Lecture #2: Direct Measurements

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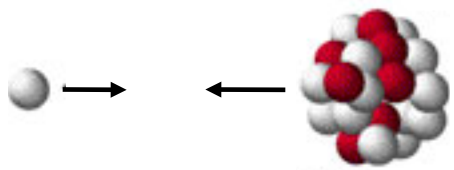
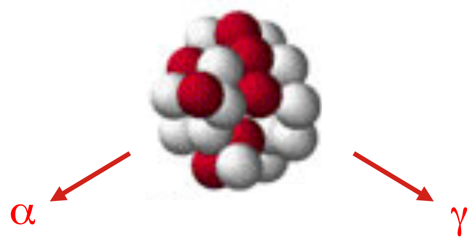
TUNL

Nuclear astrophysics experiments: direct measurements

two nuclei with kinetic energies before reaction:

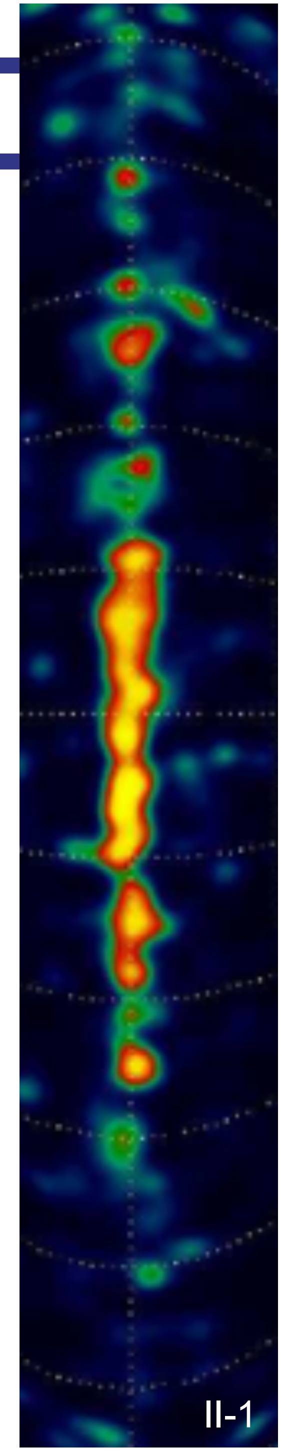


excited product nucleus after reaction:

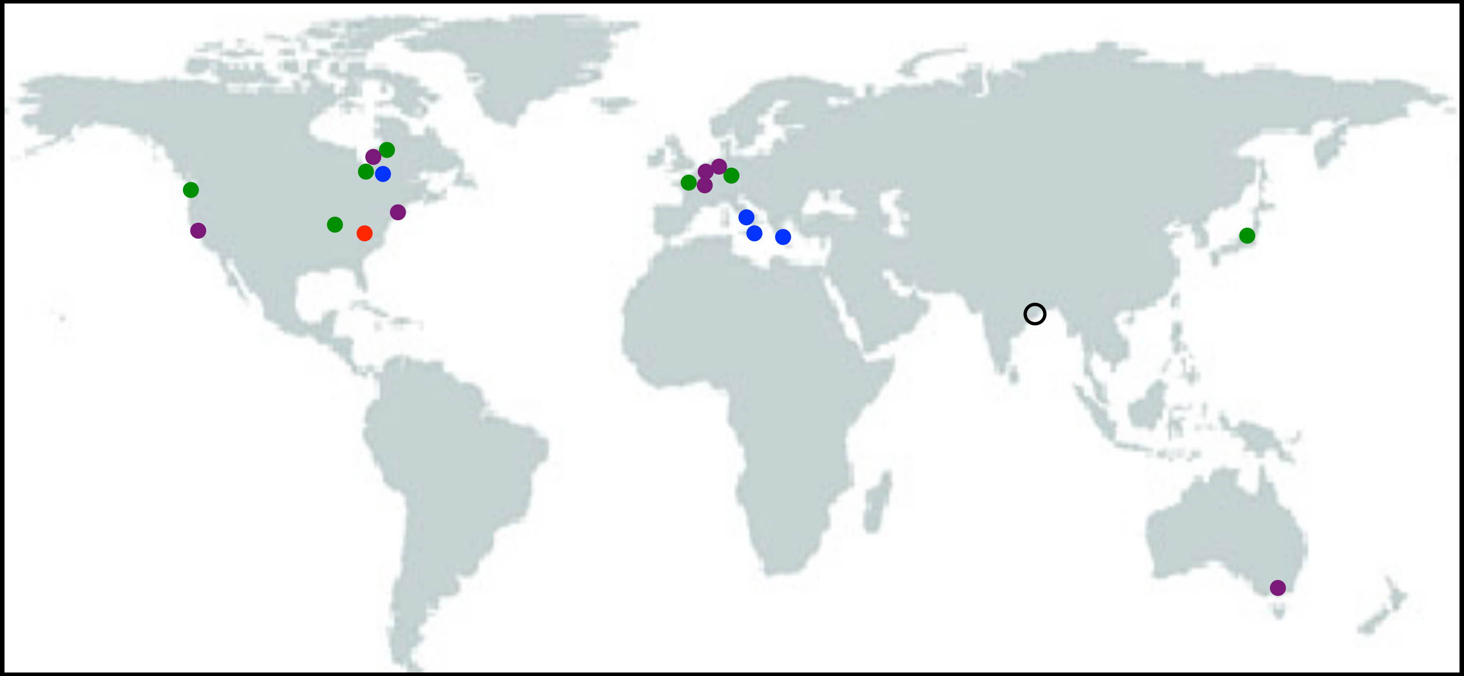


What we need:

- accelerated ion beams
- targets
- detectors



Nuclear astrophysics facilities worldwide



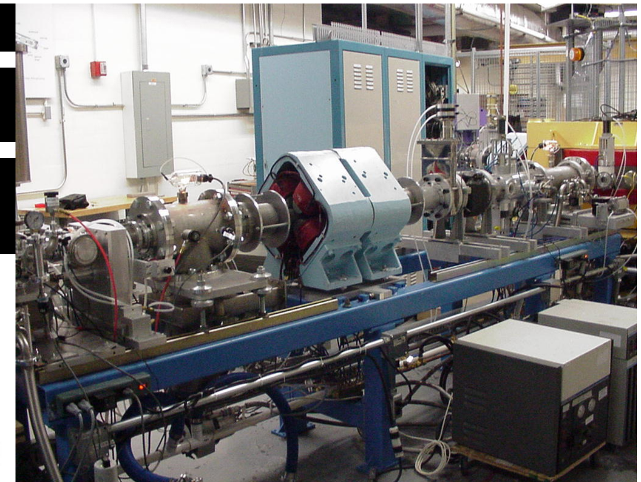
● ● present stable-ion beam facilities

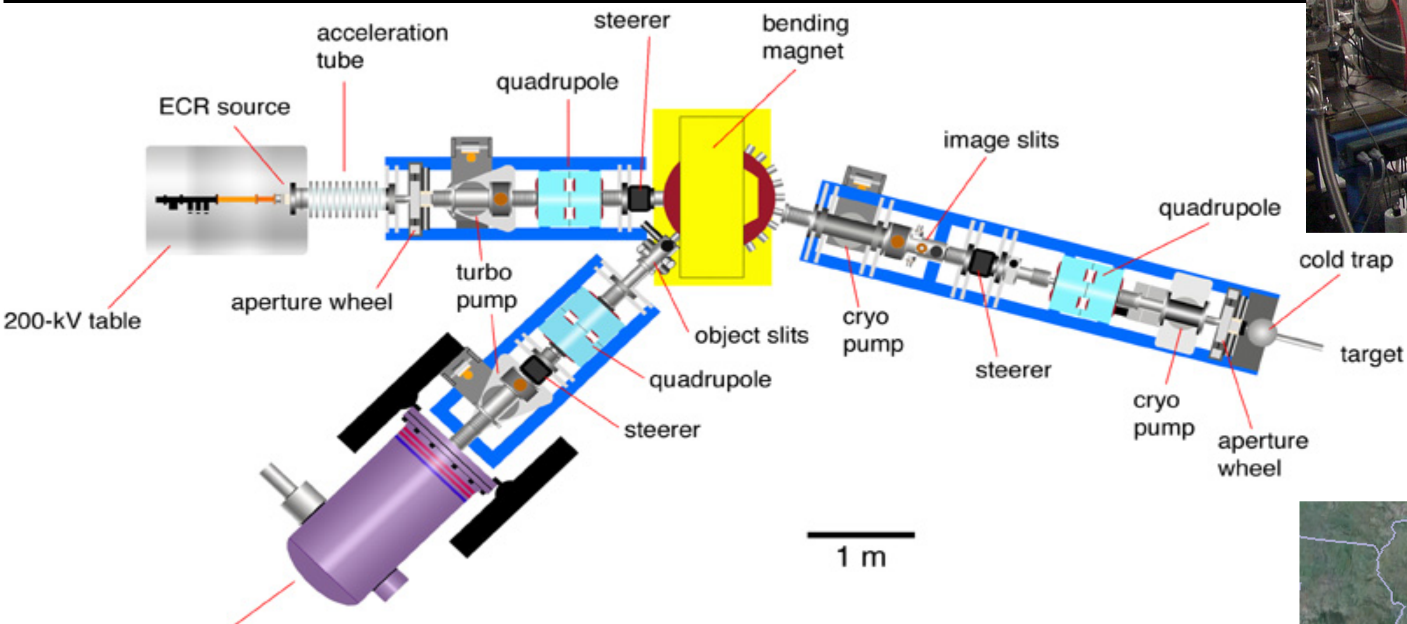
● present radioactive-ion beam facilities

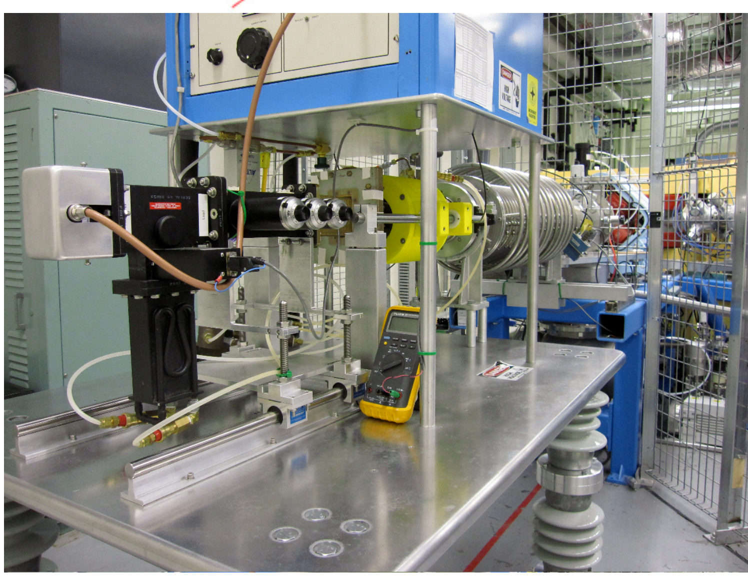
● previous facilities [not operational]

Laboratory for Experimental Nuclear Astrophysics

Cesaratto et al., Nucl. Instr. Meth. A623, 888 (2010)





