Argonne NATIONAL LABORATORY

... for a brighter future

Detectors for Nuclear Astrophysics Experiments.

U.S. Department of Energy

THE UNIVERSITY OF CHICAGO

Office of Science
U.S. DEPARTMENT OF ENERGY

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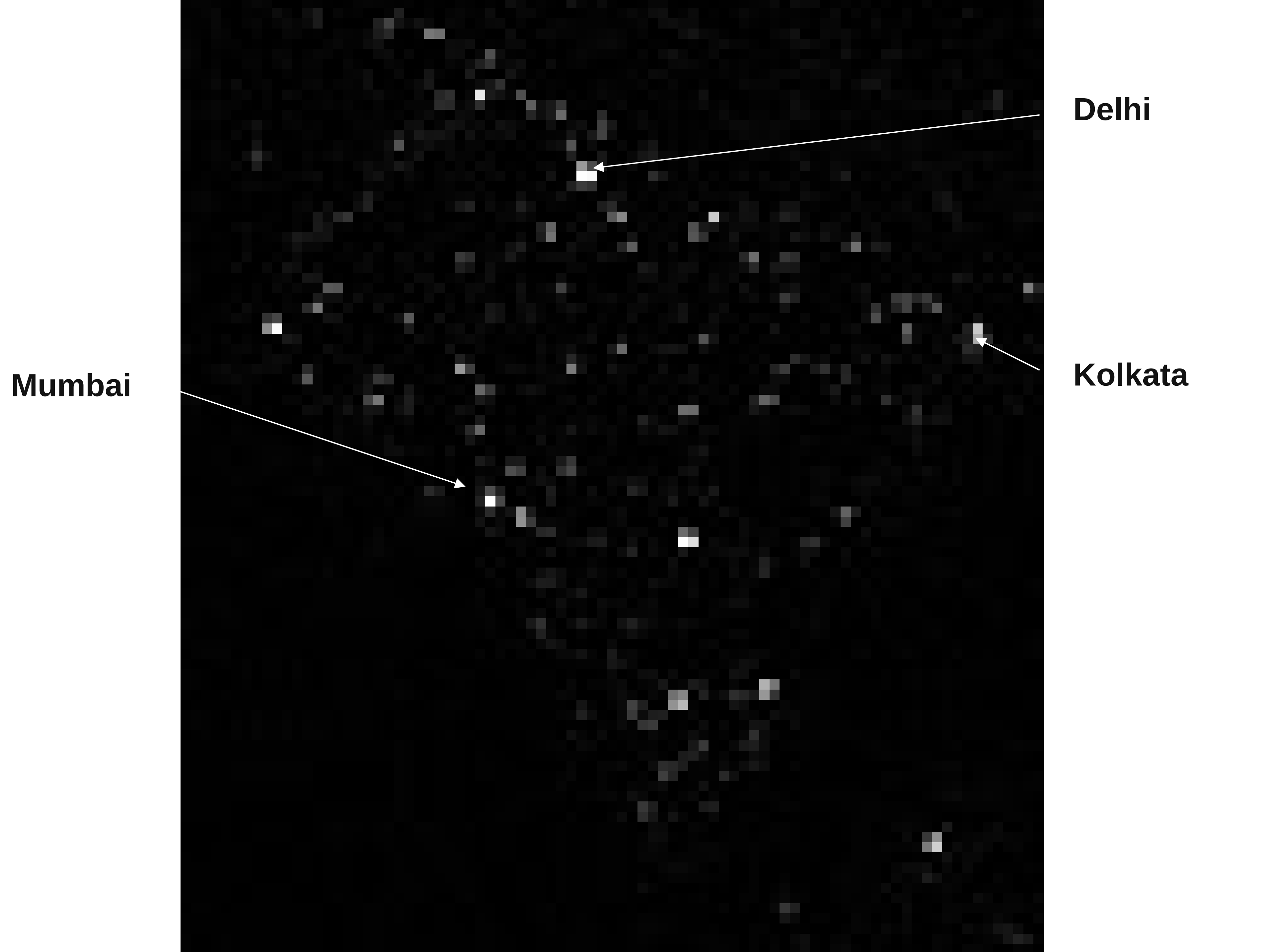
K.E. Rehm,

Argonne National Laboratory, Physics Division


Where were you on
November 13, 2007?
(Rosetta Mission (ESA))

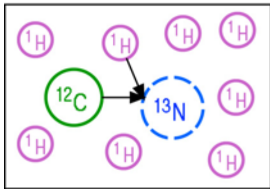
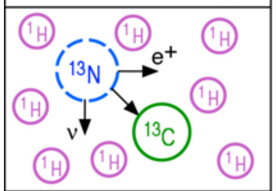
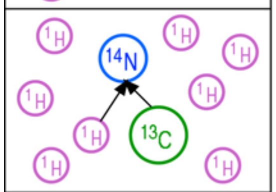
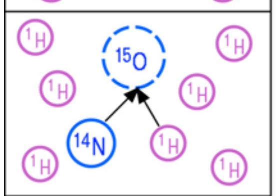
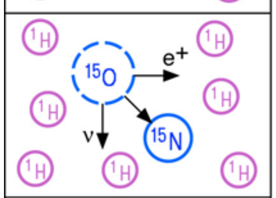
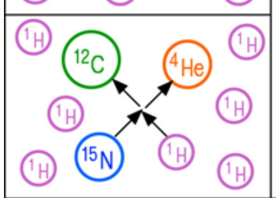

Delhi
Kolkata
Mumbai

ATLAS accelerator

my car

my office

Example of nuclear reactions: CNO cycle

	T = 10 million deg.	T = 100 million deg.		
	t = 4.3 ×10^{9} years	12.9 min	^{12}C(p,γ)^{13}N:	γ, charged particle
	+ 14.3 min	+ 14.3 min	^{13}N→ e^{+} + ν + ^{13}C:	ν, e^{+}, charged part.
	+ 1.1 ×10^{9} years	+ 3.2 min	^{13}C(p,γ)^{14}N:	γ, charged particle
	+ 2.1 ×10^{12} years	+ 3.2 hrs	^{14}N(p,γ)^{15}O:	γ, charged particle
	+ 2.9 min	+ 2.9 min	^{15}O→ e^{+} + ν + ^{15}N:	ν, e^{+}, charged part.
	+ 2.0 ×10^{8} years	0.26 sec	^{15}N(p,α)^{12}C:	α, charged particle

Many different detectors:

- Gamma detector arrays
- X-ray detectors
- Neutron detectors
- Neutrino detectors
- **Charged particle detectors**

Ideal Detector

- Excellent energy (wave length) resolution
- Excellent time resolution
- High detection efficiency (large area)
- High count rate capability
- Stable over long running times
- No (low) backgrounds
- Low cost
- Long life time
- Easy to repair

Outline:

Silicon surface barrier detector **(commercial products)**

Gas-filled ionization chambers **(built individually)**

Magnetic Spectrometer **(designed indiv., built commerc.)**

Recoil separators (lecture II) **(designed indiv., built commerc.)**

Two options of charged-particle reactions:

- Light particle (p) on heavy target (^{22}Ne).

  example: $^{22}Ne(p,\alpha)^{19}F$

  "normal kinematics"

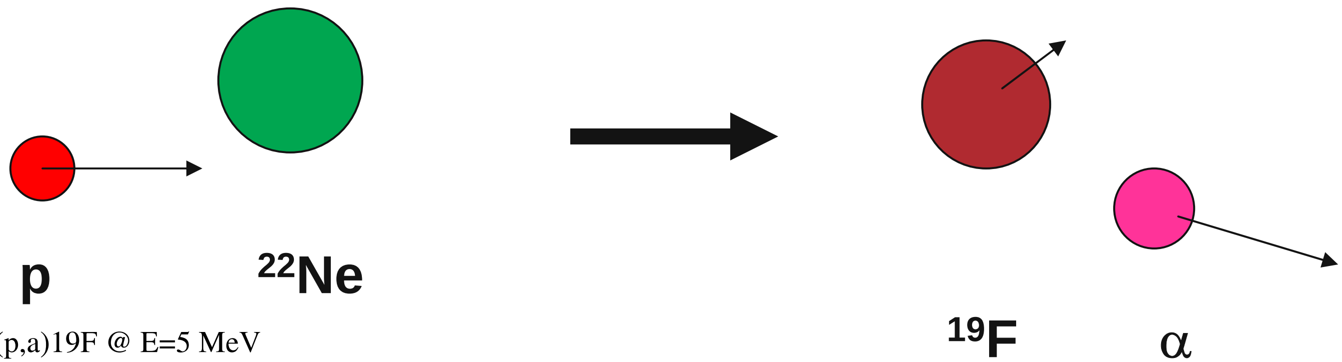
- Heavy particle (^{22}Ne) on light target (p).

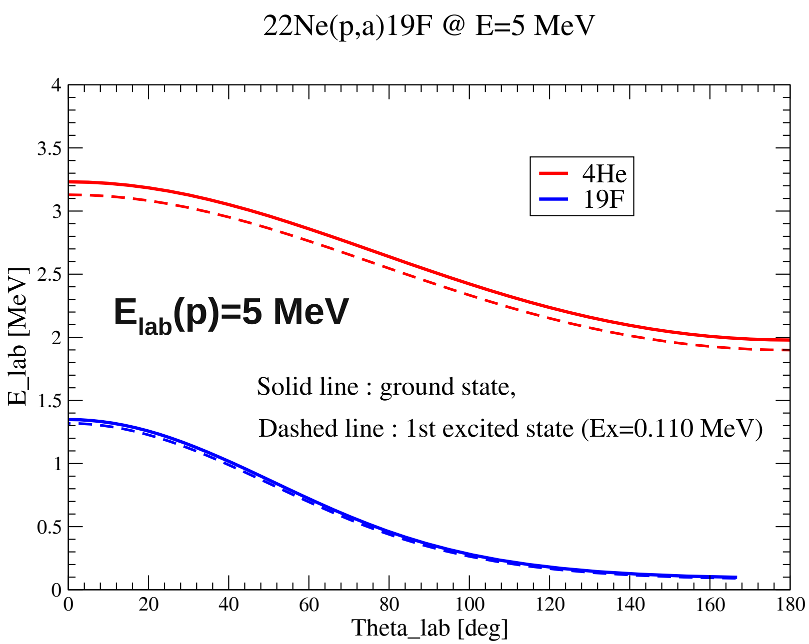
  example: $p(^{22}Ne,\alpha)^{19}F$

  "inverse kinematics"

Normal kinematics

$^{22}Ne(p,\alpha)^{19}F$

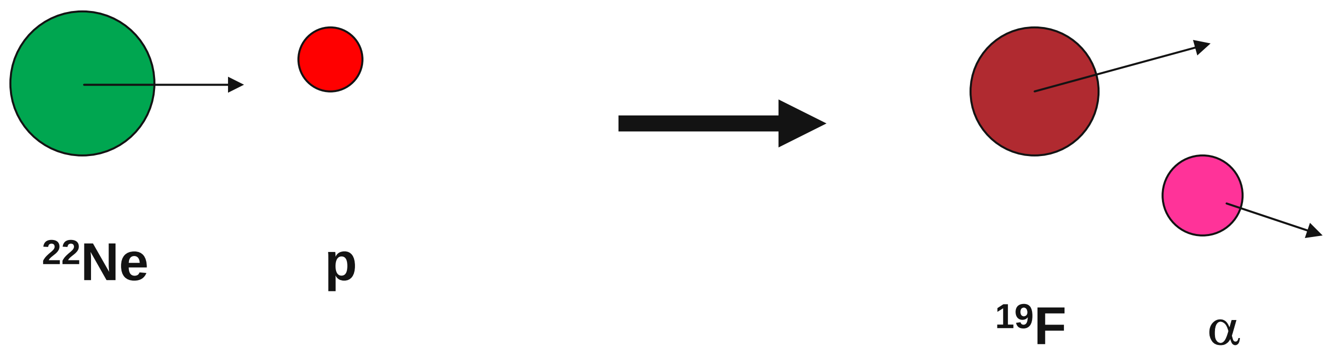


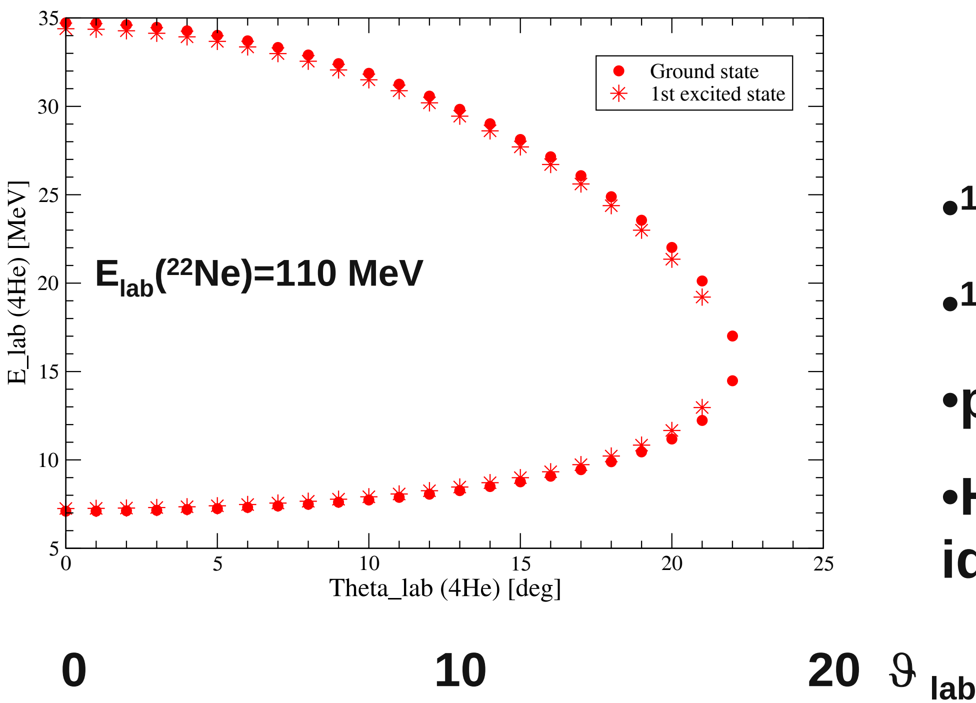


- **Alphas cover all angles (0-180°)**
- **Alphas have most of the energy**
- **^{19}F has low energy**
- **Only possible for stable targets**

