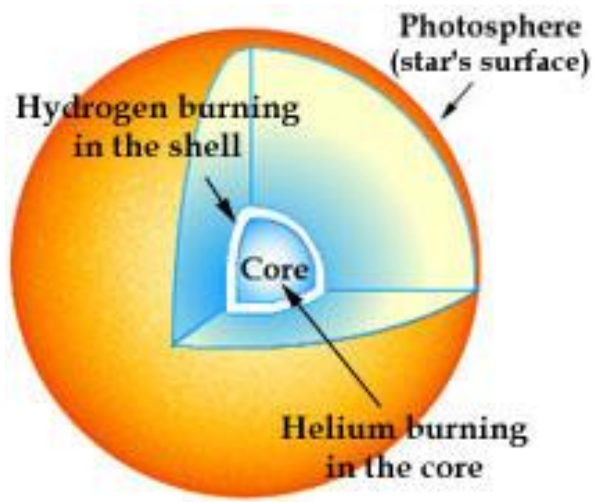
Weak s-process A≲90

massive stars > 8 $M_{\odot}$

core He-burning
3-3.5·10^8 K ~ 10^9 K
10^6 cm^{-3}

C-burning
10^{11}-10^{12} cm^{-3}

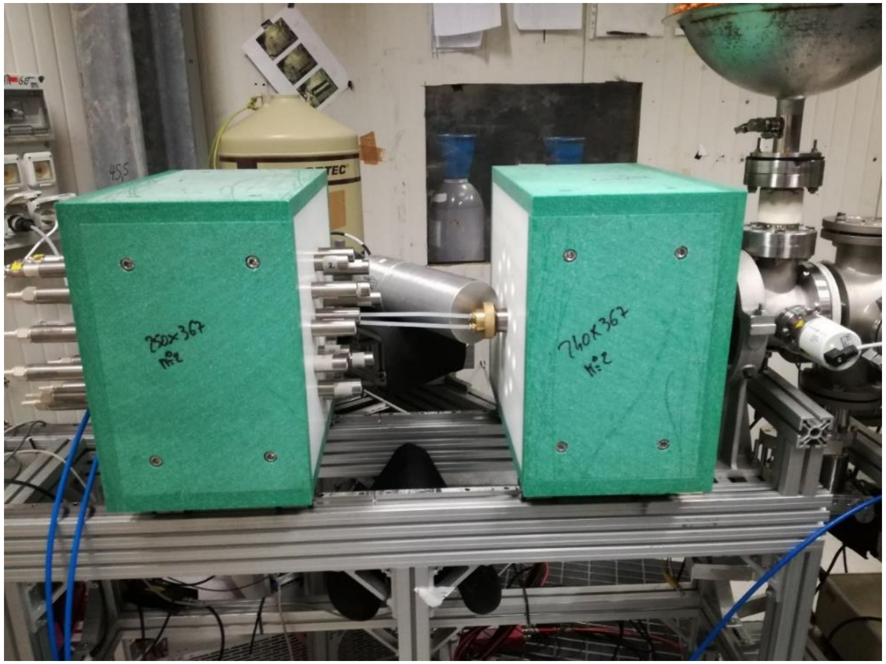
$^{22}Ne(\alpha,n)^{25}Mg$

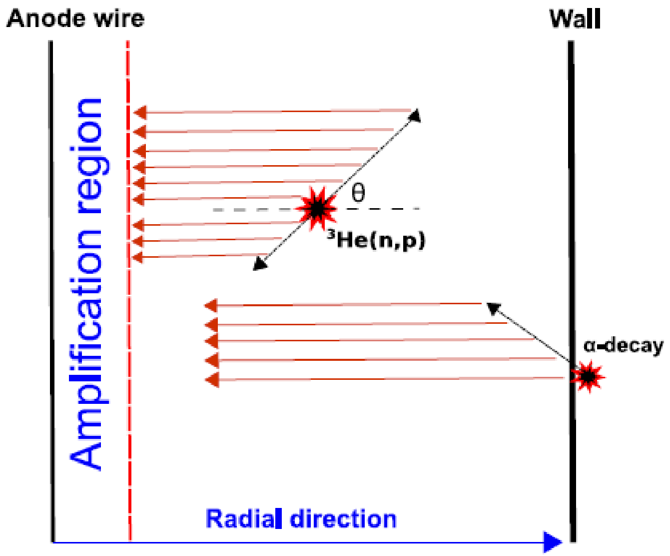


$^{13}C(\alpha,n)^{16}O$: experimental setup

Neutrons produced with an energy of approximately 2.5 MeV

- ✓ Neutrons are slow down by the polyethylene and captured by the ^{3}He tubes
- ✓ $^{3}He + n \rightarrow {}^{3}H + p$ (Q = 764 keV)