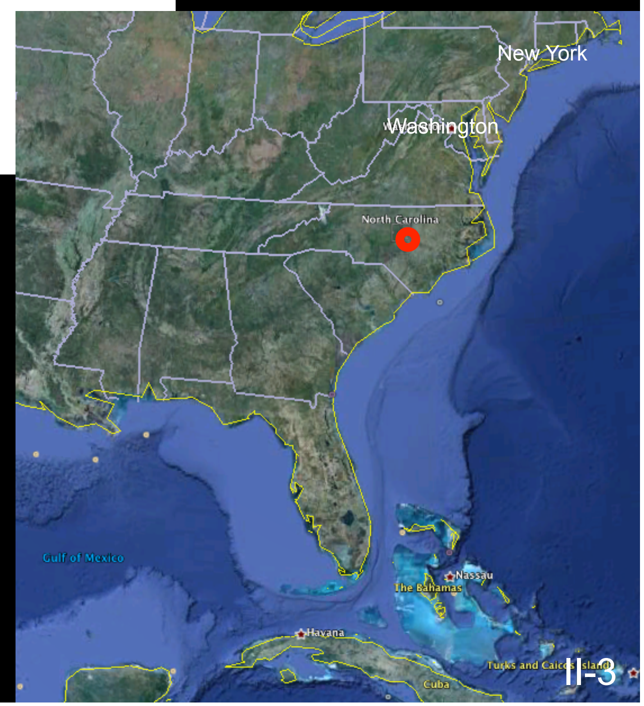


ECR:

- 200 kV max
- 1.5 mA H^+ *average*
- ΔE=1 keV

JN:

- 1 MV max
- 200 μA H^+ *max*
- ΔE=2 keV



Historical perspective on high-current ion accelerators

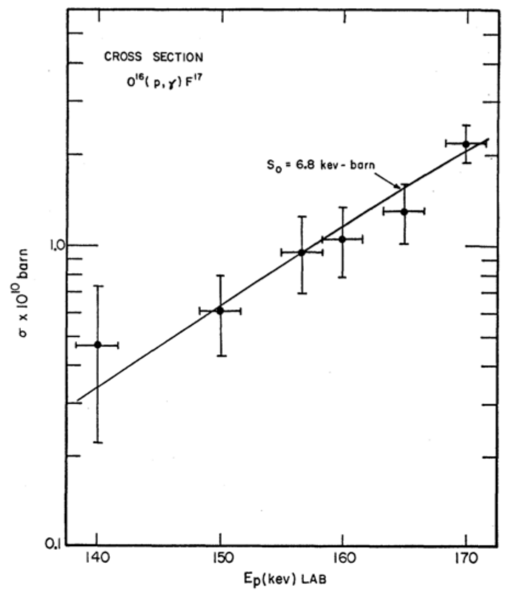
PHYSICAL REVIEW VOLUME 111, NUMBER 6 SEPTEMBER 15, 1958

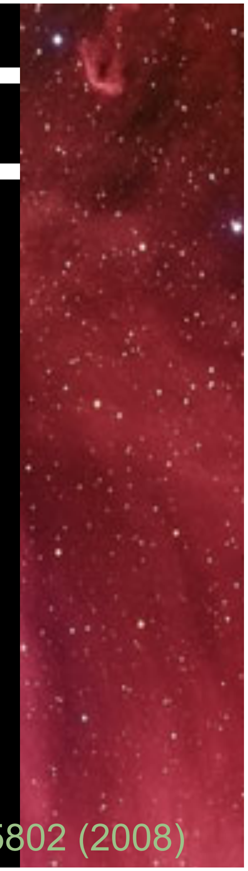
Radiative Capture of Protons in Oxygen at 140 to 170 kev*

R. E. Hester, R. E. Pixley, and W. A. S. Lamb
University of California Radiation Laboratory, Livermore, California

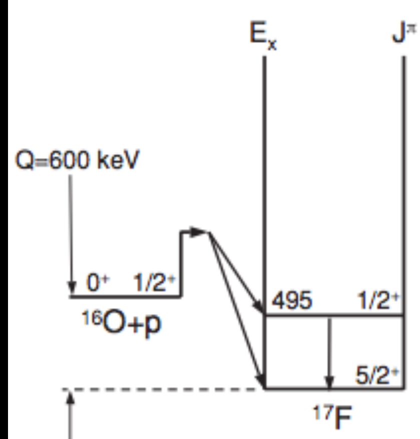
(Received May 26, 1958)

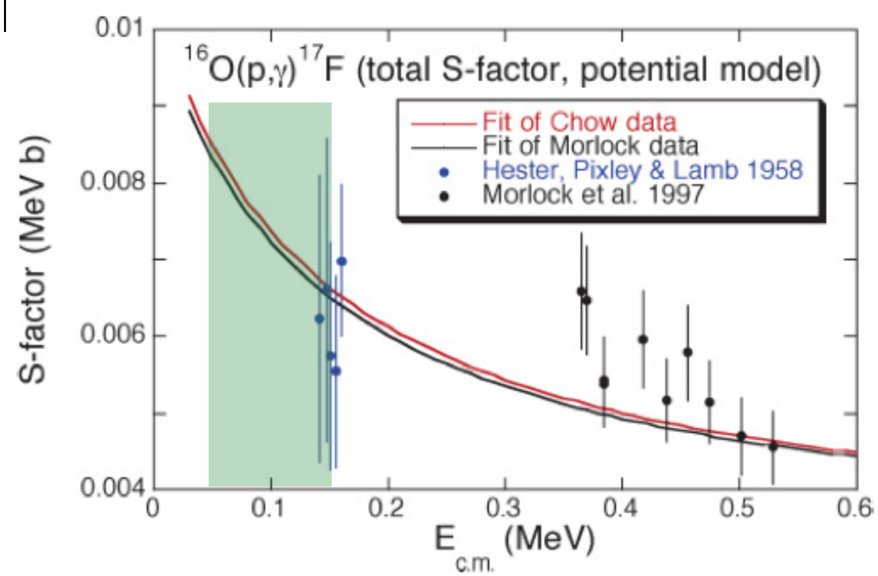
The thick-target yield of the reaction $O^{16}(p,\gamma)F^{17}$ has been measured by bombarding Al_2O_3 targets with protons from 140 to 170 kev using currents from 3 ma to 10 ma and counting the induced positron activity of the F^{17}. The thick-target yield ranges from $(1.9\pm1)\times10^{-17}$ beta/incident proton at 140 kev to $(1.47\pm0.15)\times10^{-16}$ beta/incident proton at 170 kev. The corresponding cross sections are $(4.6\pm2.4)\times10^{-11}$ barn at 140 kev and $(2.34\pm0.3)\times10^{-10}$ barn at 170 kev. The activity was identified by observing the half-life. The cross-section factor S_0 was found to be 6.8±1.4 kev-barns between 140 kev and 170 kev bombarding energy.





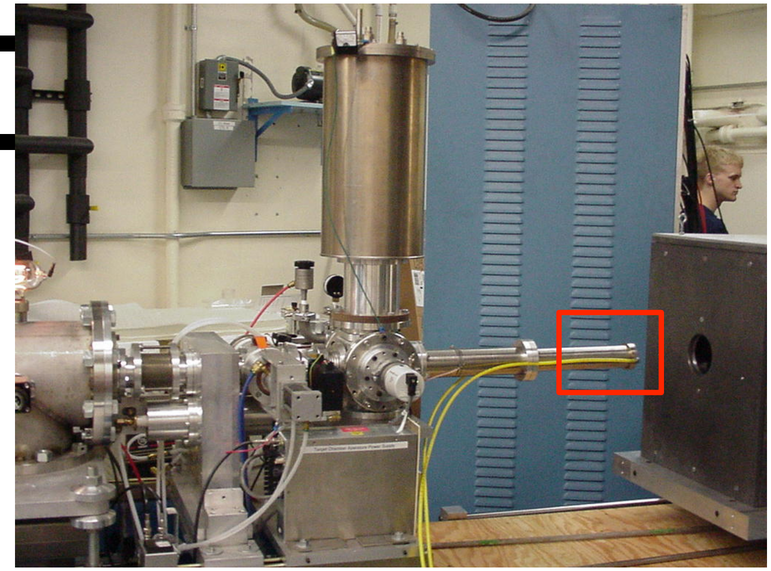
Iliadis et al., Phys. Rev. C 77, 045802 (2008)

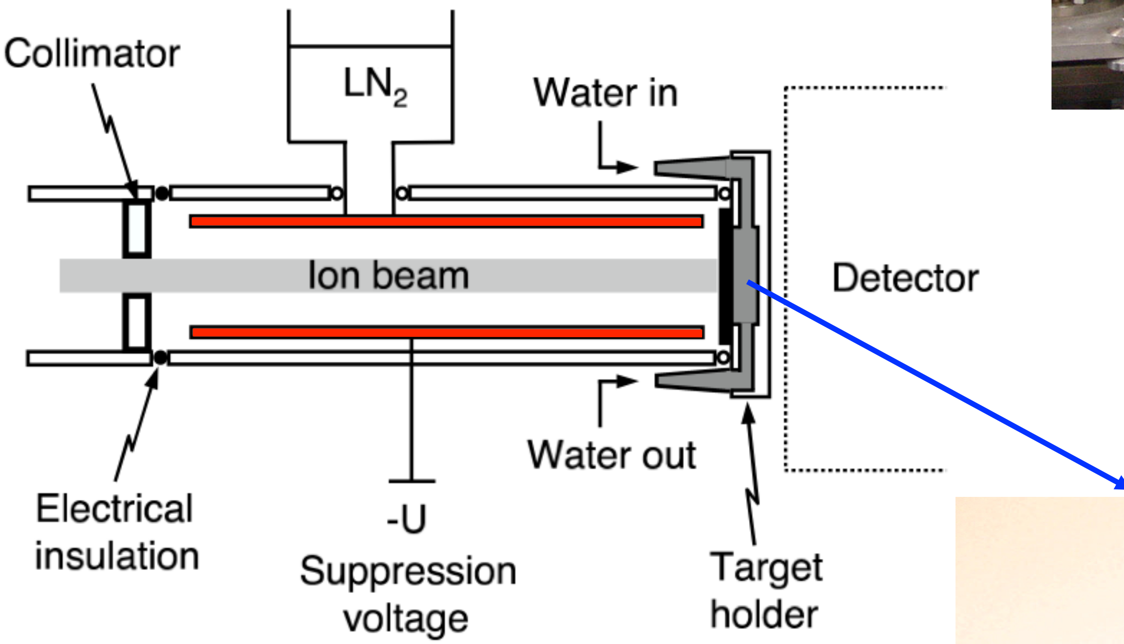


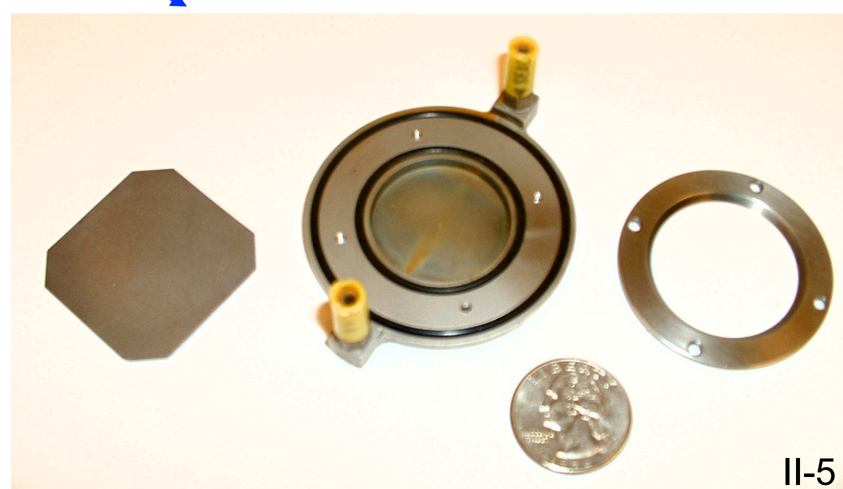


Target chamber design

Location where:
- reactions occur
- incident particle charge is measured







Beam power:
$P = U \cdot I = (0.1\ \text{MV})(1000\ \mu\text{A})$
$= 100\ \text{W}$