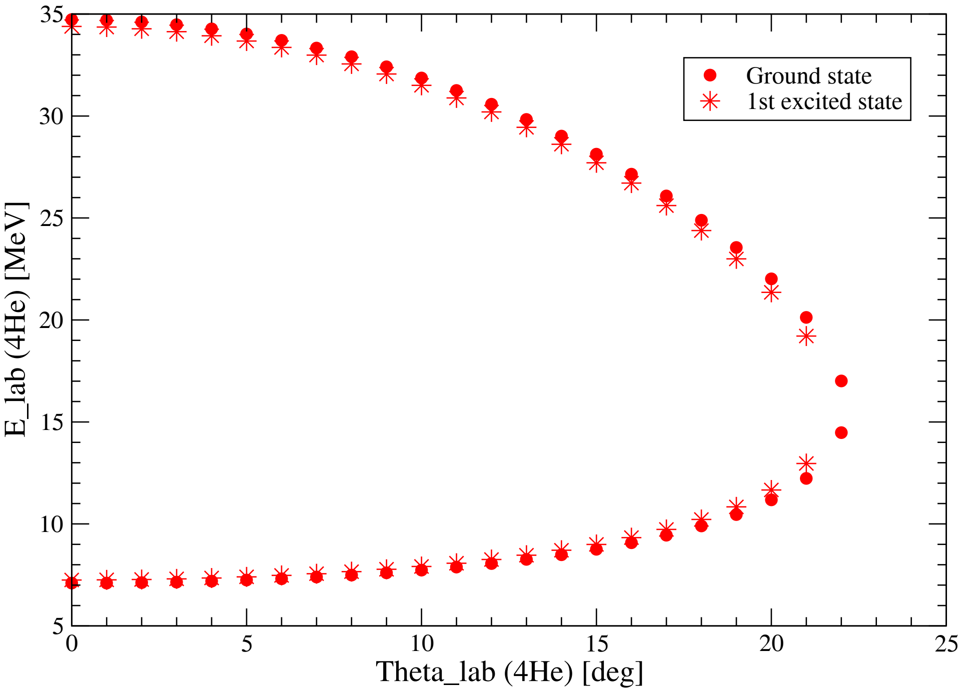
Inverse kinematics

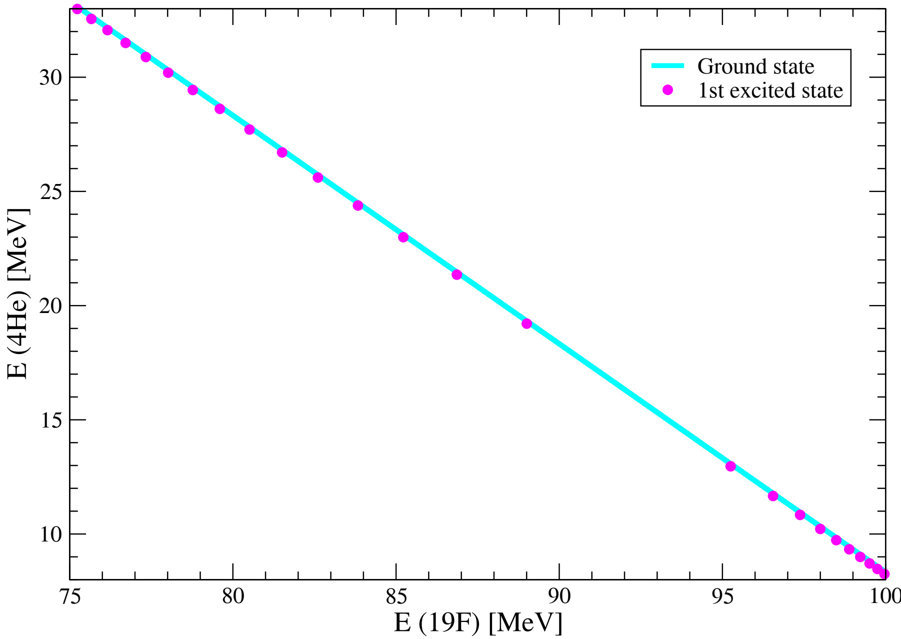
p(^{22}Ne,α)^{19}F

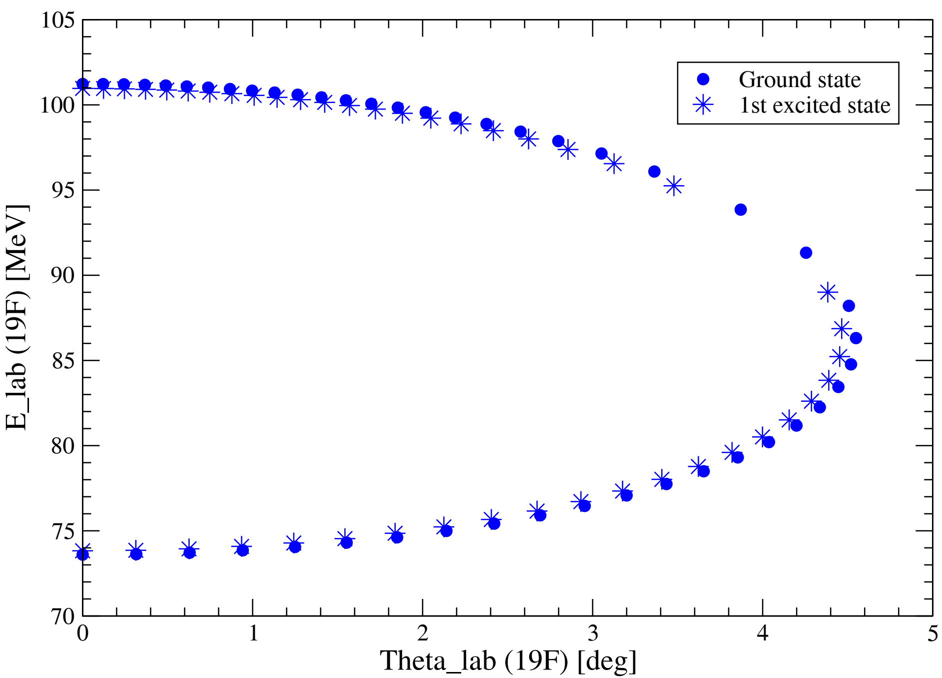




- ^{19}F and α's are emitted forward
- ^{19}F and α share the energy
- possible for short-lived particles
- High ^{19}F energy good for identification





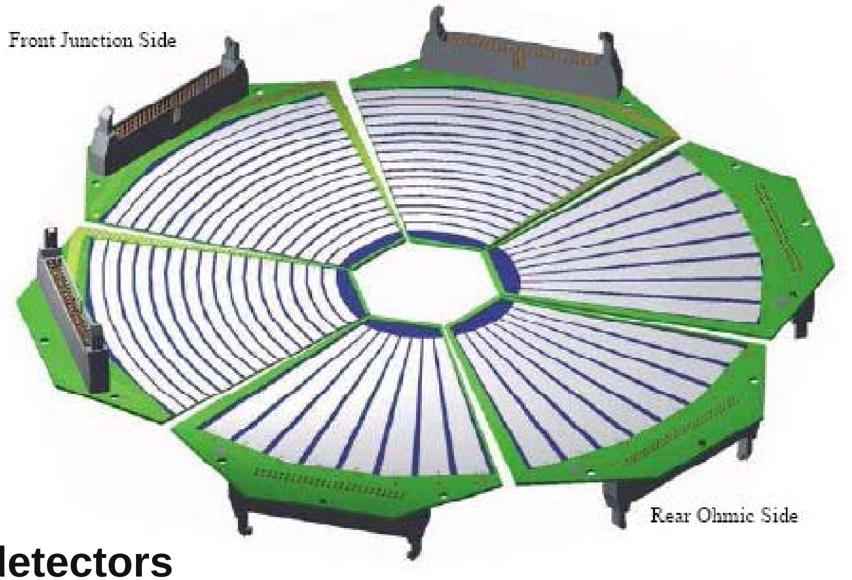


Inverse kinematics:

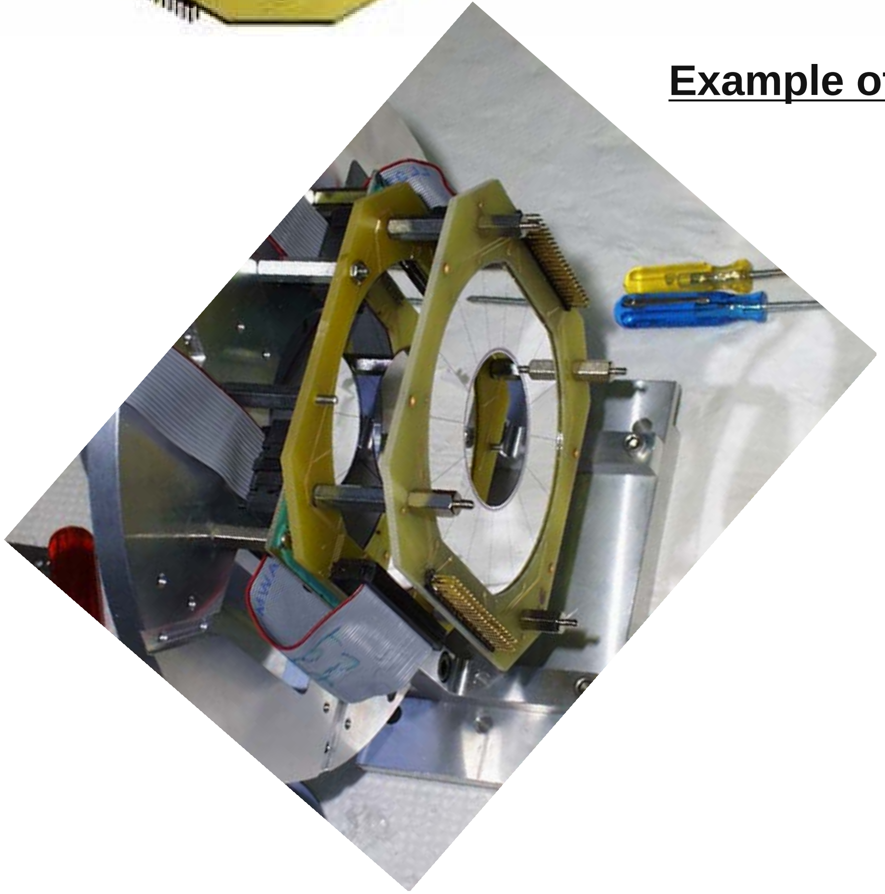
Much higher energies, but

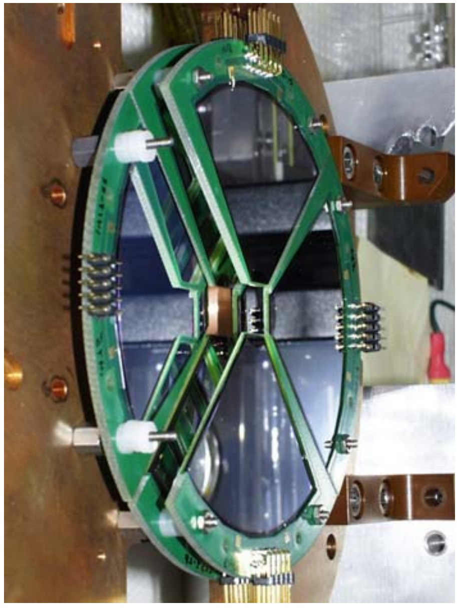
Kinematic lines very close together

Geometry (e.g. beam spot) critical



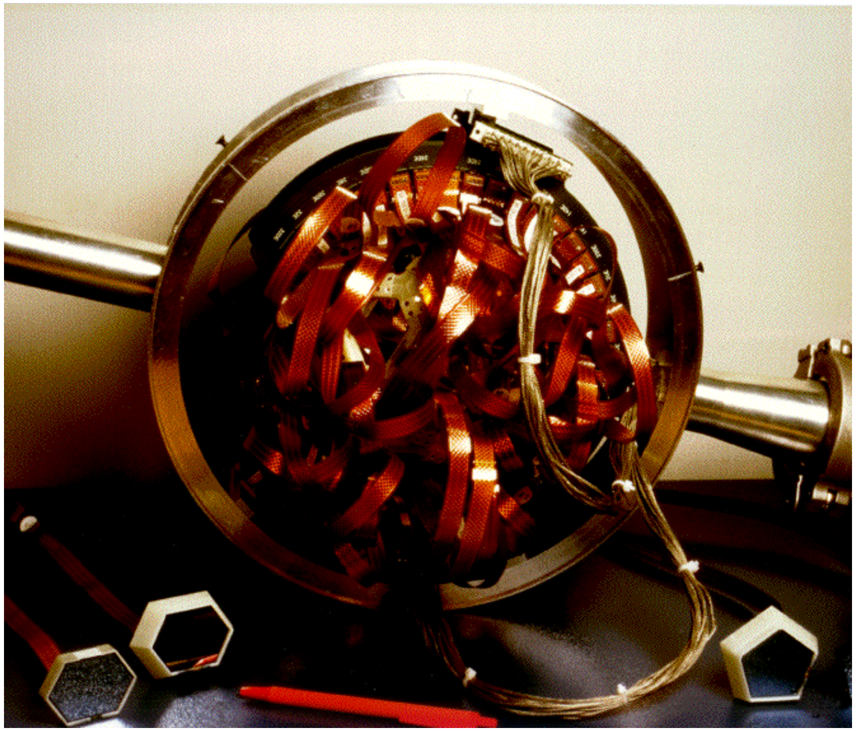
Example of Si detectors



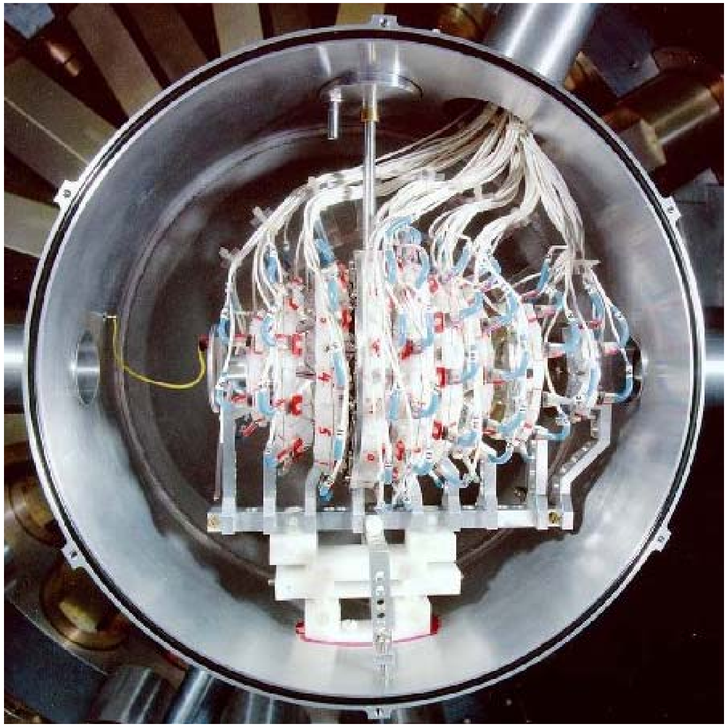


Particle Detector Arrays

(coincidence exp., particle transfer studies)

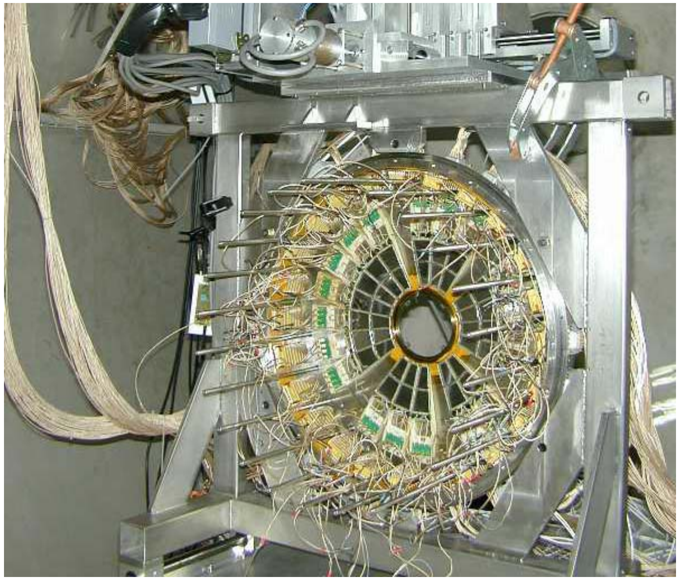


(Legnaro)



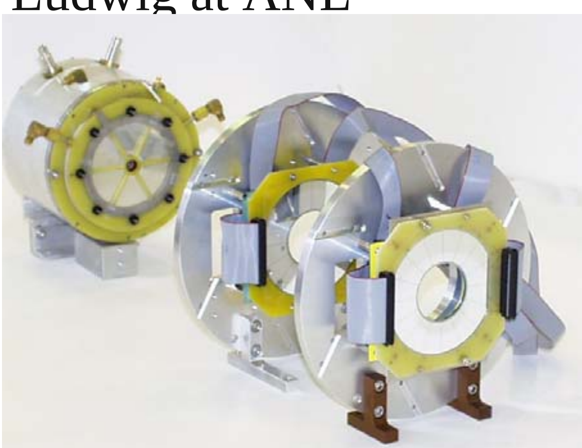
Microball

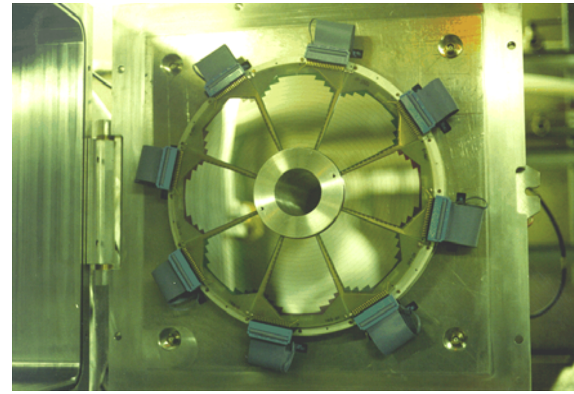
Particle Detectors



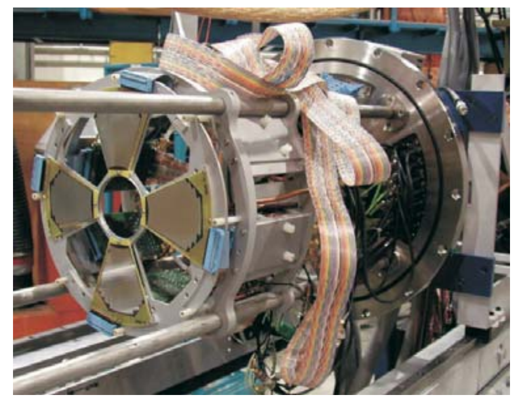
Garfield at Legnaro

Ludwig at ANL





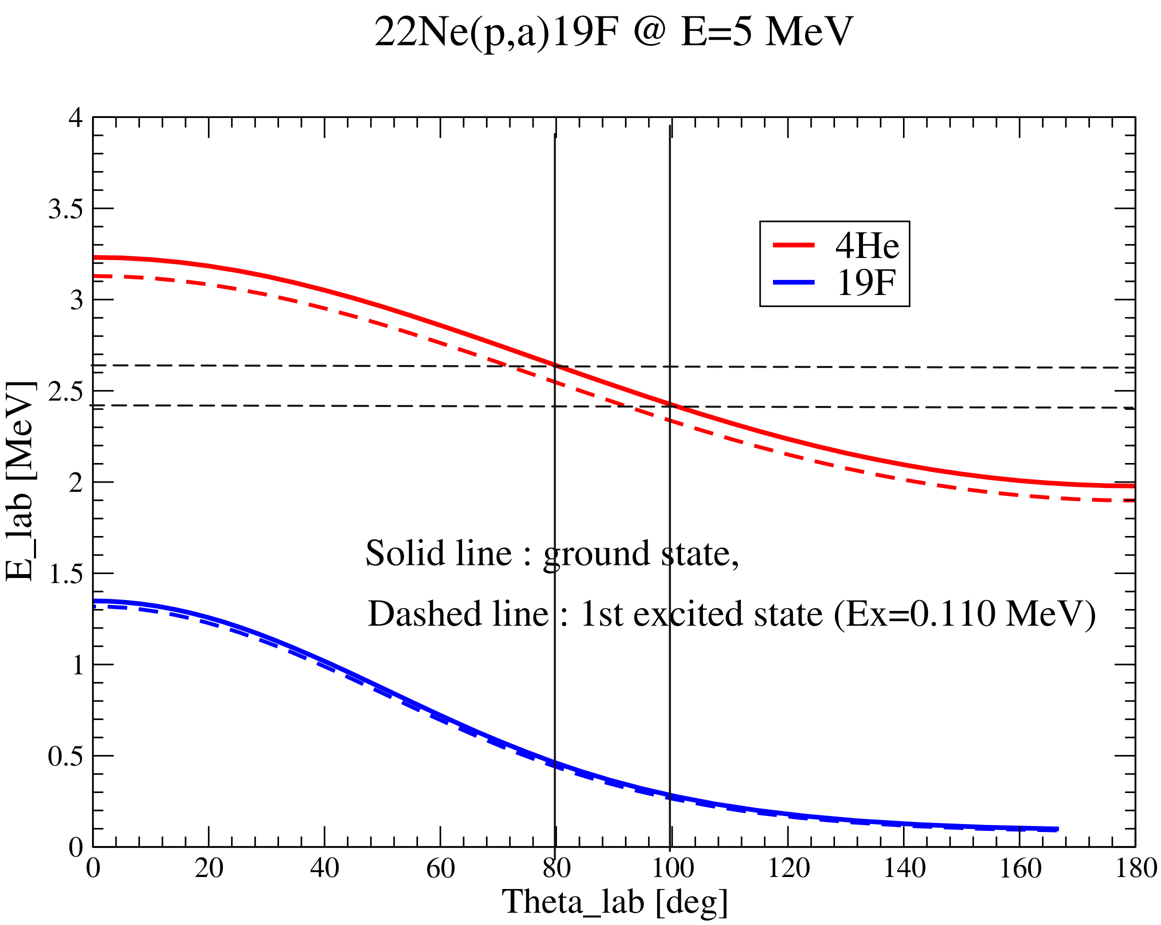
LEDA at Louvain-la-Neuve



TUDA at TRIUMF ISAC

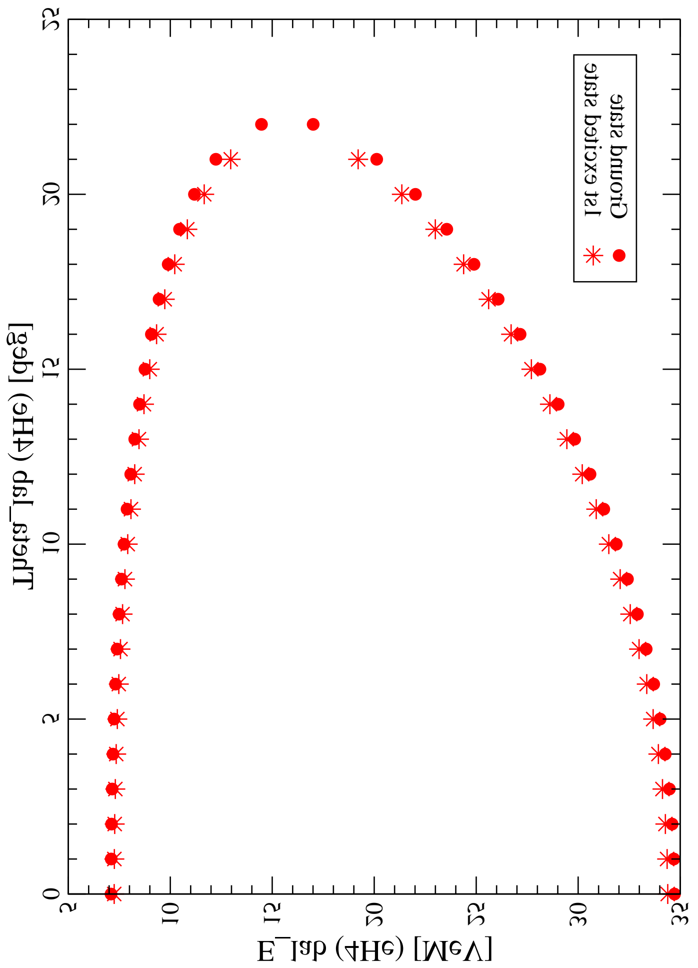
A few hundred channels of electronics

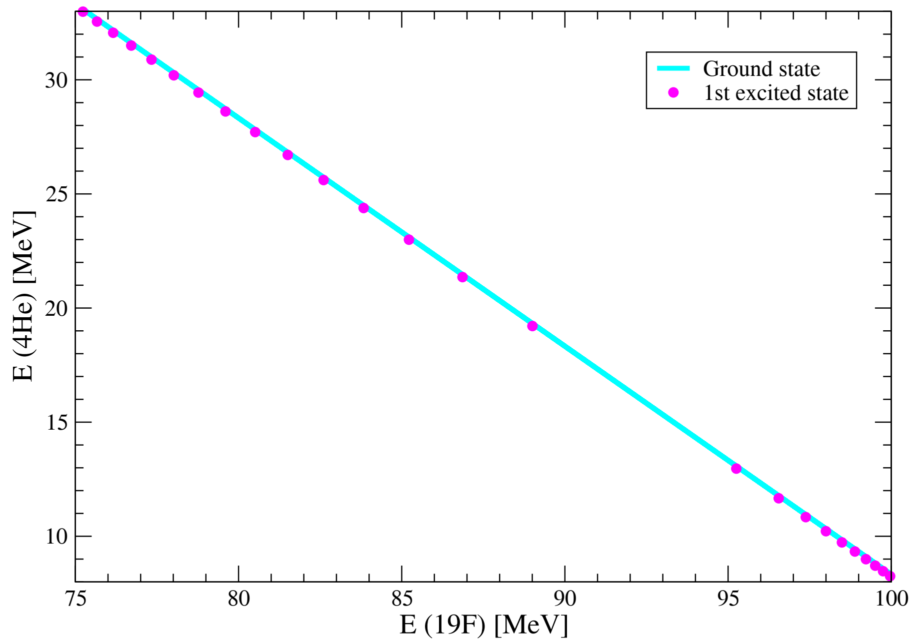
Difficulties: Kinematic shifts dE/dϑ



- Low energies (no particle identification)
- use small detectors
- Coincidences very difficult