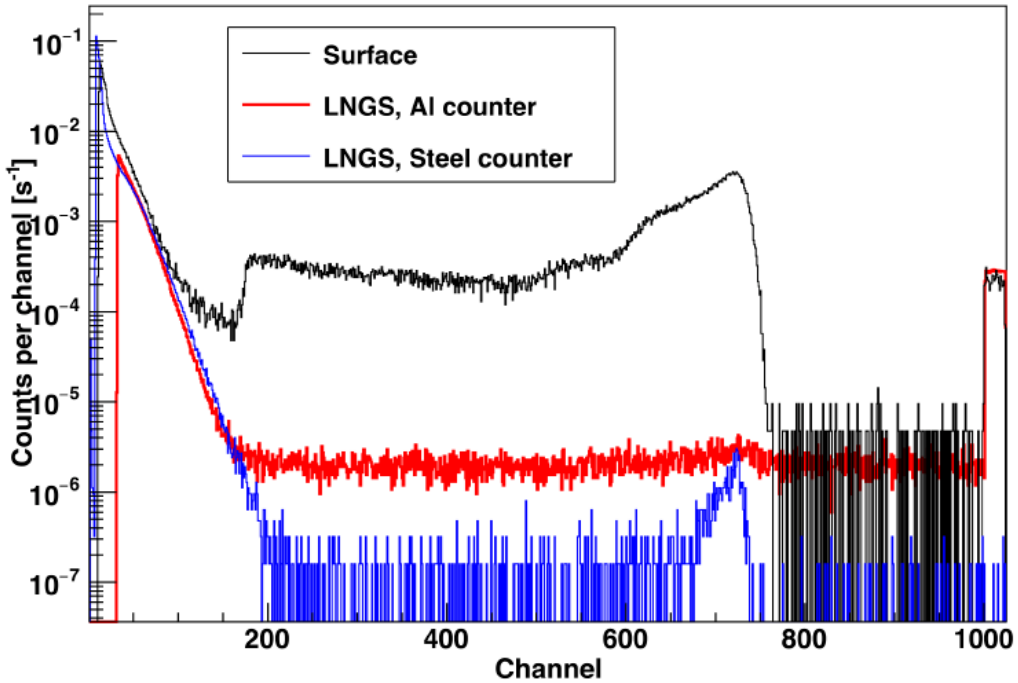




- ✓ 10 atm pressurized ^{3}He counters with a stainless steel case with low intrinsic background
- ✓ 12 ^{3}He steel counters 40 cm length
- ✓ 6 ^{3}He steel counters 25 cm length

^{3}He counter spectra

- ✓ Comparison between spectra acquired underground and at the Earth surface with ^{3}He counters of different materials



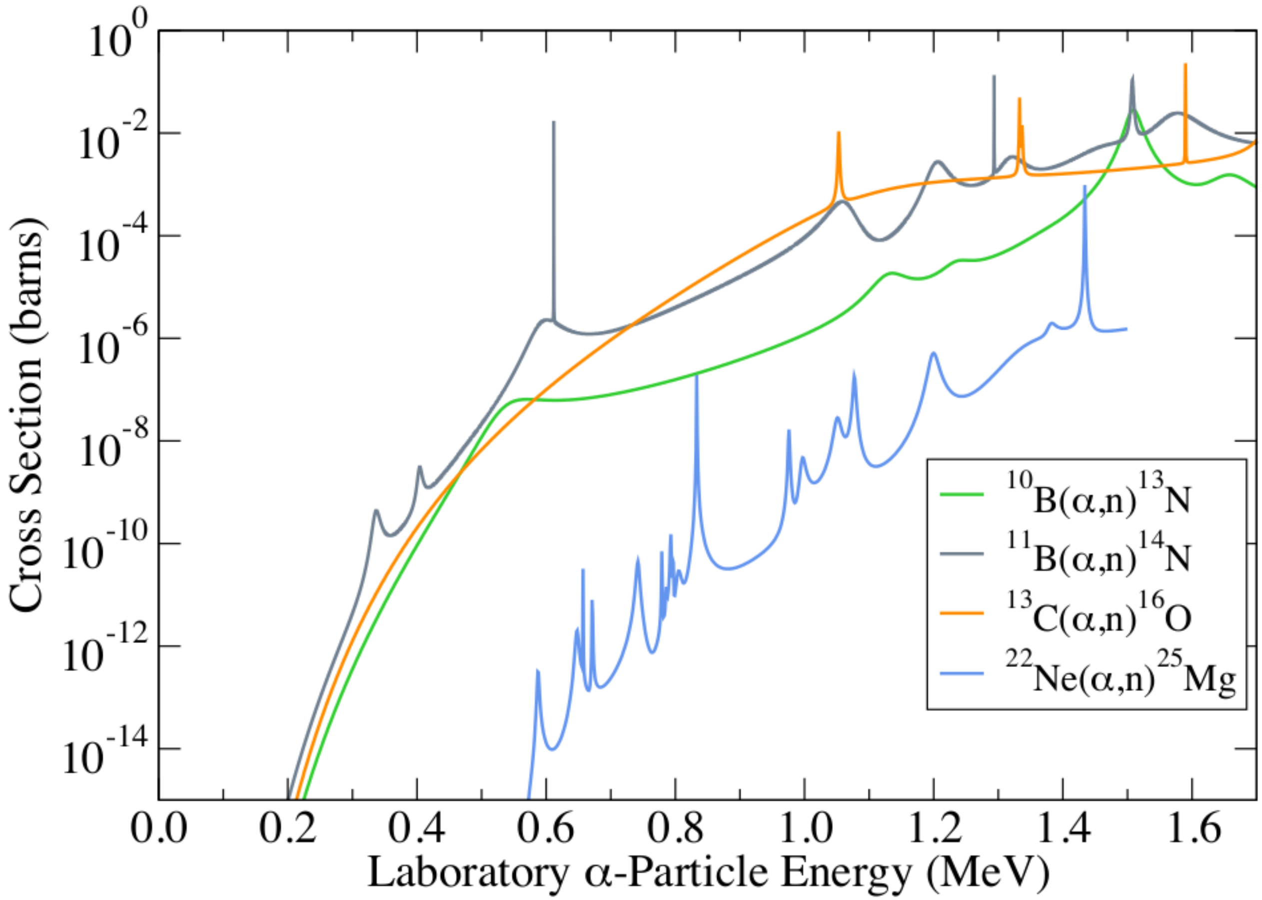
- ✓ Comparison between spectra acquired underground and at the Earth surface with ^{3}He counters of different materials
- ✓ **Environmental background**: neutron flux reduction of a factor 1000 in Underground Laboratory
- ✓ **Intrinsic background:** α particles source of intrinsic background from U and Th impurities in the case of the counters