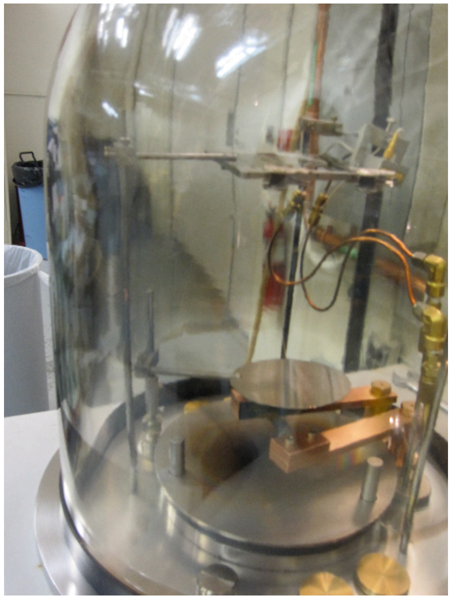
Target material deposited on a "backing"

targets should: (ideally)

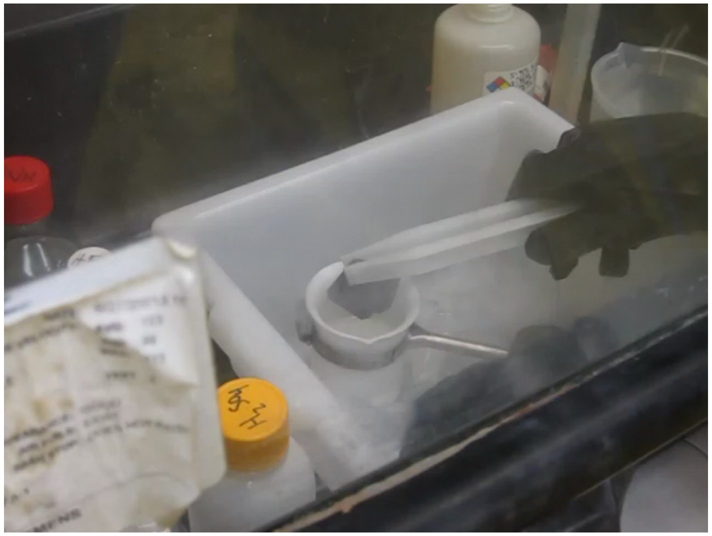
- have a well-known stoichiometry
- not degrade under ion bombardment
- have no contaminants

backings: Ta, Ni, Cu

contaminants: ^{11}B, ^{19}F, ^{13}C

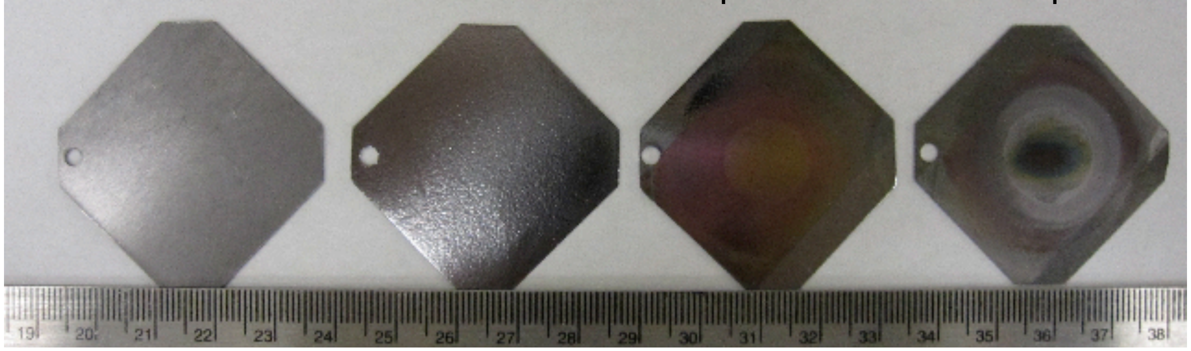


evaporation onto backing



etching of backings using acids

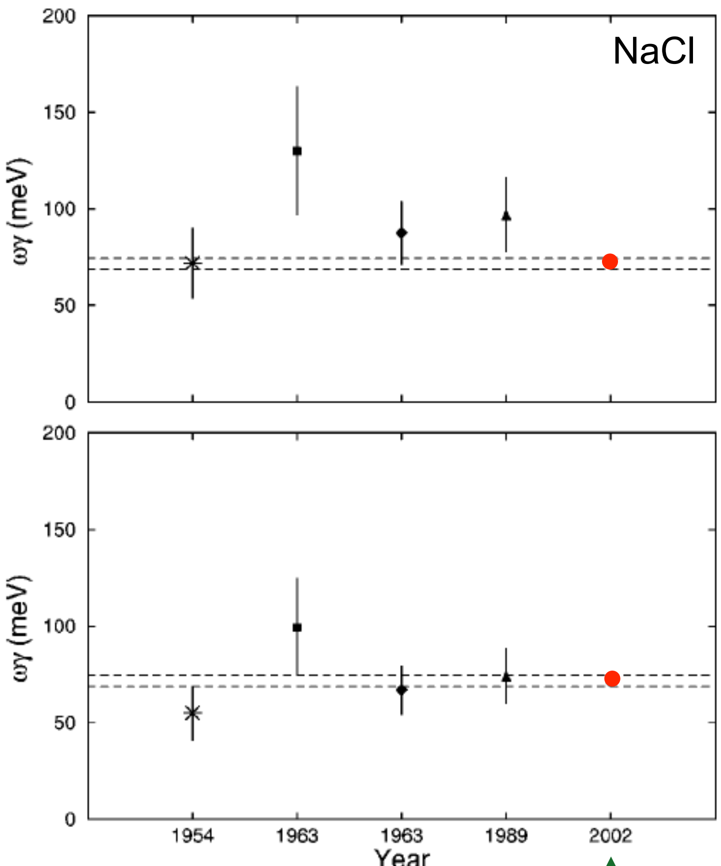
raw Ta metal | etched | evaporated | beam exposure

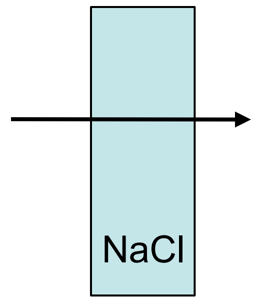


A common mistake…

the ion beam can change the target stoichiometry!

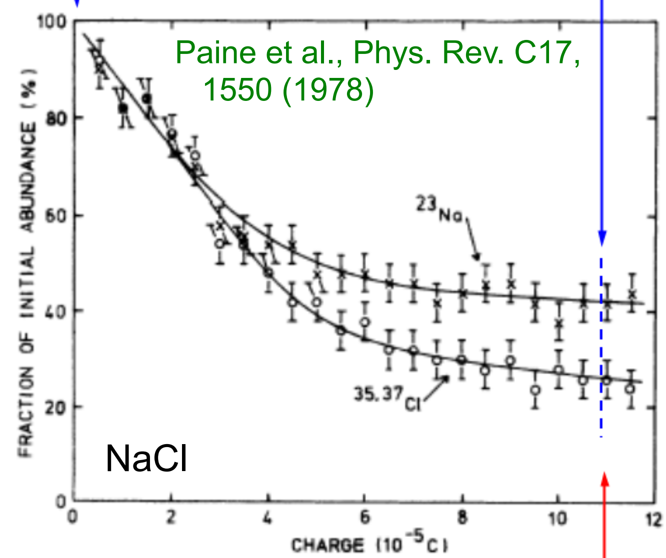
$^{23}Na(p,\alpha)^{20}Ne$: resonance at 338 keV





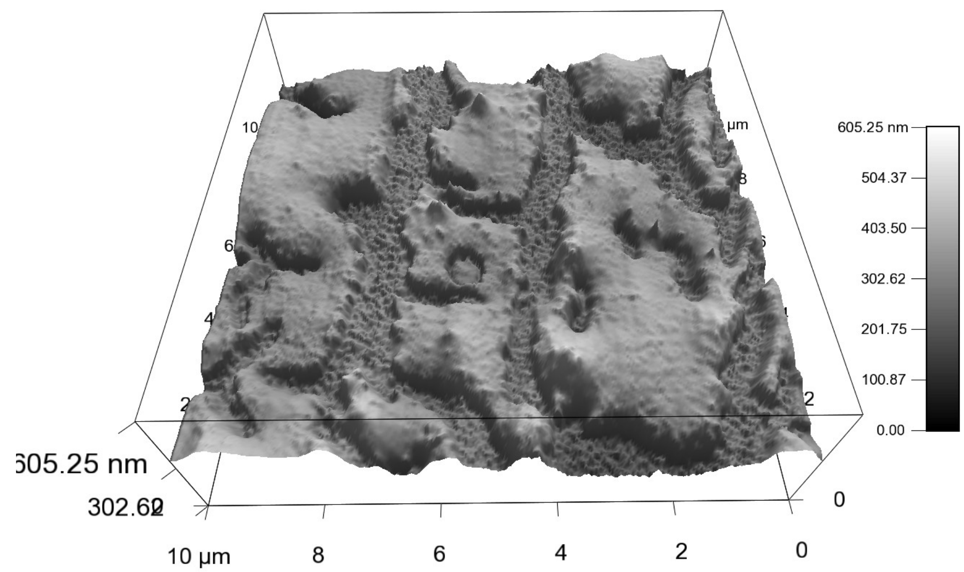
Na:Cl=1:1

Na:Cl=17:10



360 s with 300 nA beam
2.2 s with 50 μA beam

Rowland, Iliadis et al., Phys. Rev. C65, 064609 (2002)



Atomic Force Microscope image of Na_2WO_4 target

Detectors: semiconductors & scintillators

$p + {}^{17}O \rightarrow {}^{18}F + \gamma$

$p + {}^{17}O \rightarrow {}^{14}N + \alpha$

radiation [reaction products] deposits energy in matter

Germanium [semiconductor for γ-rays]