Inverse kinematics: detect both particles

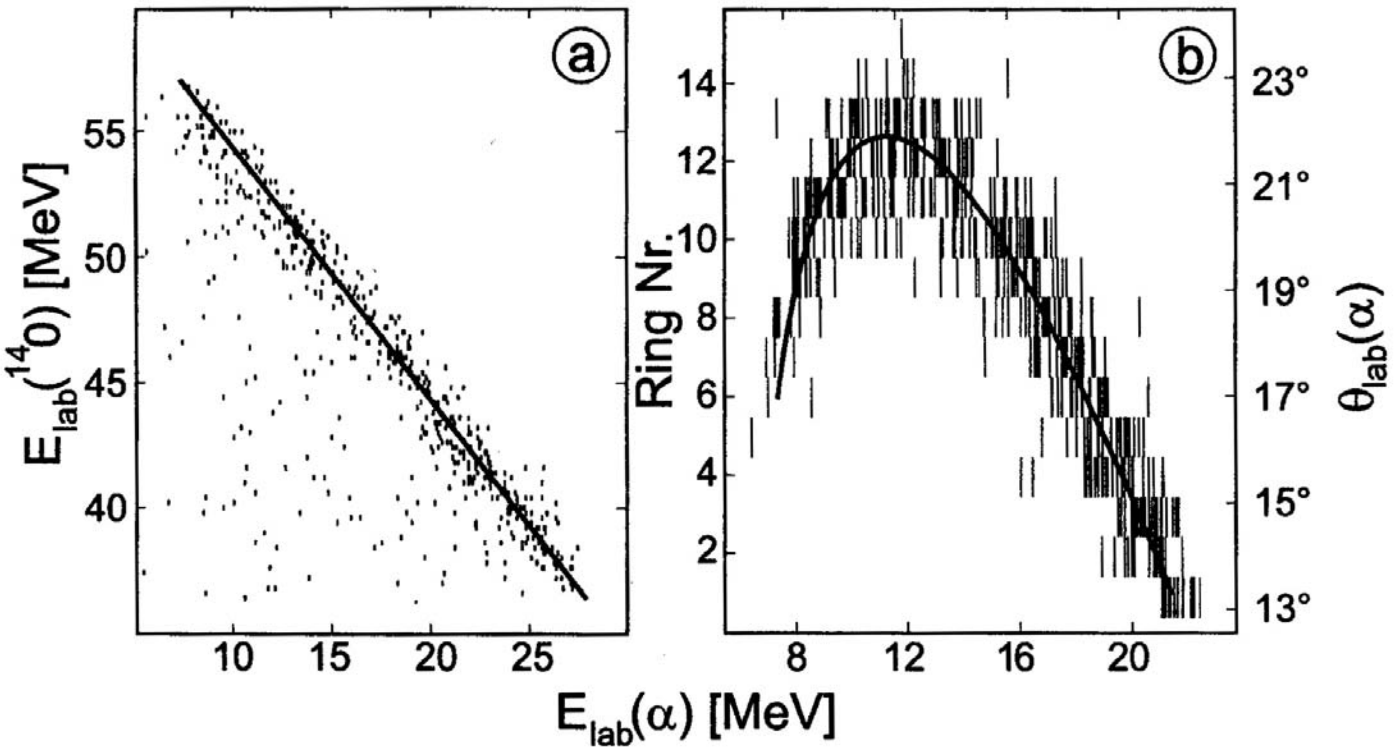




- Difficult to get good angle definition
- Difficult to separate individual states

Inverse kinematics: detect both particles

Example: $^{1}H(^{17}F,\alpha)^{14}O$



Angle uncertainty in close geometry!

Advantages/disadvantages of Si detectors

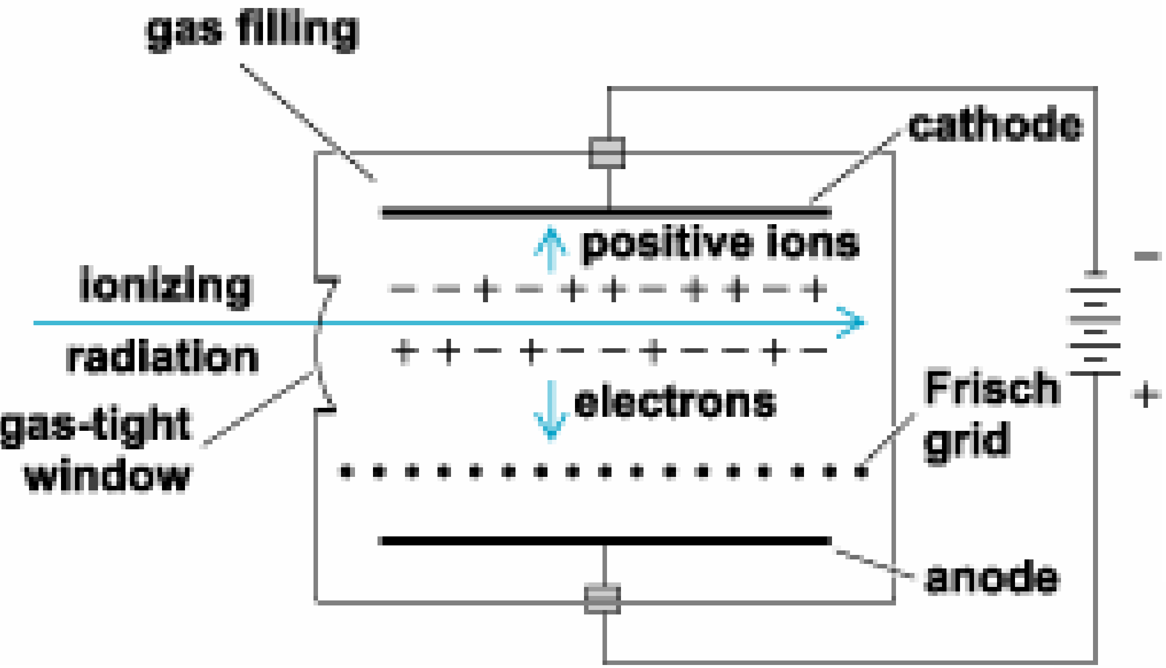
- \+ Commercially available
- \+ Compact
- \+ Good time resolution
- \+ Good count rate capabilities
- \- Expensive
- \- Easy to destroy
- \- difficult to produce thin and homogeneous.

⬇

Use a gas-filled ionization chamber

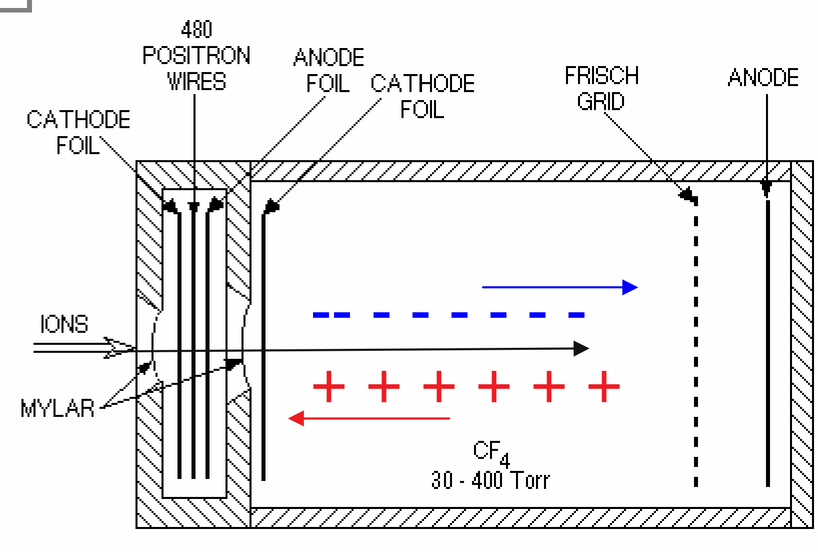
Ionization chambers

Types of ionization chambers:



- + good Bragg peak
- + good range signal
- - long drift distance

BRAGG CURVE DETECTOR



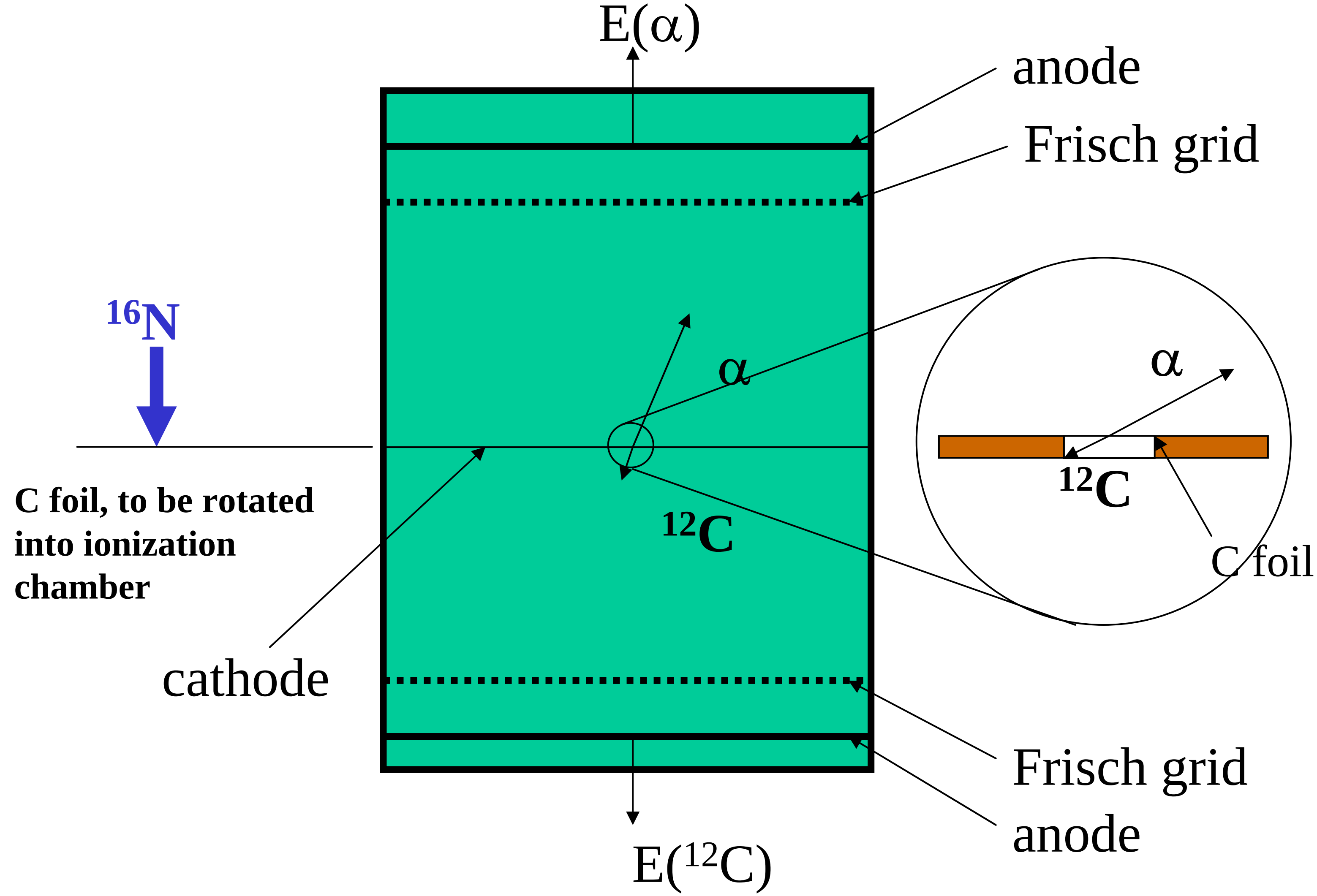
Cross section of Detector 1 available for the spectrographs.