The $^{22}Ne(\alpha,n)^{25}Mg$ reaction

- ✓ Low energy neutrons are produced: E_n < 700 keV
- ✓ Several beam induced reaction with impurities in the target can compromise the measurement
- ✓ Very low cross section compared with contaminants

Possible contaminants

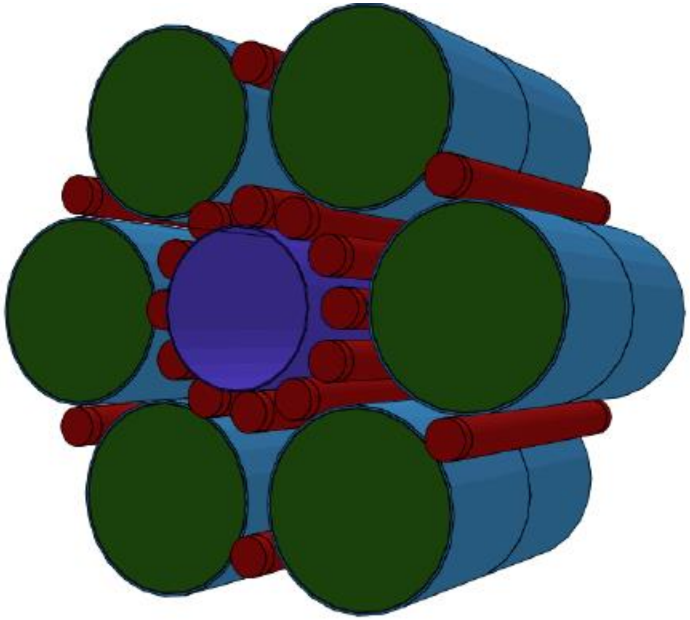
✓ A proper reduction of the beam induced background is crucial



Courtesy of A. Best

SHADES Detector array

- Scintillator-^{3}He Array for Deep-underground Experiments on the S-process
- ERC starting grant. P.I. Andreas Best
- Need to measure very low event rate
- Require some sort of energy sensitivity
- Hybrid detector array: ^{3}He counters and liquid scintillators
- High efficiency



- 12 organic liquid scintillator detectors
- 18 ^{3}He counters
- Anticoincidence between the signal of the liquid scintillators and ^{3}He counters to reject beam induced background

Courtesy of A. Best

Conclusions

- ✓ Nuclear fusion reactions power stars and they are responsible for the creation of the elements which build up our Universe
- ✓ A significant reduction of the cosmic and environmental background is needed to study their cross sections. This can be obtained by going underground and with a proper shielding of the detector
- ✓ In low counting experiments it is crucial to have an high beam intensity, high target density and suitable detectors
- ✓ Depending on the radiation we want to detect we use different kind of detectors and we arrange them to maximize the detection efficiency
- ✓ The energy resolution is also crucial to disentangle different nuclear transitions

Conclusions

Making experiments is not only an hard work….
we have also a lot of fun