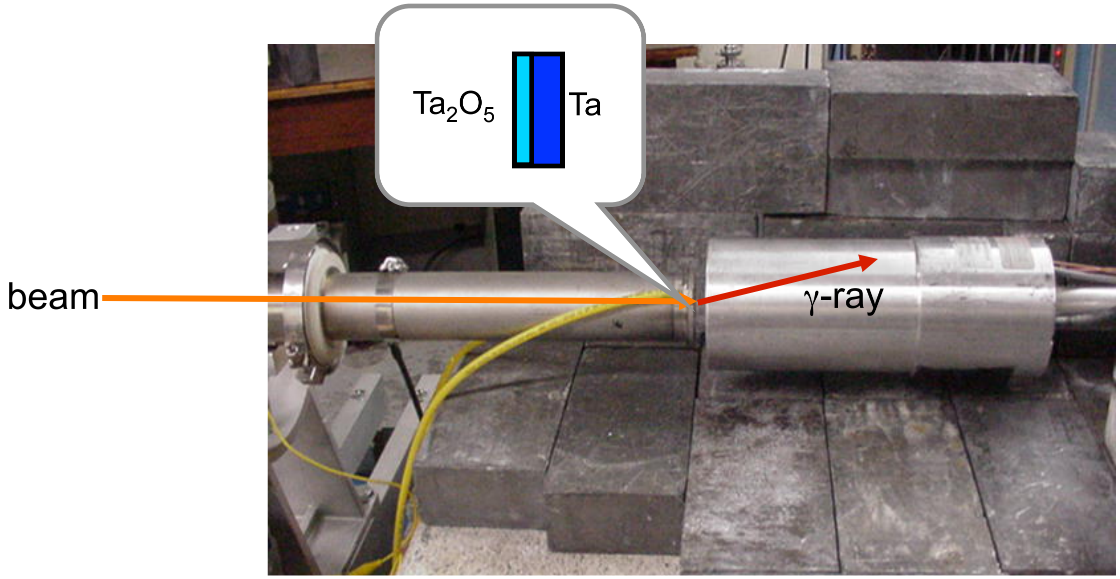
Textbook resources:
• Knoll, Radiation Detection and Measurement (Wiley, 1999)
• Gilmore, Practical γ-Ray Spectrometry (Wiley, 2011)

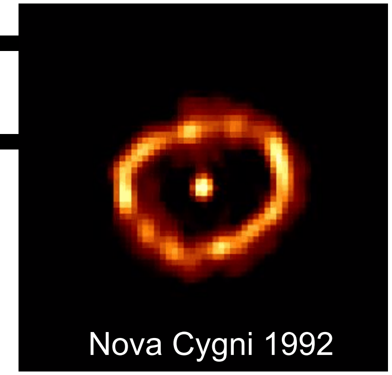
NaI(Tl) [scintillator for γ-rays]

plastic [scintillator for muons]

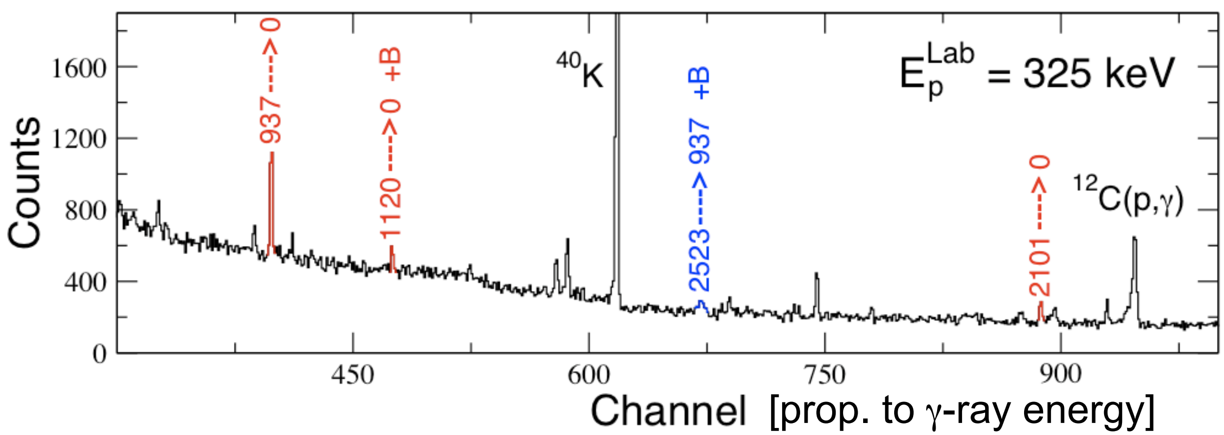
silicon [semiconductor for charged particles]

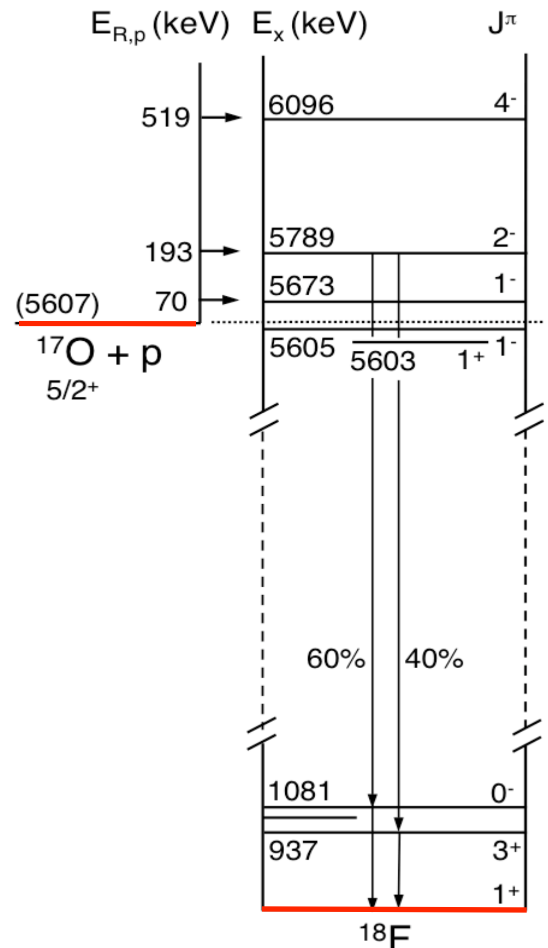
Measured Germanium detector γ-ray spectrum



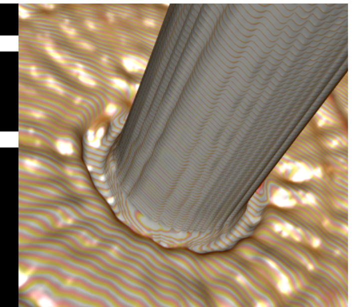


$p + {}^{17}O \rightarrow {}^{18}F + \gamma$



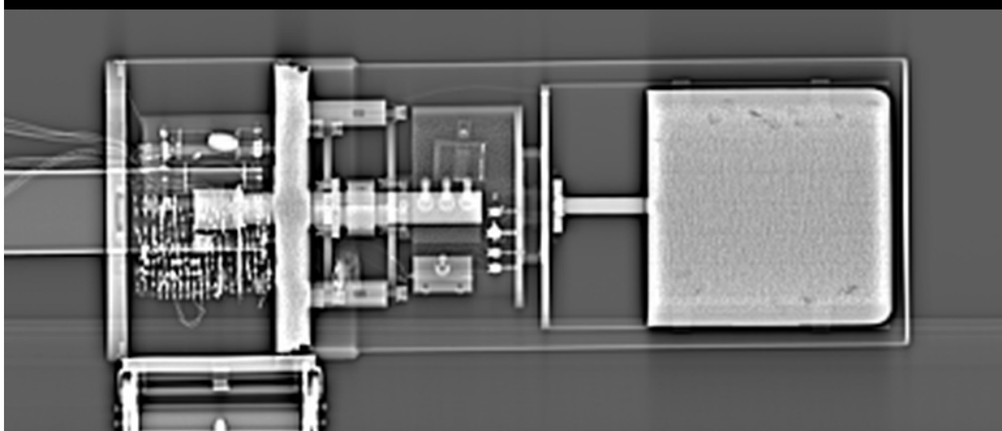


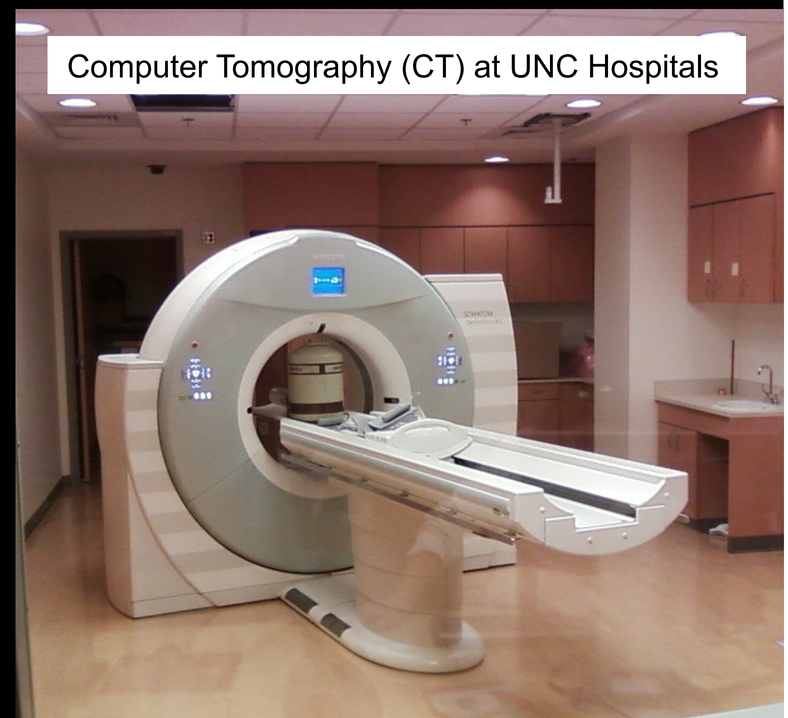
Detector characterization and simulation



Detector characterizations and simulations:

- detection efficiency
- coincidence summing corrections
- background

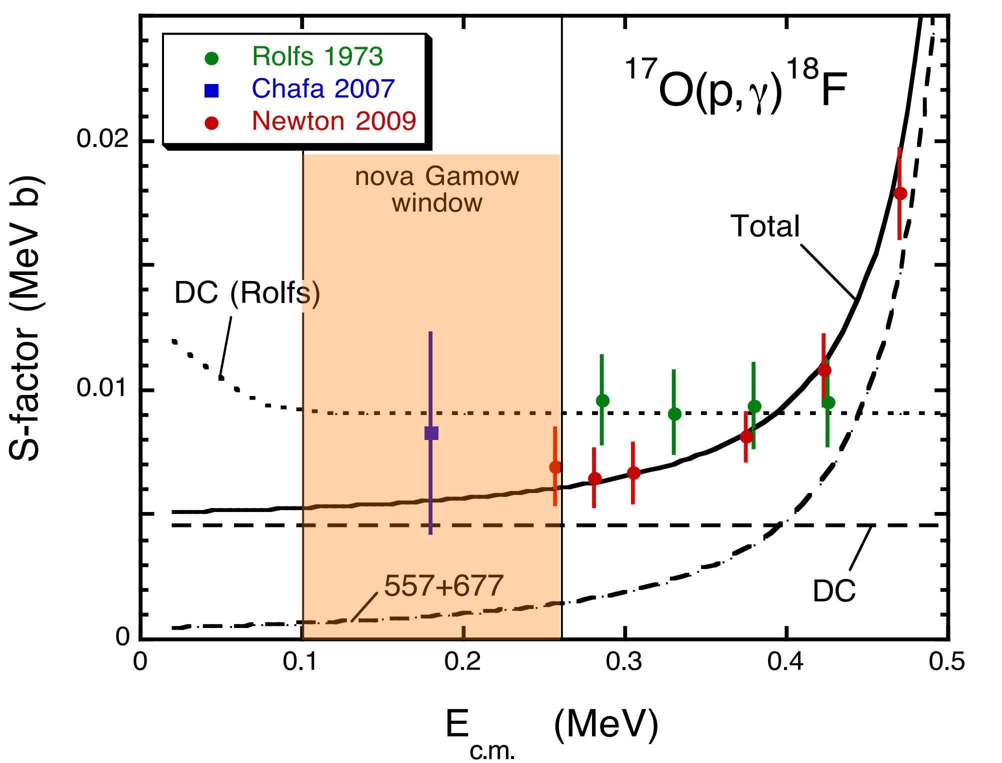




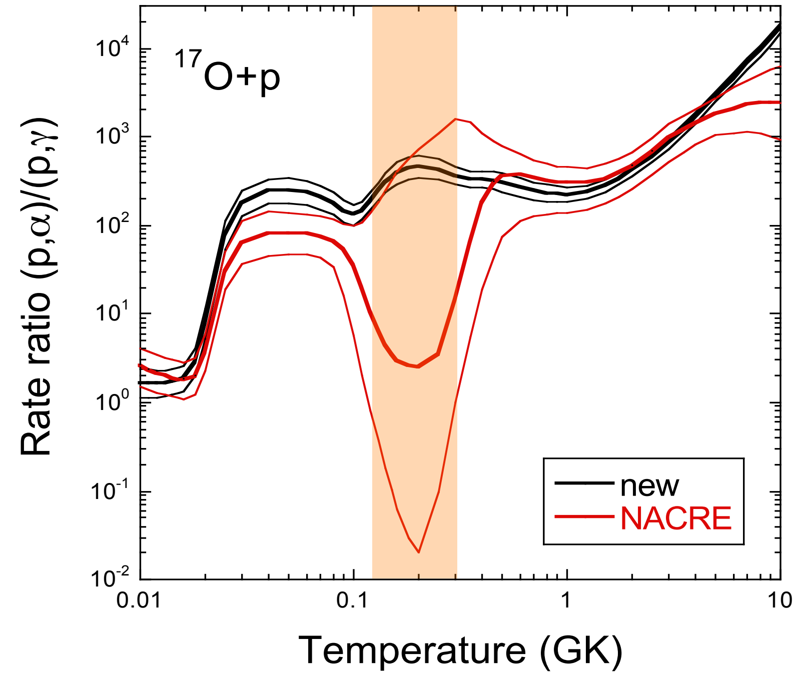
Carson, Iliadis et al., Nucl. Instr. Meth. A 618, 190 (2010)

Directly measured S-factor for $^{17}O(p,\gamma)^{18}F$

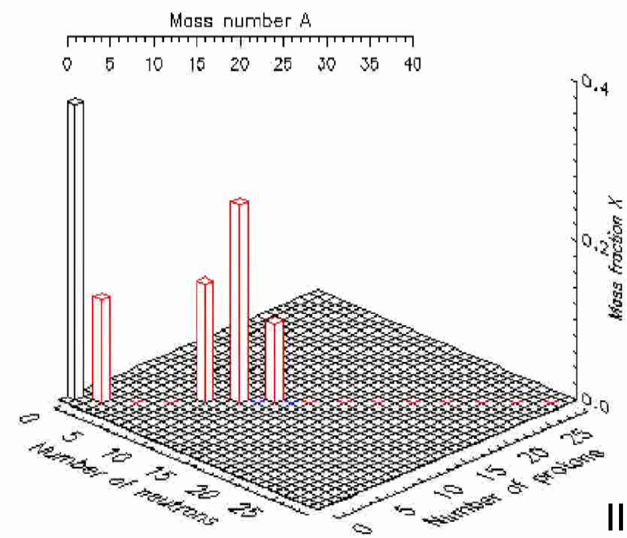
$$\sigma(E) \equiv \frac{1}{E} e^{-2\pi\eta} S(E)$$



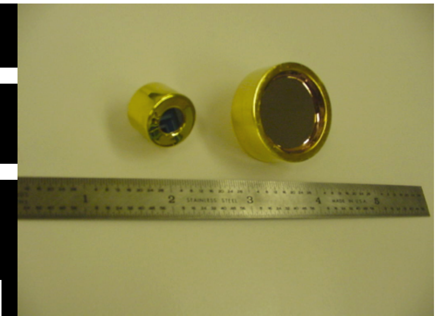
Newton, Iliadis et al., Phys. Rev. C 81, 045801 (2010)

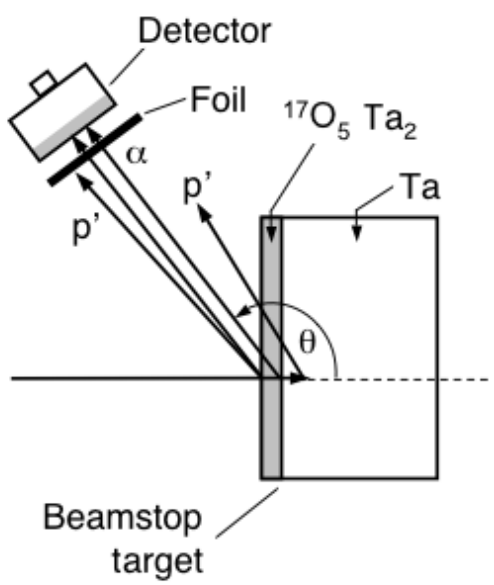


Iliadis et al., Nucl. Phys. A 841, 31 (2010)

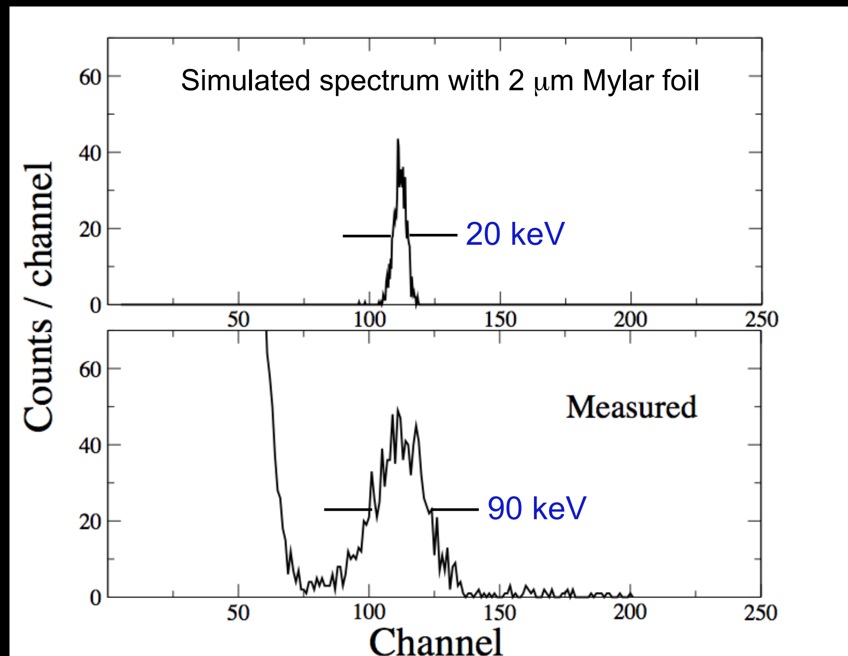


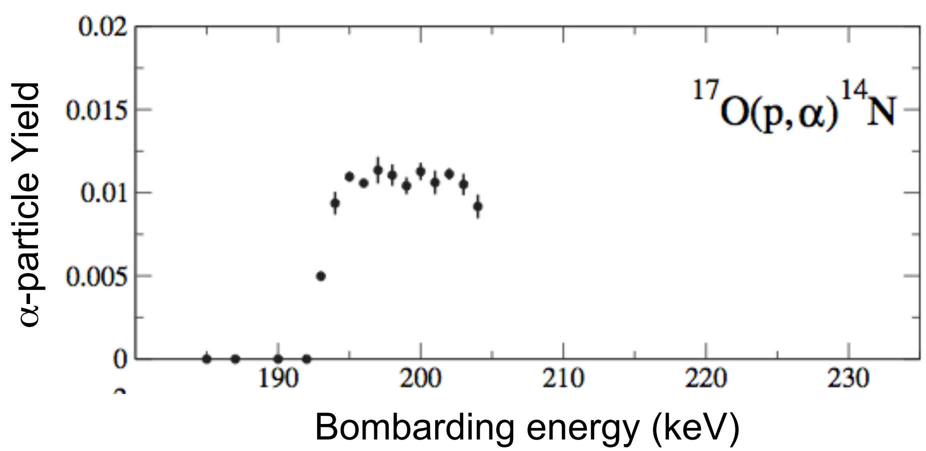
Directly measured resonance in $^{17}O(p,\alpha)^{14}N$ at 190 keV





Newton, Iliadis et al., PR C 75, 055808 (2007)



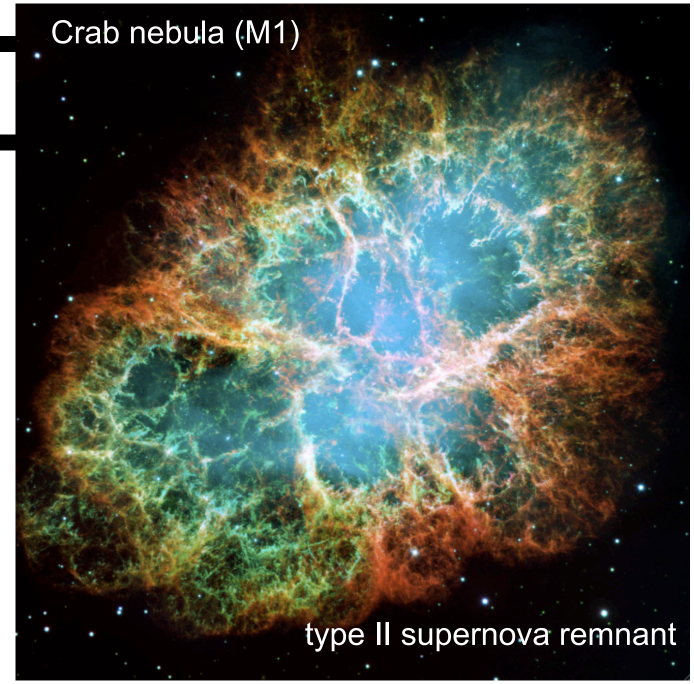


Other recent work:

Chafa et al., Phys. Rev. Lett. 95, 031101 (2005)

Moazen et al., Phys. Rev. C 75, 065801 (2007)