Standard ionization chamber

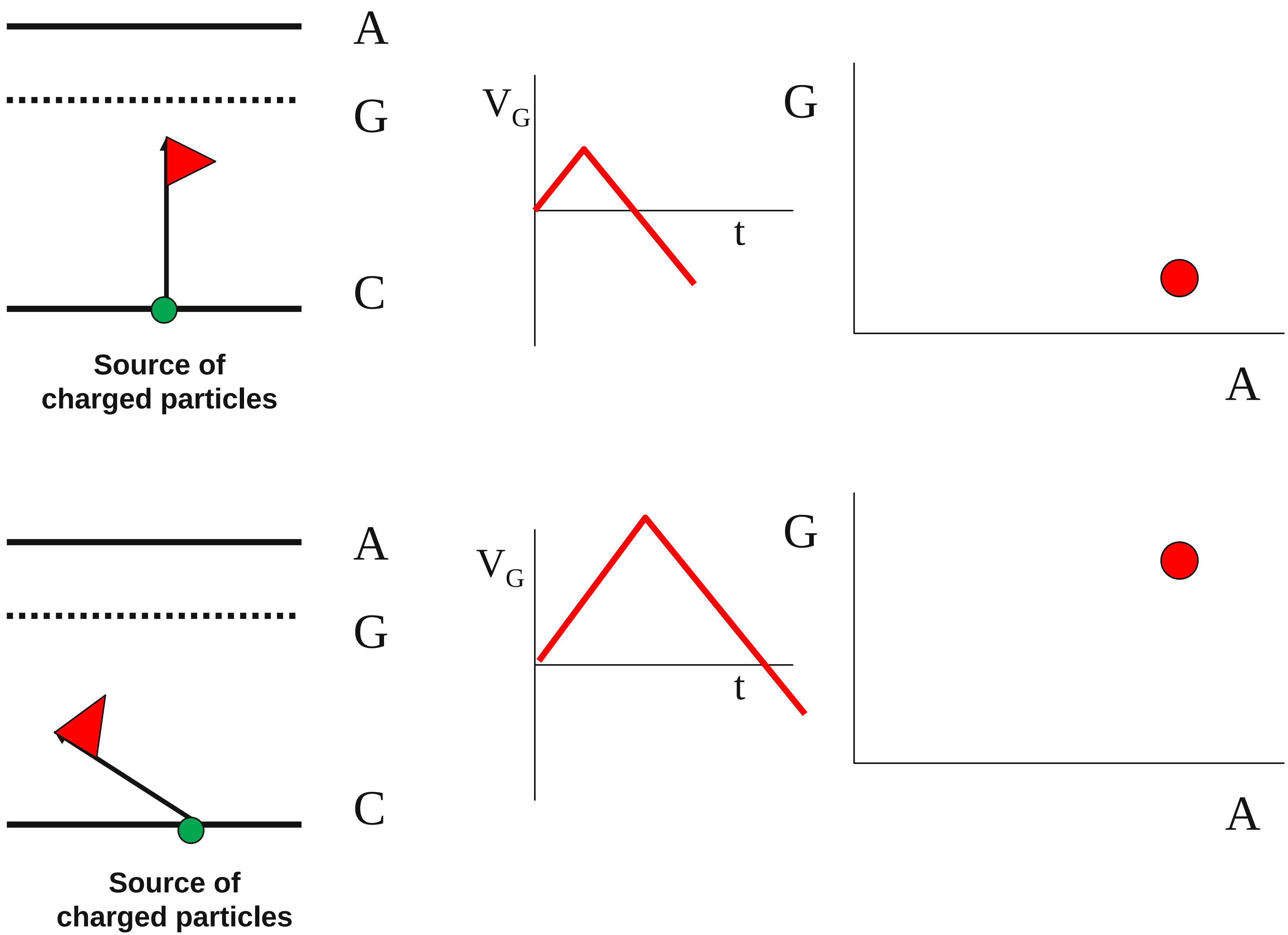
- + short drift distances
- + subdivided anode (ΔE)
- - inferior Z-separation

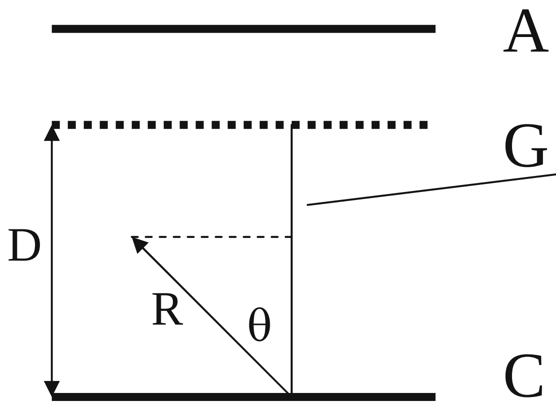
Some advanced ionization chambers

Twin-Ionization Chamber



Emission angle dependence of the Frisch grid signal





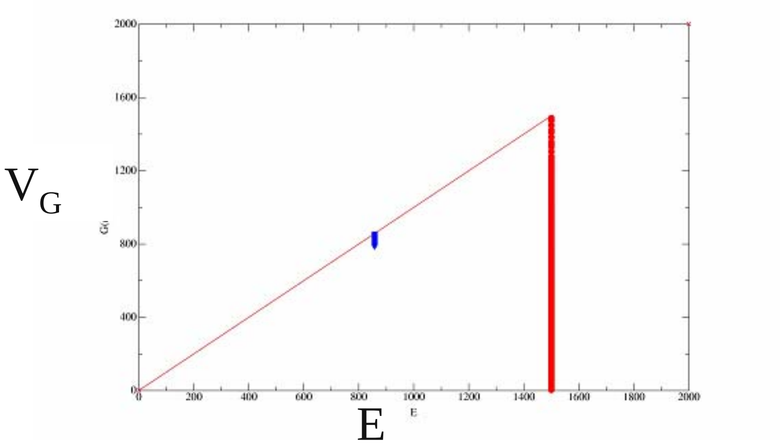
$$V_G \sim E \cdot (D - R\cos\theta)$$

$$V_G \sim E \cdot \left(1 - \lambda \frac{E^2}{mZ^2} \cos\theta\right)$$

For $^{10}B(n,\alpha)^7Li$

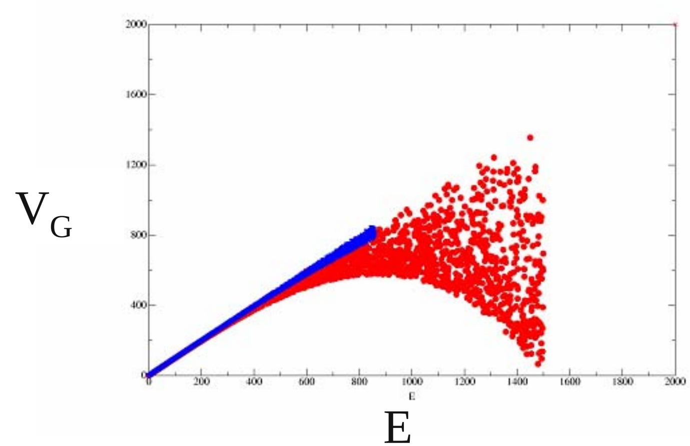
E_α=1.5 MeV, random θ

$E_{Li}=4/7*E_\alpha$

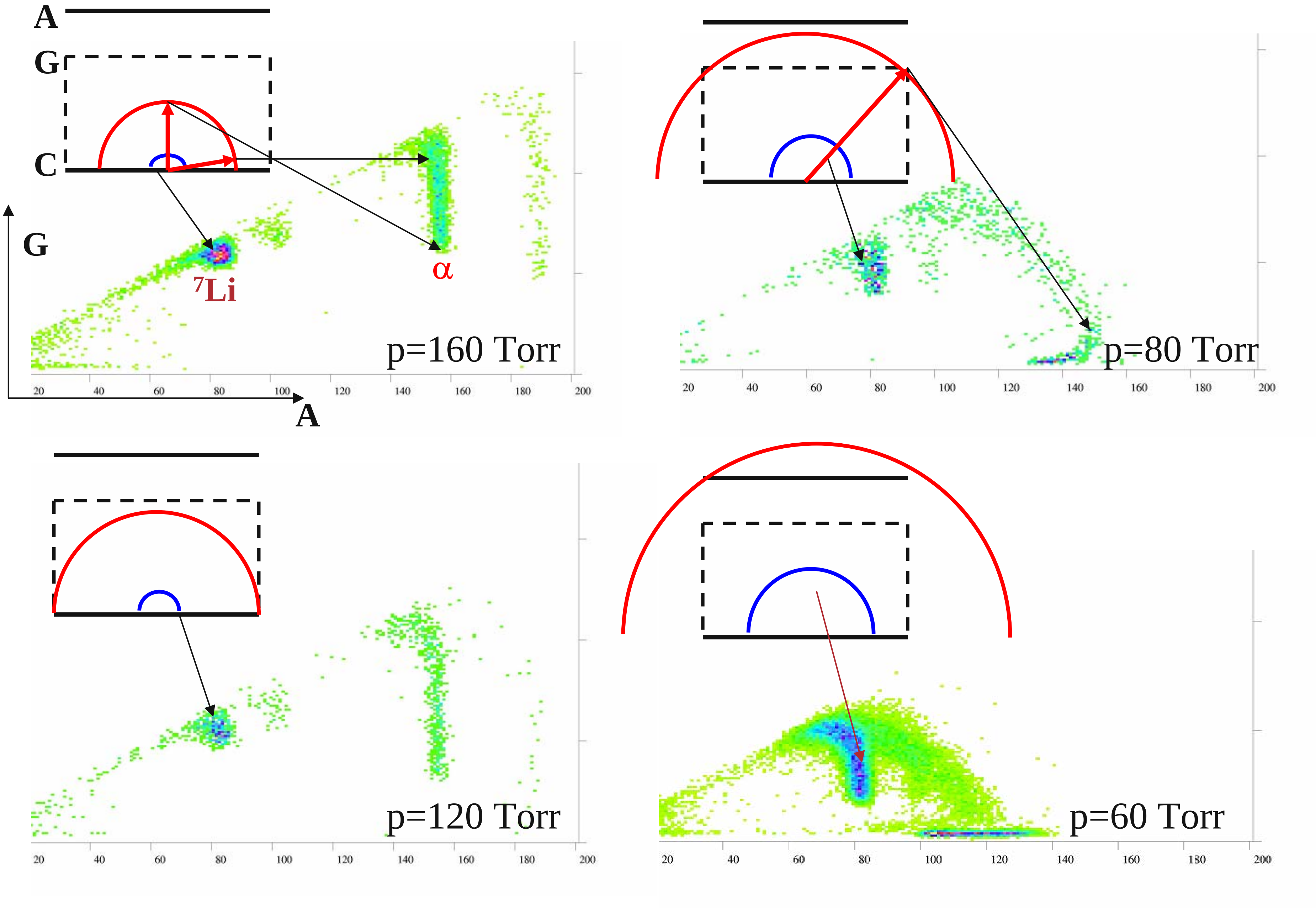


random E_α, random θ

$E_{Li}=4/7*E_\alpha$



Pressure dependence



Some comments about backgrounds:

Well-known for γ-detectors (e.g. ^{40}K)

For particle detectors:

- Cosmic rays
- Radon/Uranium contamination in the counter material

(see articles about low-background, underground experiments)

Background run – 0.925x10^6 s (257 hr)