Background radiation: sources

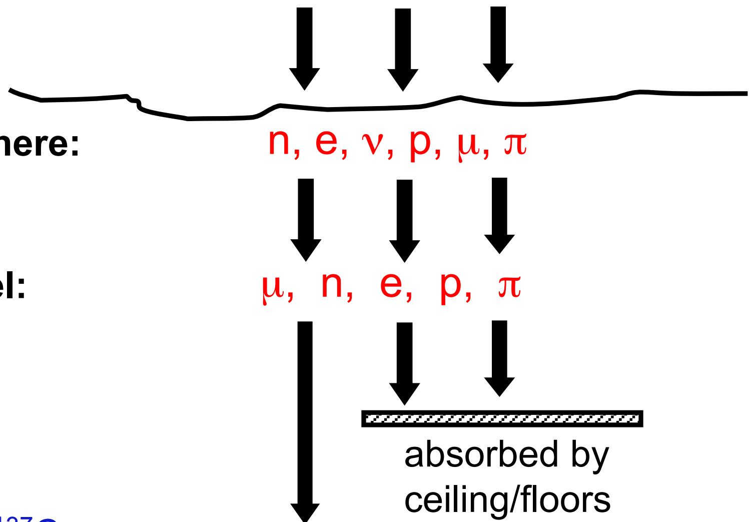


90% p; 9% α; 1% HI
(1000 $m^{-2}s^{-1}$)

upper atmosphere: n, e, ν, p, μ, π

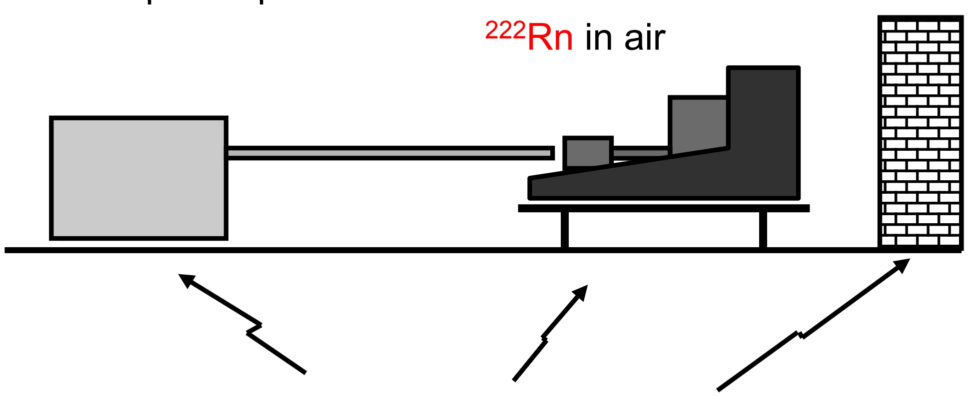
sea level: μ, n, e, p, π

absorbed by ceiling/floors



^{3}H, ^{14}C, ^{60}Co, ^{90}Sr , ^{137}Cs
- nuclear weapons testing
- nuclear power plants

^{222}Rn in air

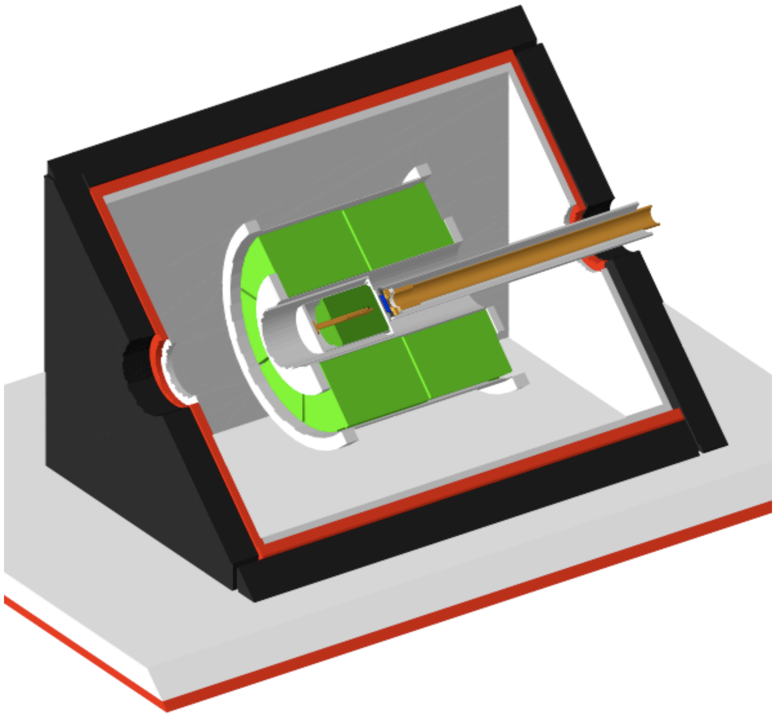


U, Th, ^{40}K in building/shielding/detector material

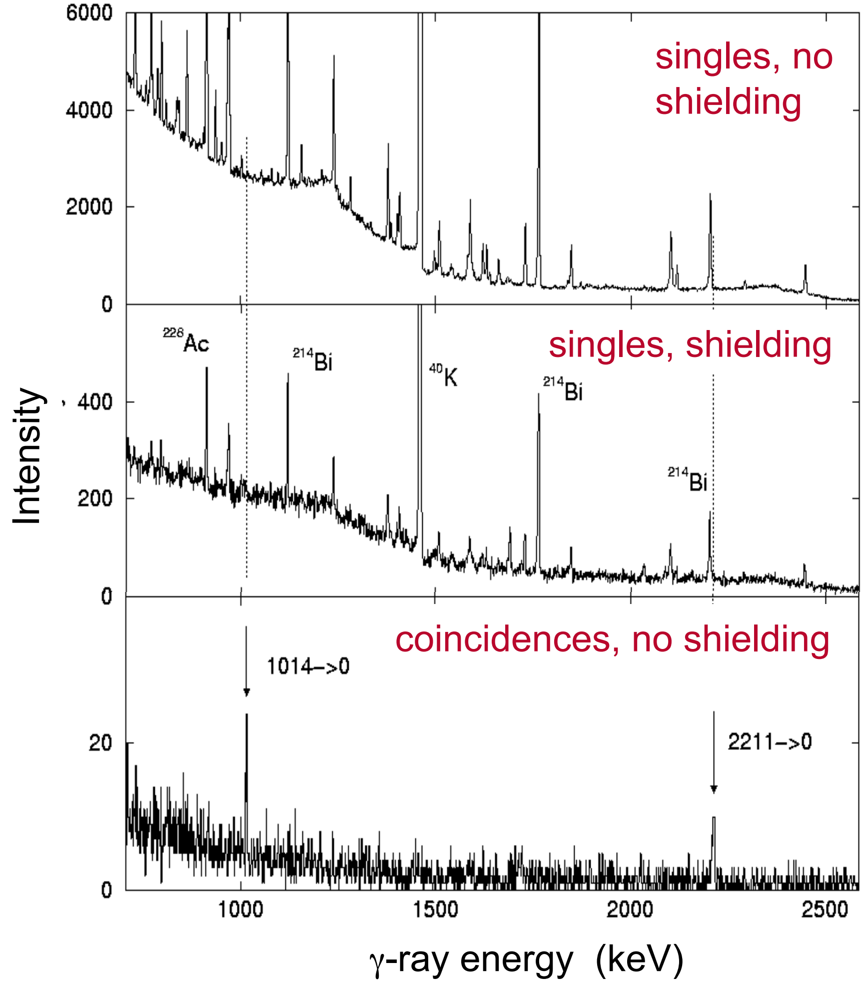
Half lives:

^{3}H:	12.3 y
^{14}C:	5730 y
^{40}K:	$1.3 \cdot 10^{9}$ y
^{60}Co:	5.2 y
^{90}Sr:	28.8 y
^{137}Cs:	30.2 y
^{222}Rn:	3.8 d
^{238}U:	$4.5 \cdot 10^{9}$ y
^{232}Th:	$1.4 \cdot 10^{10}$ y

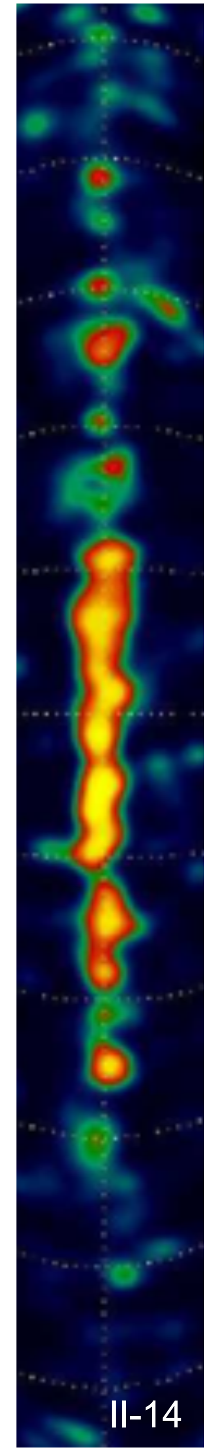
Coincidence-Anticoincidence Detection Apparatus



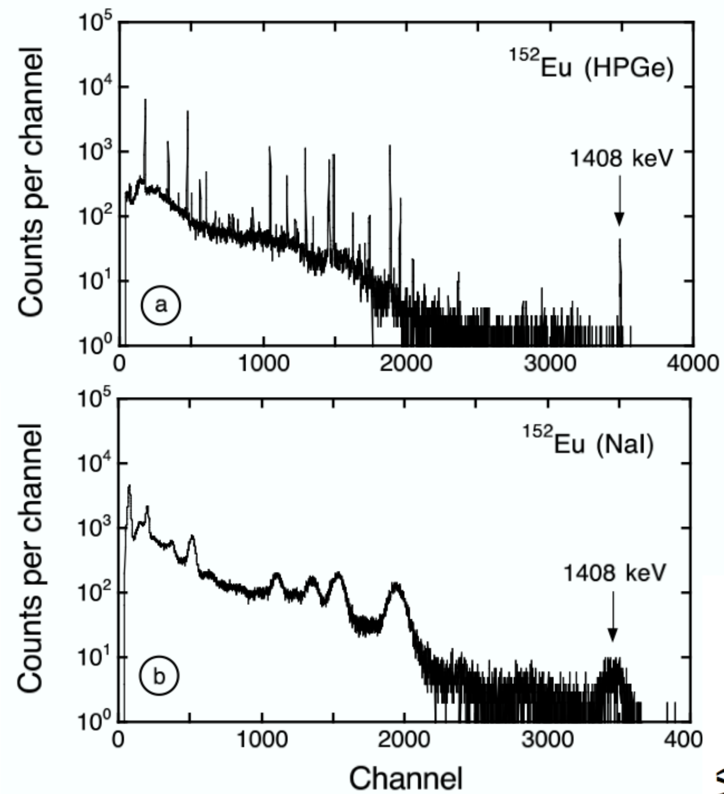
Resonance at 227 keV in $^{26}Mg(p,\gamma)^{27}Al$, 1μA