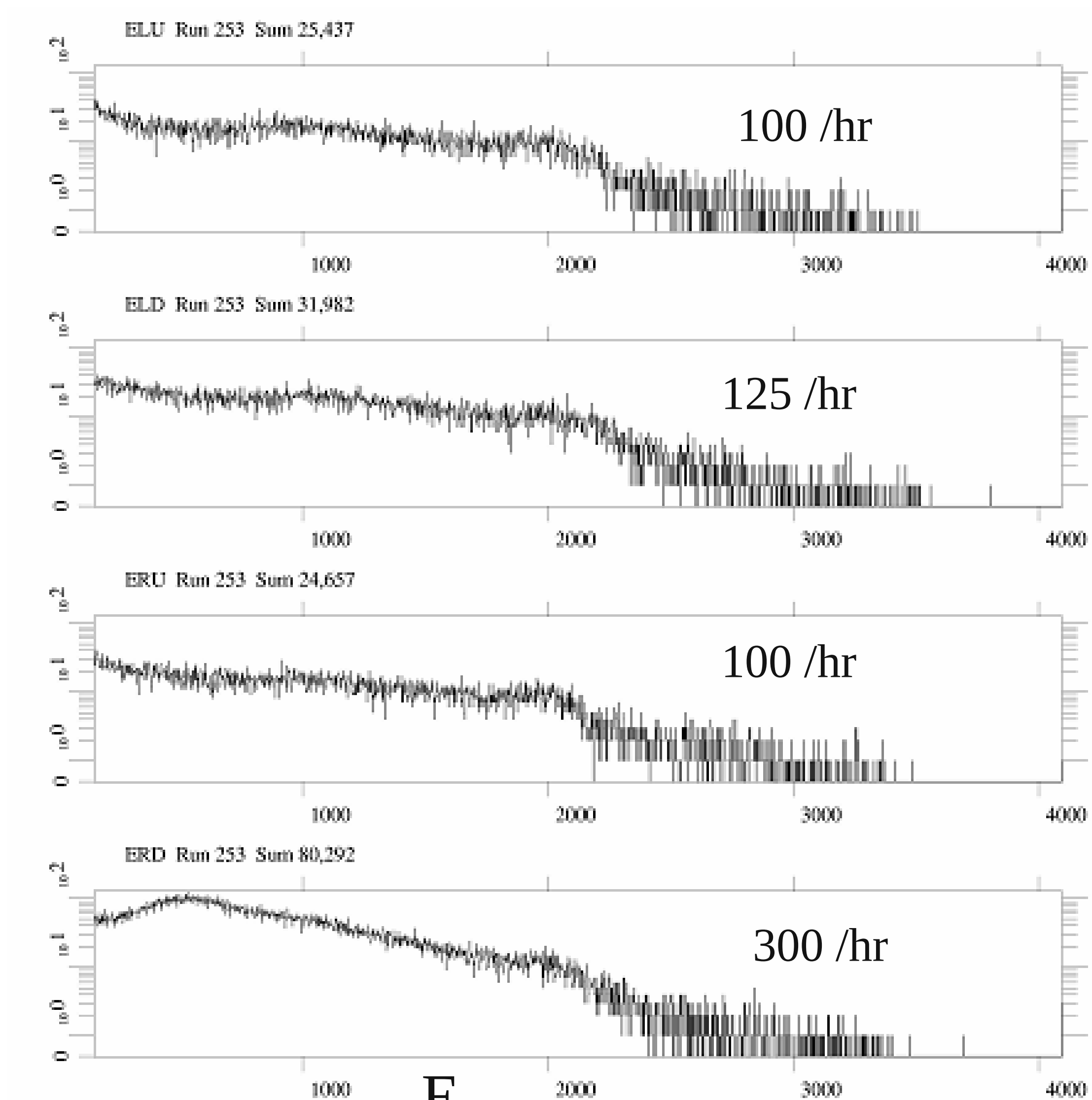
ELU

ELD

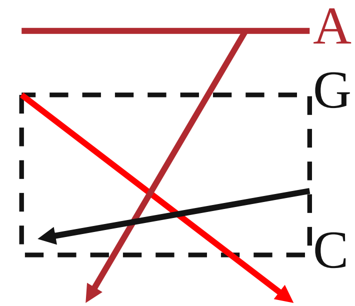
ERU

ERD

counts



E



Al: 16/hr

SS: 12/hr

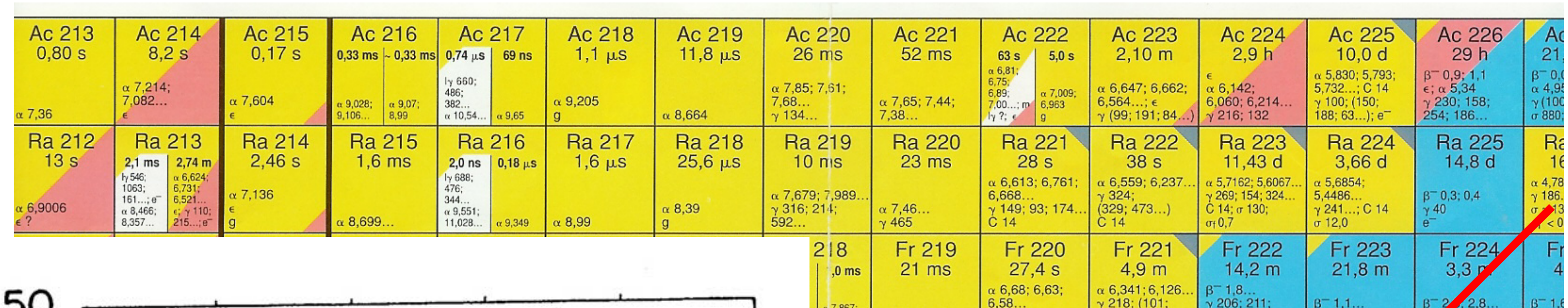
Solder: 240/hr

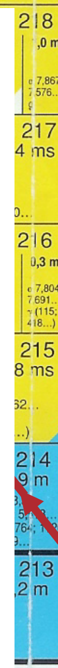
Background in double β decay

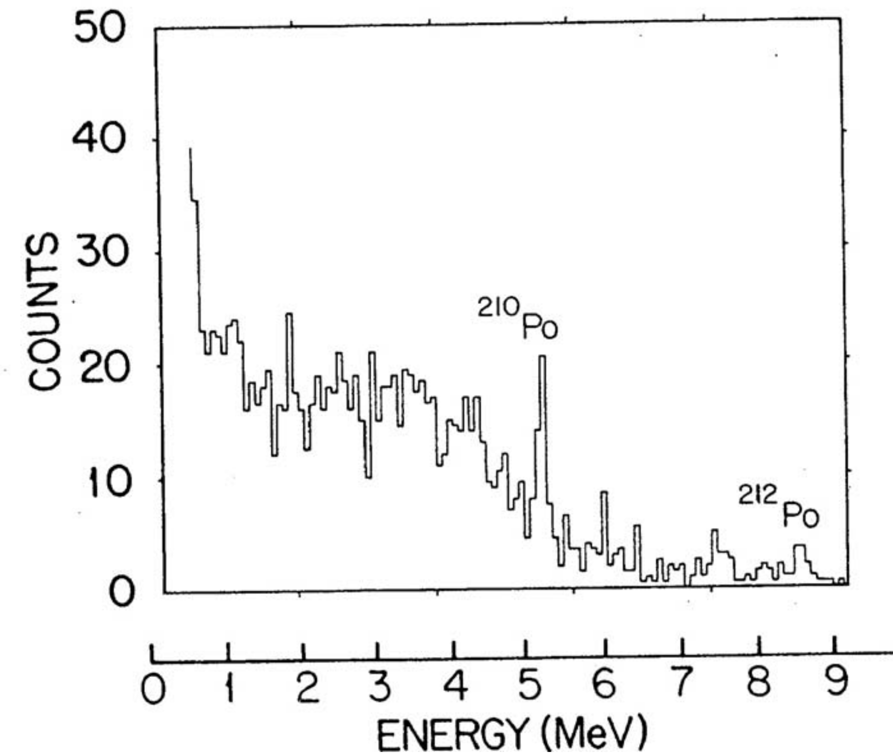
We have discovered a broad peak at 5.2 MeV with its leading edge at 5.3 MeV followed by a significant continuum. A similar peak has been observed in the UCSB-LBL detector[31] at 5.1 MeV and has been attributed to a Doppler broadened line produced by the reaction $^{28}Si(n,n\gamma)^{28}Si$. We have been successful in reproducing our line at 5.2 MeV in a simple laboratory experiment. When soft solder is melted, the ^{210}Po, from the sequential decays of ^{210}Pb and ^{210}Bi, concentrates on the surface of the bead. After melting and solidifying several beads of solder, α spectra from their surfaces observed with a surface barrier detector were also found to contain this peak. The same phenomenon was observed in the UCI (University of California, Irvine) time projection chamber, and

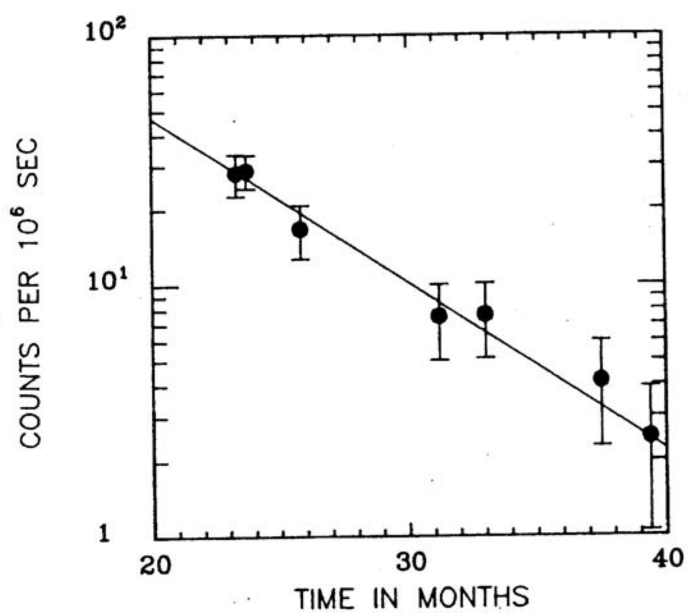
T. Avignone et al. PRC 34,666(1986)

^{210}Po background









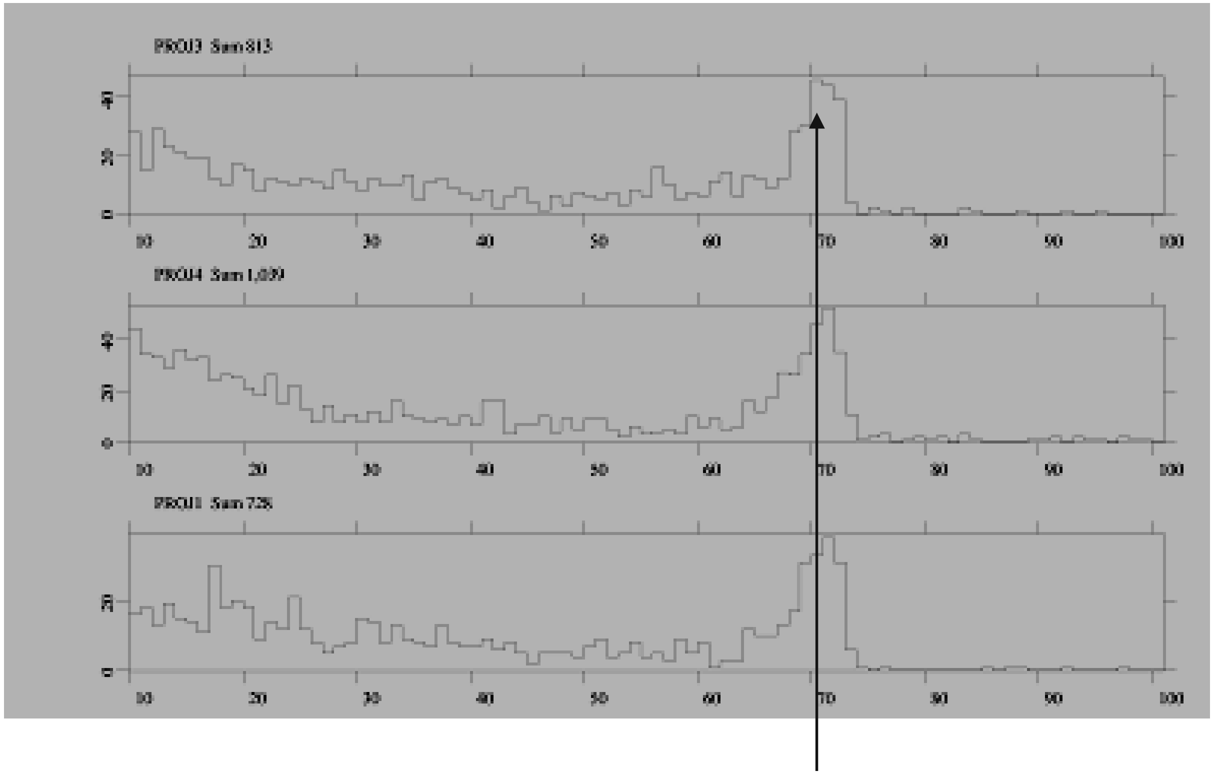
Alpha background (2.5x10^4 s)