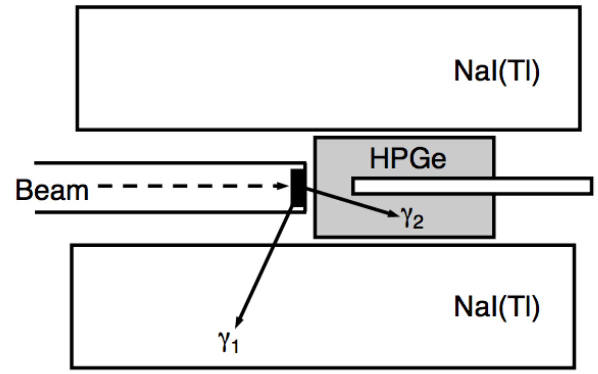


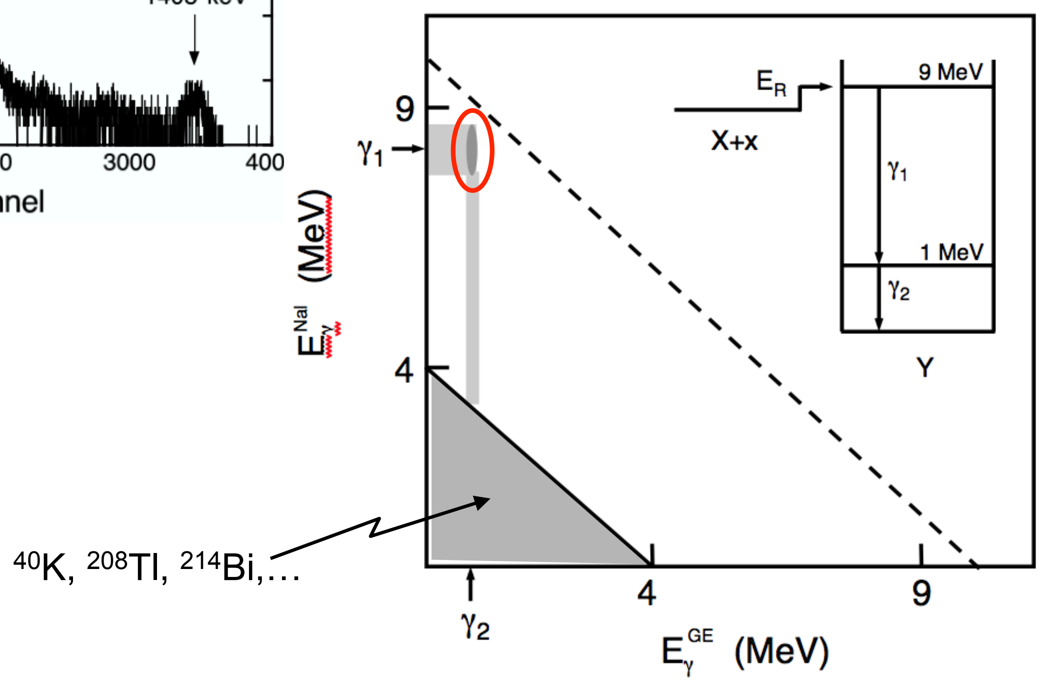
- Rowland, Iliadis et al., Nucl. Instr. Meth. A 480, 610 (2002)
- Longland, Iliadis et al., Nucl. Instr. Meth. A 566, 452 (2006)

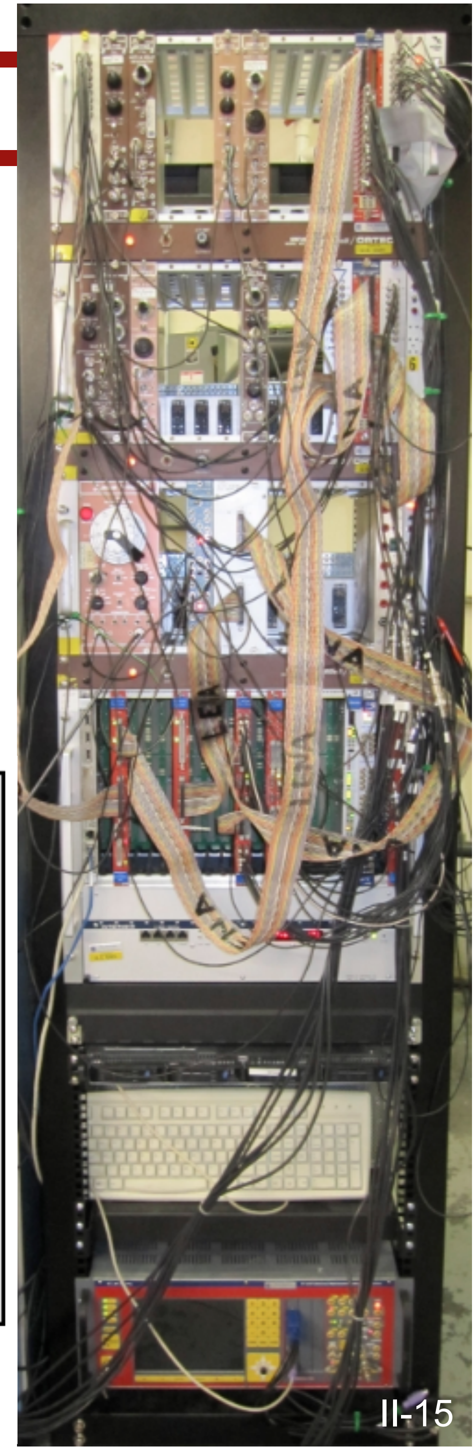


The power of electronics: coincidence gating

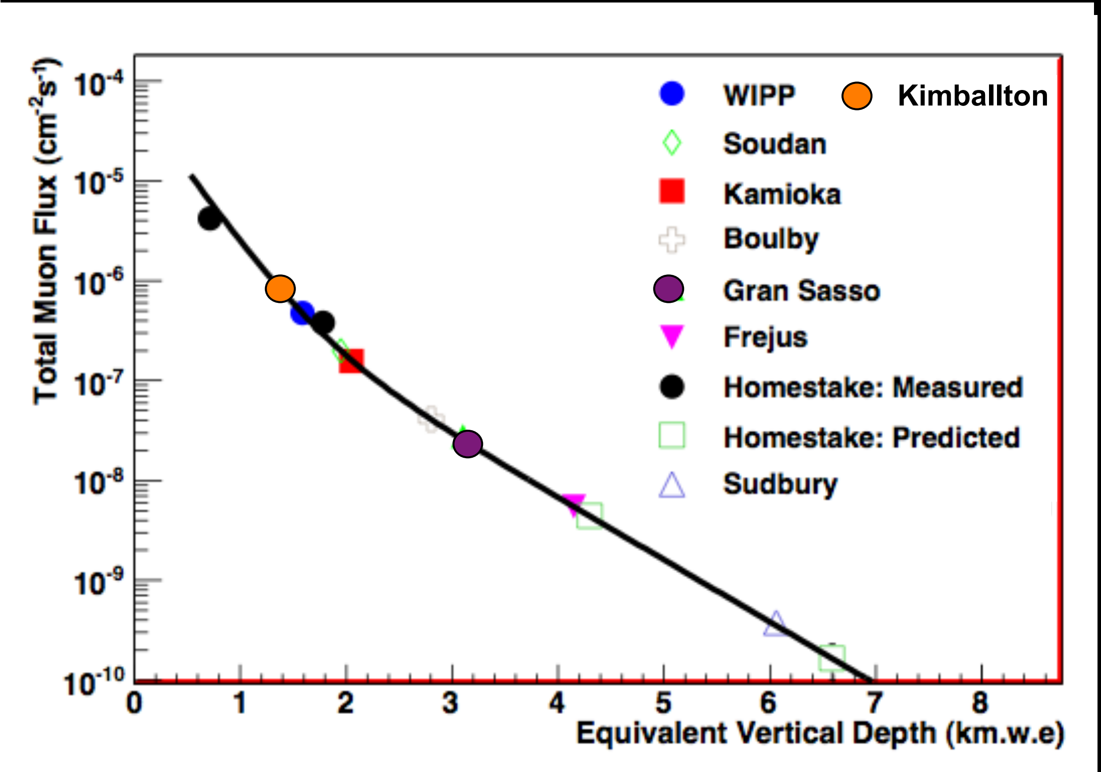






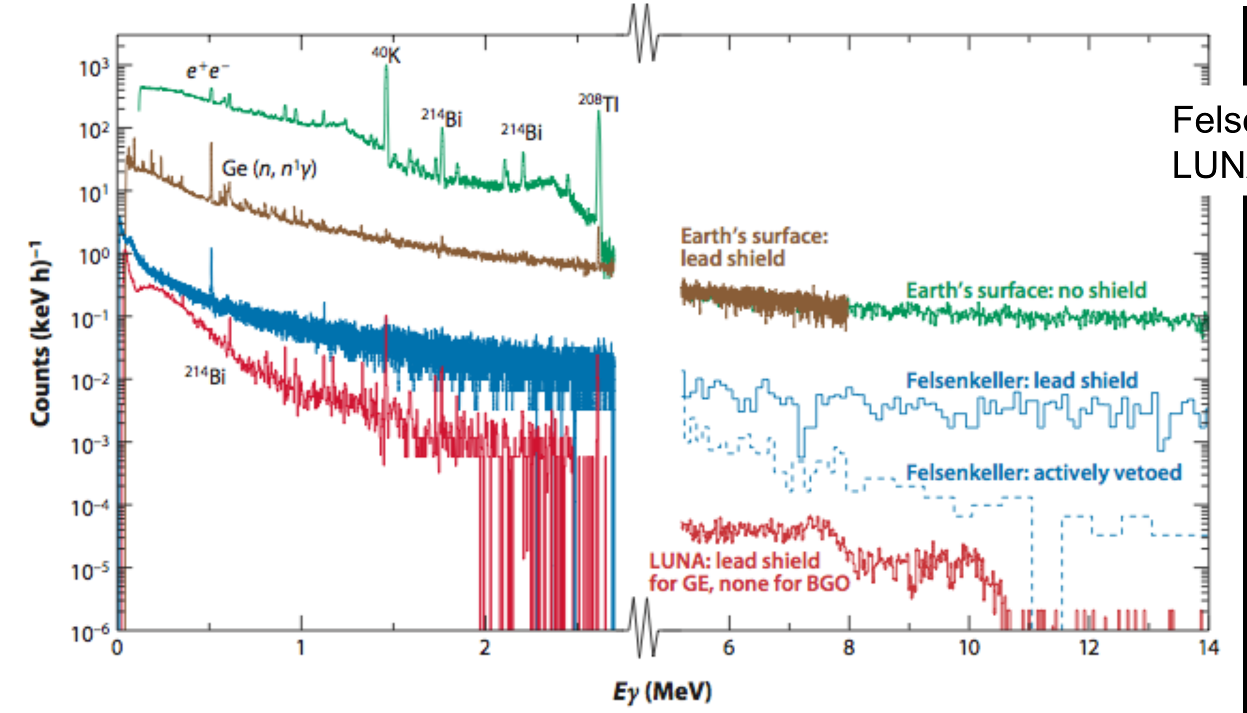


Another background reduction technique: experiments underground



Gray et al., arxiv: 1007.1921

Another background reduction technique: experiments underground

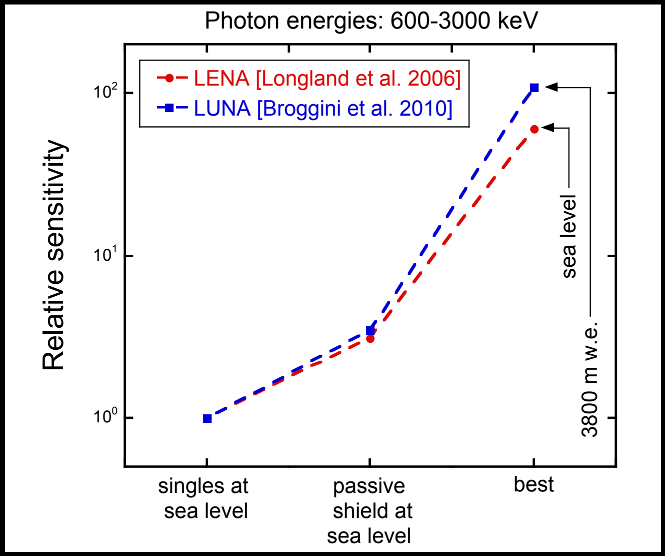


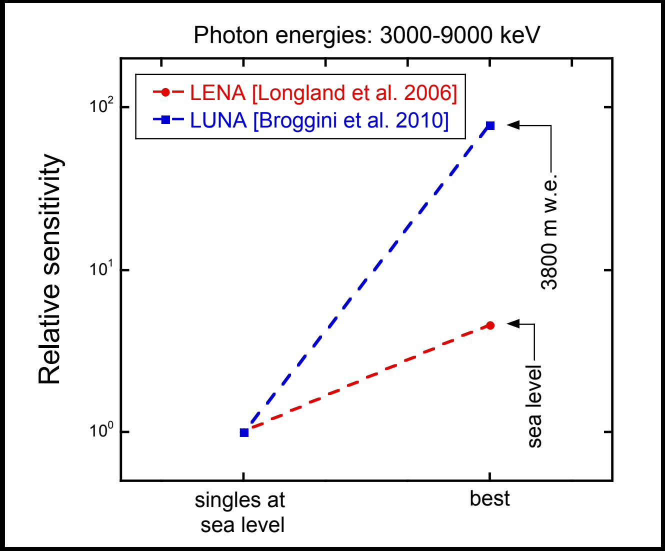
Felsenkeller: 110 m w.e.
LUNA: 3800 m w.e.