P=760 Torr

ELU 130/hr

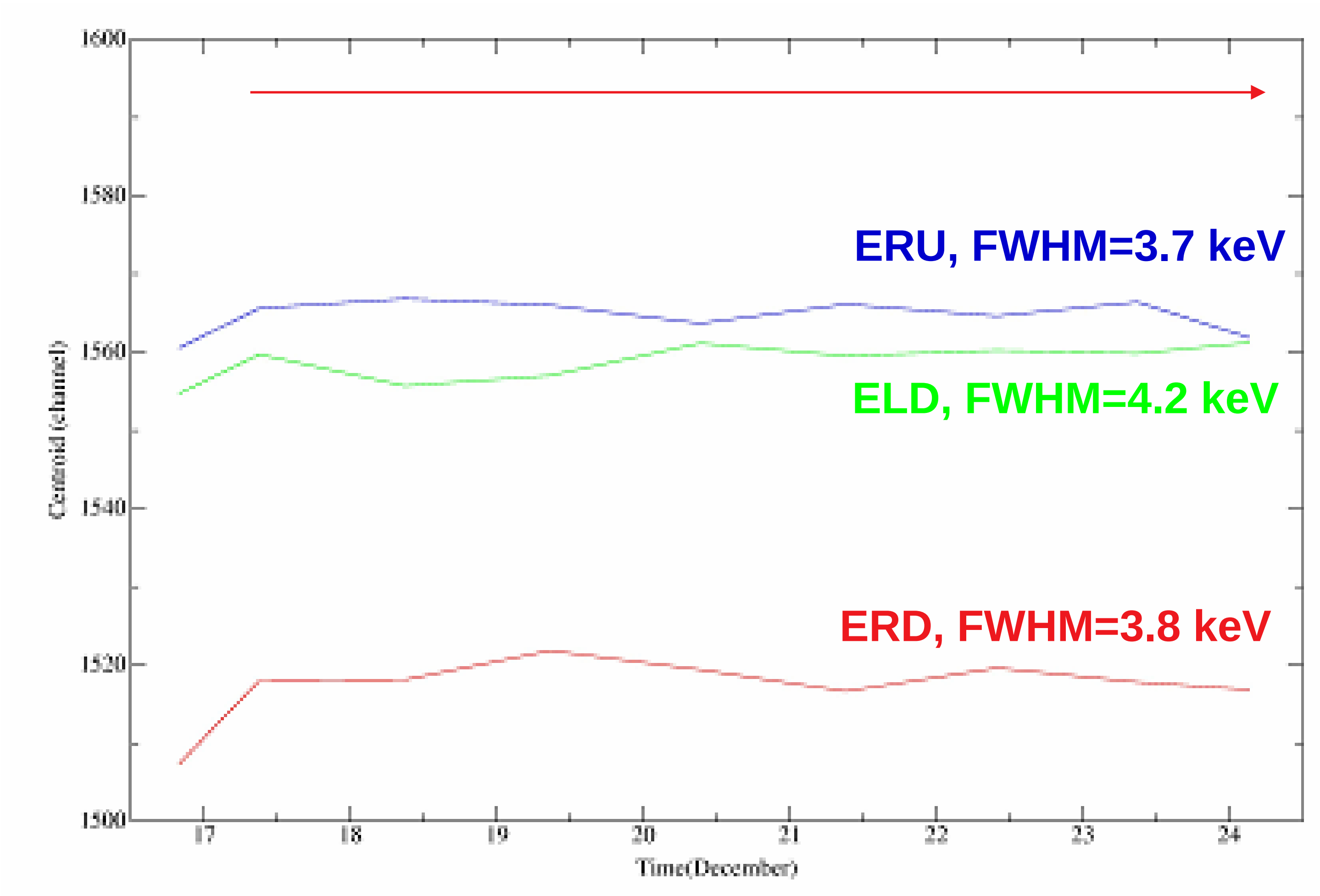
ELD 170/hr

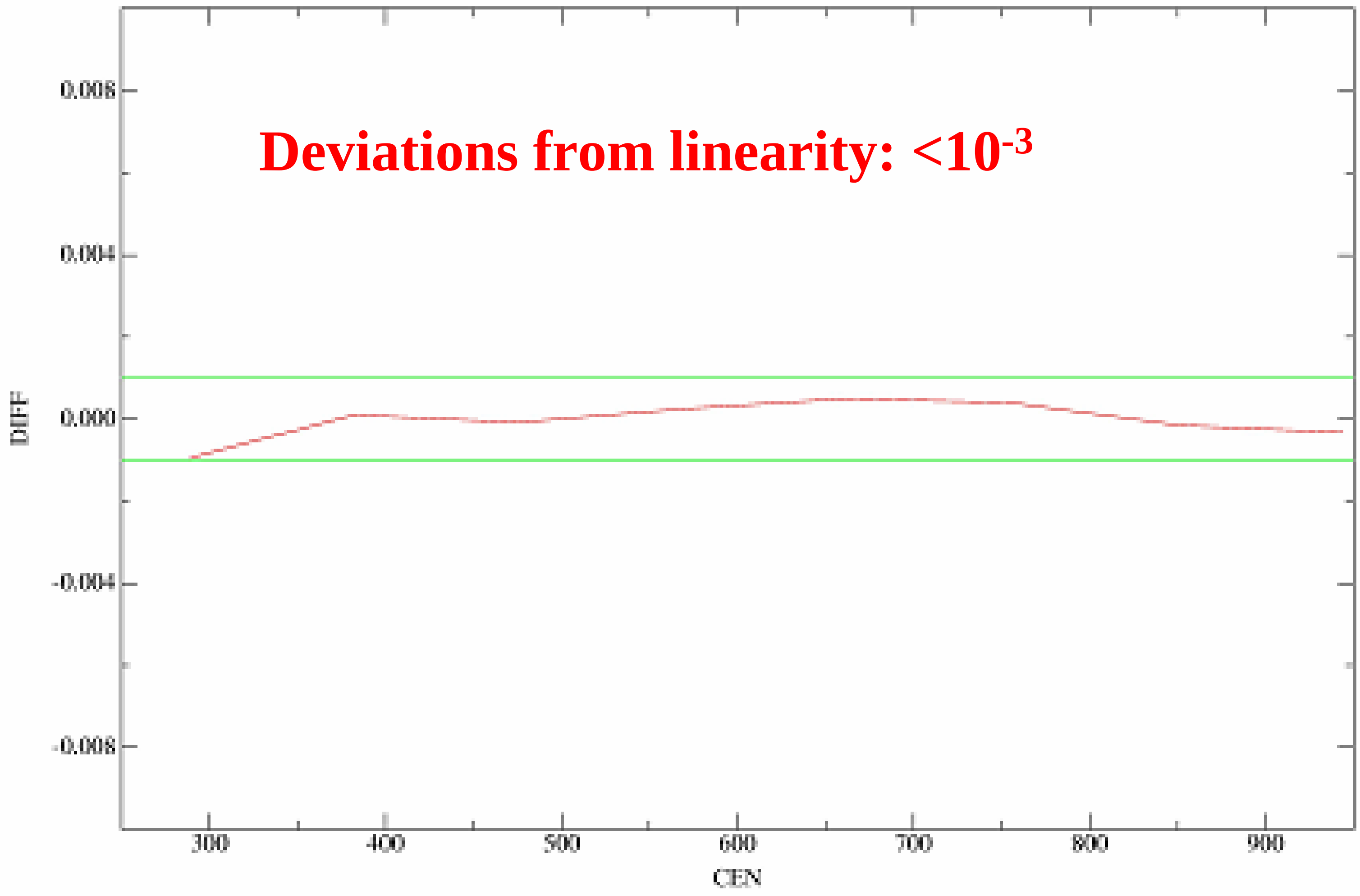
ERU 110/hr



~5.2 MeV

Long-time stability of ionization chambers





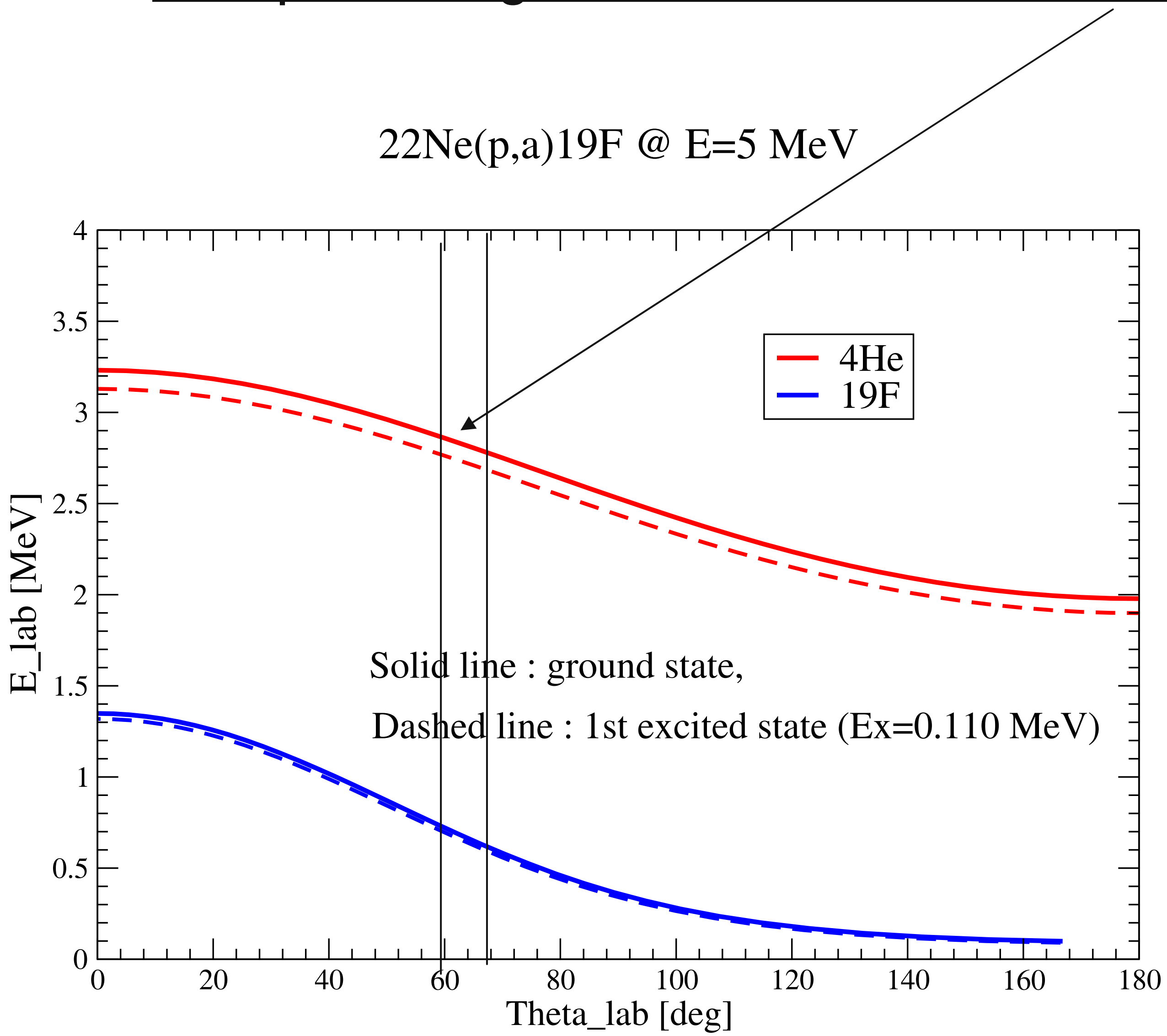
Deviations from linearity: <10-3
0.008
0.004
0.000
-0.004
-0.008
DIFF
300
400
500
600
700
800
900
CEN

Advantages/disadvantages of ionization chambers

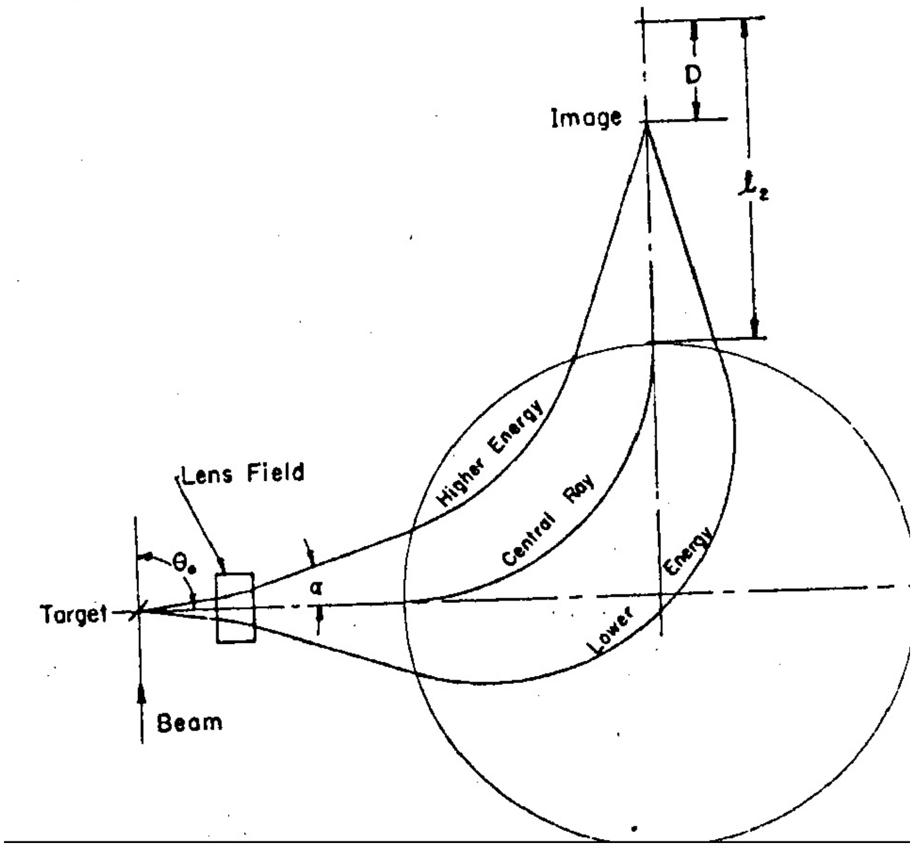
- \+ can be optimized for application
- \+ available in large sizes
- \+ can be built very thin and homogeneous
- \+ good energy resolution and stable
- \+ inexpensive
- \+ hard to destroy
- \- poor time resolution (add timing detector)
- \- need good entrance foils (see next lecture)
- \- choose special Pb-free solder