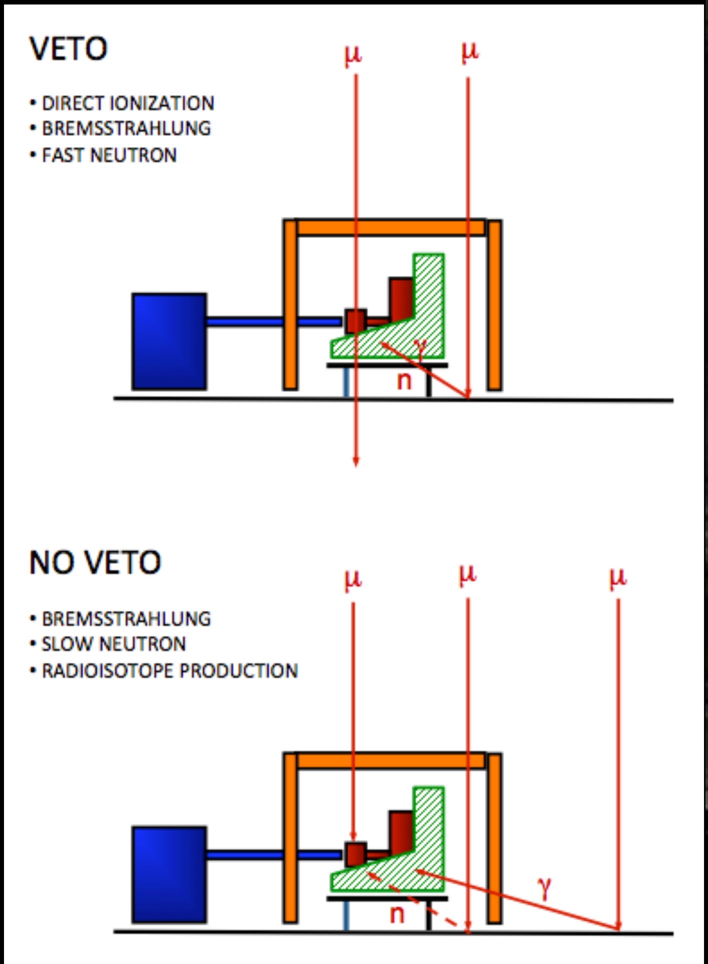
Broggini et al., Annu. Rev. Nucl. Part. Sci. 60, 53 (2010)

- at energies E_γ<3 MeV, specially selected materials must be used or background is not much reduced
- at energies E_γ>3 MeV, background is strongly reduced, even with conventional detectors
- beam-induced background is not reduced!

Sensitivity Comparison of SEA LEVEL versus UNDERGROUND

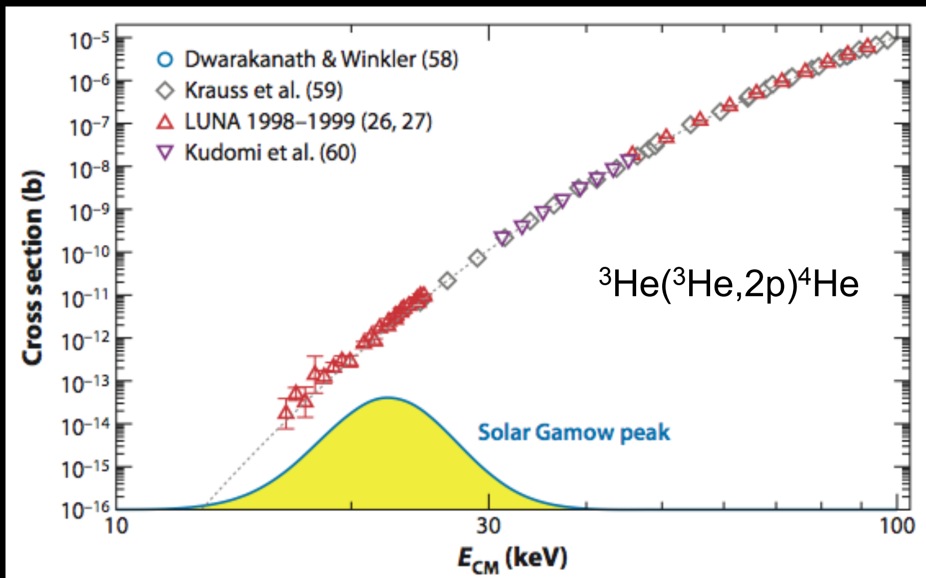


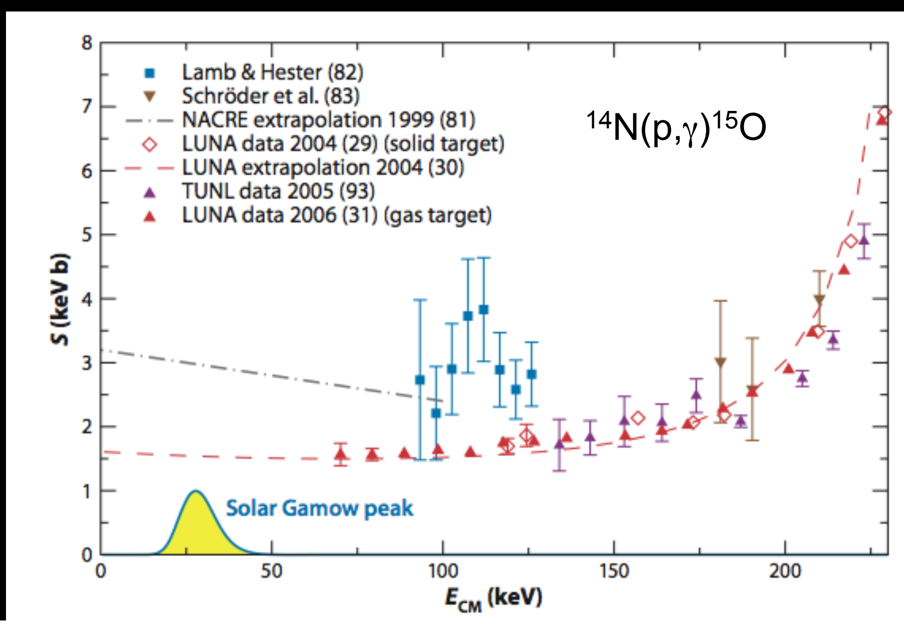


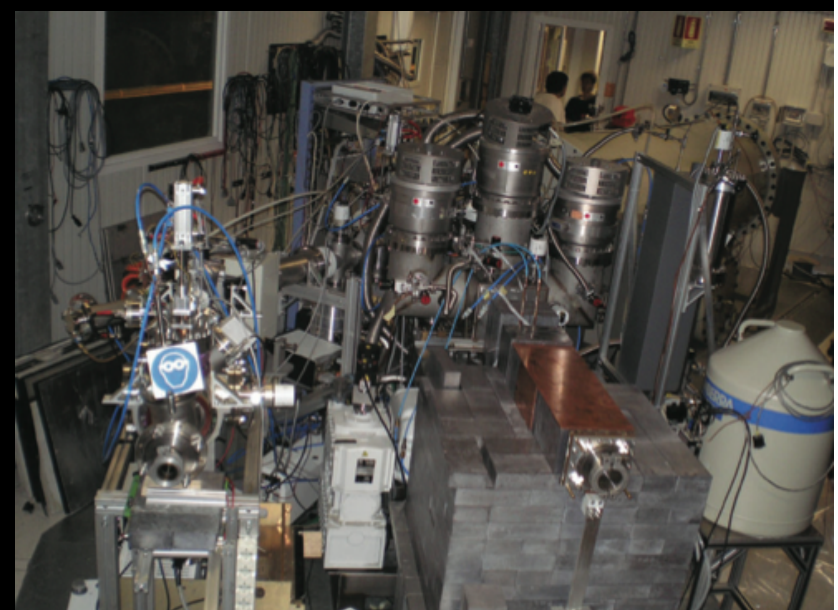


- Longland, Iliadis et al., Nucl. Instr. Meth. A 566, 452 (2006)
- Broggini et al., Annu. Rev. Nucl. Part. Sci. 60, 53 (2010)

Laboratory for Underground Nuclear Astrophysics

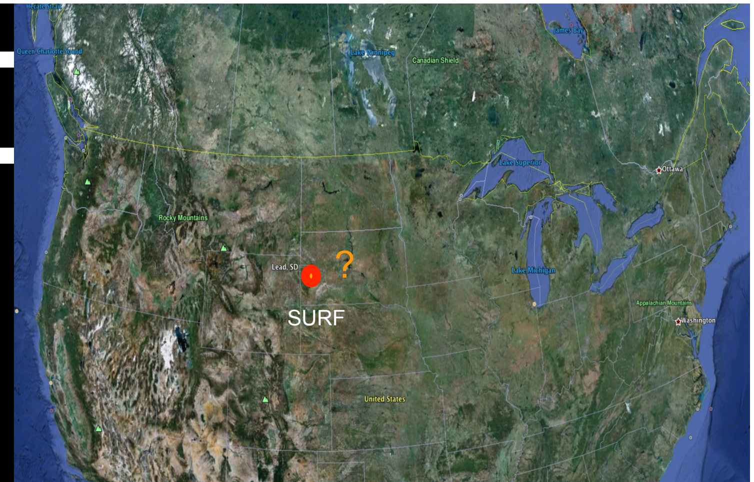






Broggini et al., Annu. Rev. Nucl. Part. Sci. 60, 53 (2010)

Proposed U.S. Underground Laboratory



DIANA: "Dual Ion Accelerator for Nuclear Astrophysics"; collaboration includes:

Lawrence Berkeley National Lab	[accelerators, facilities]
Michigan State University	[accelerators]
University of Notre Dame	[ion optics, gas targets, neutron detectors]
University of North Carolina	[γ-ray detectors]
Colorado School of Mines	[gas jet design]
Western Michigan University	[background and shielding simulations]

Core program:

$^{3}He(\alpha,\gamma)^{7}Be$	solar neutrinos
$^{14}N(p,\gamma)^{15}O$	CNO cycles
$^{12}C(\alpha,\gamma)^{16}O$	helium burning
$^{12}C+^{12}C$	carbon burning
$^{13}C(\alpha,n)^{16}O$	s-process
$^{22}Ne(\alpha,n)^{25}Mg$	

Dynamitron
0.3-3 MV
several mA
microwave, ECR
sources

High-Voltage Platform
40-400 kV
100 mA (p); 10 mA (α)
microwave, ECR
sources

high-density
supersonic
gas-jet target
10^{18}-10^{19}
atoms/cm^2

high-
energy
target
station