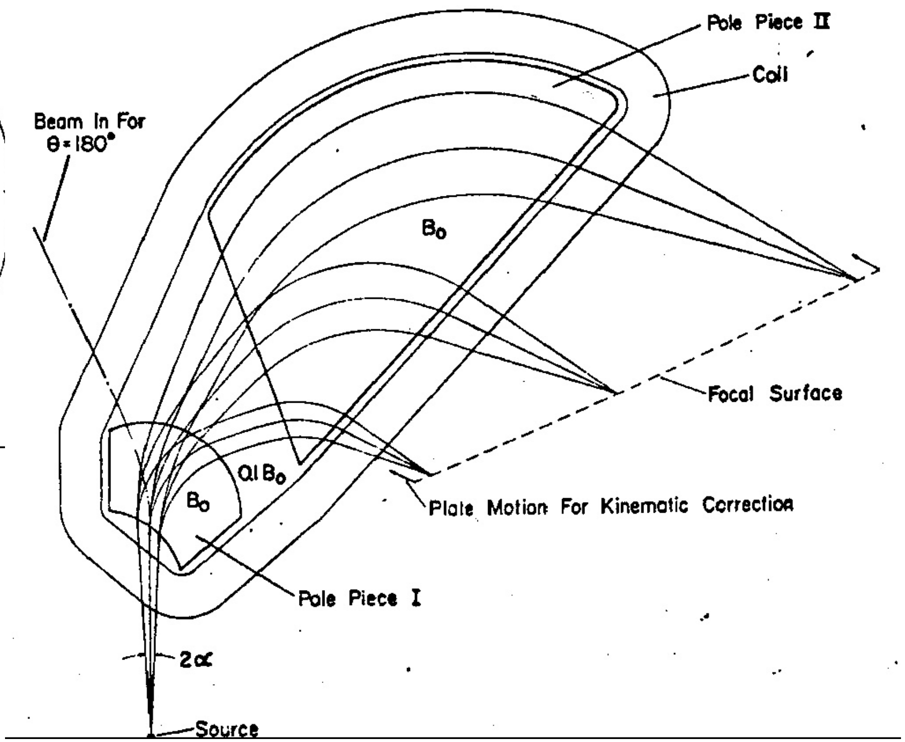
Magnetic Spectrographs

Compensating the kinematic shift dE/dϑ



Compensating the kinematic shift in a magnetic spectrometer



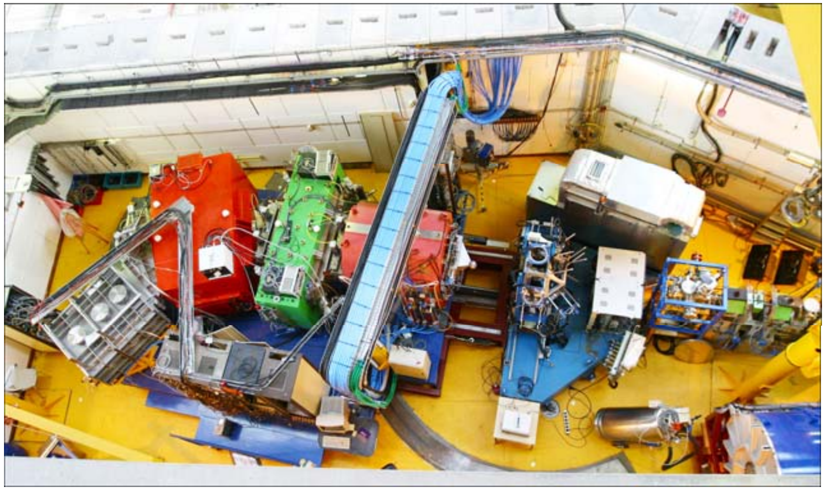


Large Acceptance Spectrometers – Recent Examples:

(identification of exotic nuclei, coincidence studies)

MAGNEX (Catania)

PRISMA(Legnaro)



VAMOS (GANIL)

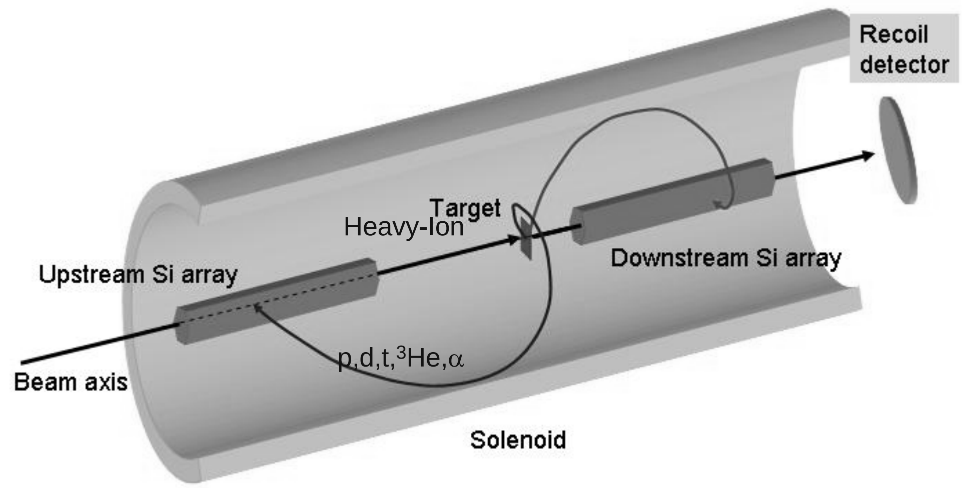
Ω<100 msr

Advantages/disadvantages of magnetic spectrometers

- + can compensate for kinematic shifts
- + best energy resolution
- + good count rate capabilities
- + good particle separation (m and Z) (see lecture II)
- - large and expensive
- - small solid angle (< 100 msr)

HELIOS spectrometer , a new spectrometer for 'inverse reactions'

Inverse kinematics



Measured quantities

Flight time: $T_{flight} = T_{cyc}$

Position: z

Energy: E_{lab}

Derived quantities

Part. ID: m/q

Energy: E_{cm}

Angle: θ_{cm}

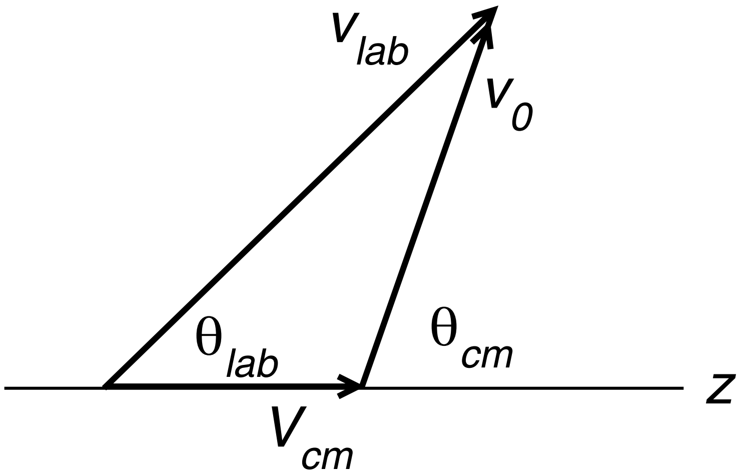
$$\frac{m}{q} = \frac{eB}{2\pi} \times T_{flight}$$

$$E_{cm} = E_{lab} + \tfrac{1}{2} m V_{cm}^2 - \frac{V_{cm} qeB}{2\pi} z$$

$$\theta_{cm} = \arccos\left(\frac{1}{2\pi} \frac{qeBz - 2\pi m V_{cm}}{\sqrt{2mE_{lab} + m^2 V_{cm}^2 - mV_{cm} qeBz / \pi}} \right)$$

Field: 3 Tesla	
Particle	**T_{cyc} (ns)**
p	**21.8**
d,α	**43.6**
t	**65.7**
^{3}He	**32.8**

Simple kinematics



$$z = v_{\parallel} T_{cyc} = (V_{cm} + v_0 \cos\theta_{cm}) T_{cyc}$$

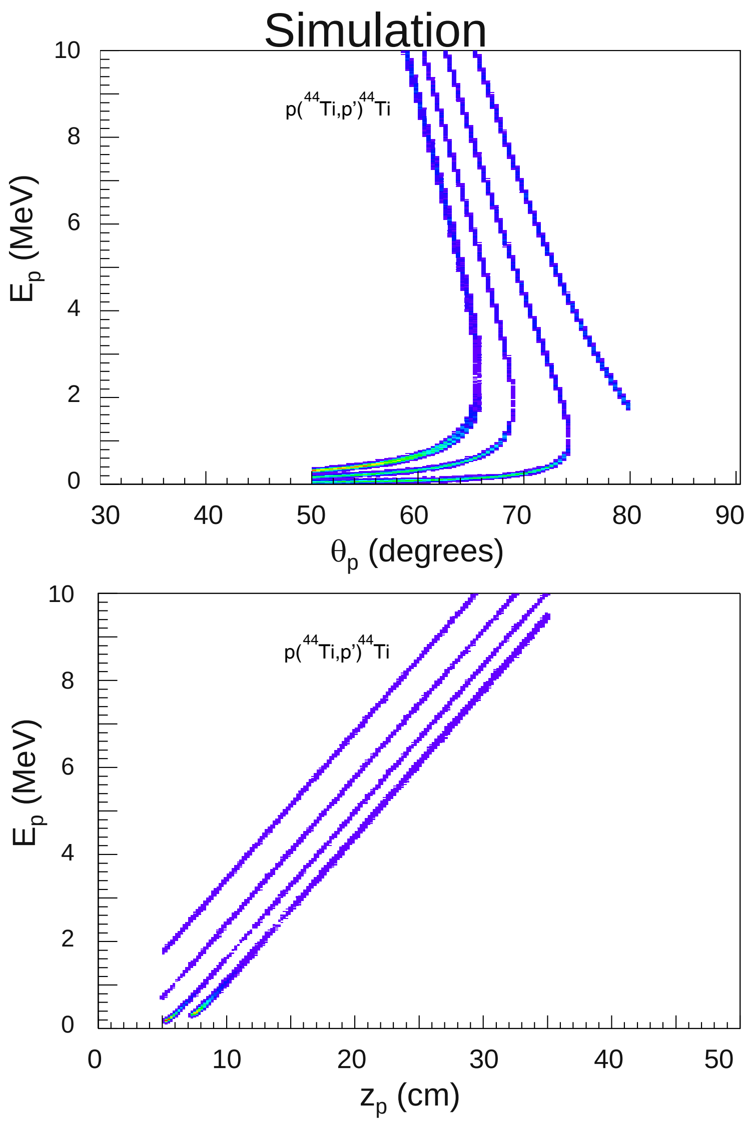
$$\Rightarrow v_0 \cos\theta_{cm} = \frac{z}{T_{cyc}} - V_{cm}$$

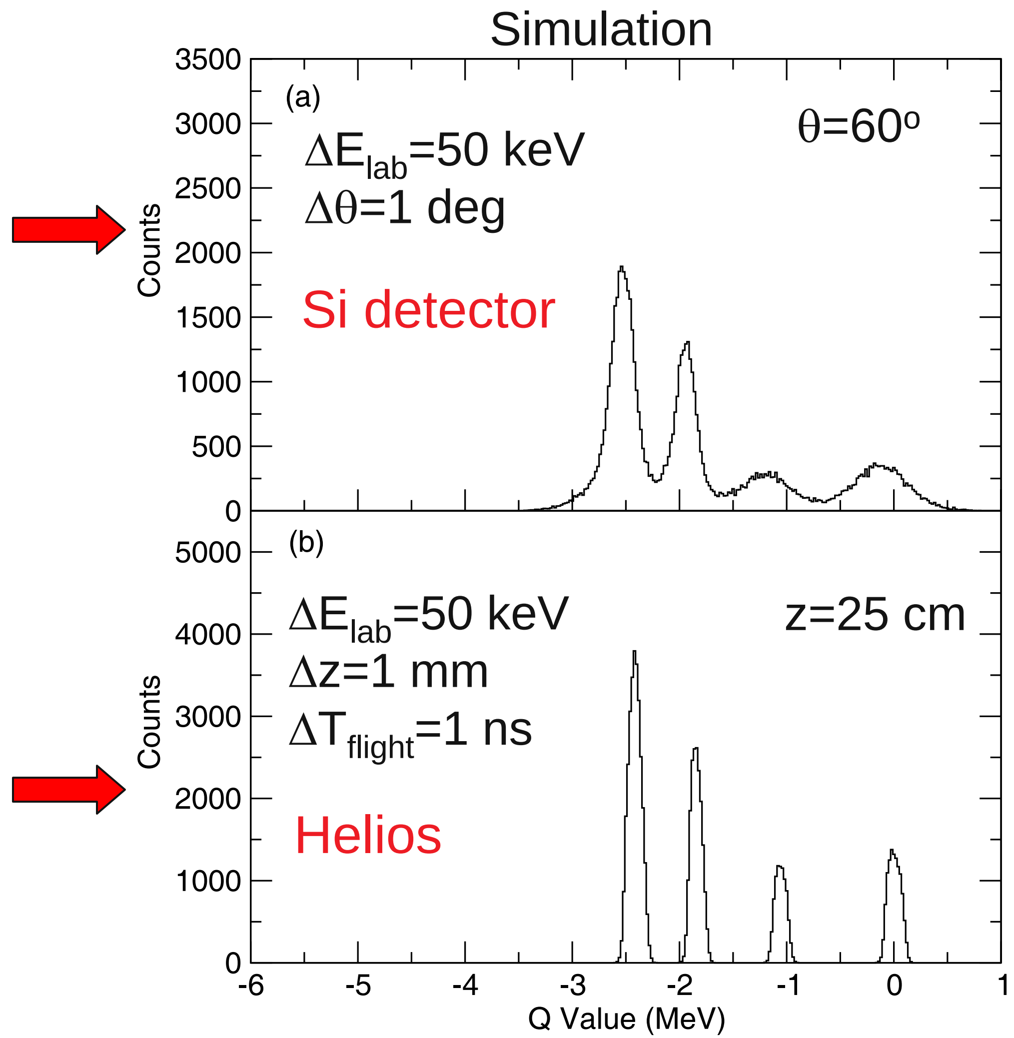
$$E_{lab} = \frac{m}{2}\left[v_{\parallel}{}^2 + v_{\perp}^2\right] = \frac{m}{2}\left[(v_0 \cos\theta_{cm} + V_{cm})^2 + v_0{}^2 \sin^2\theta_{cm}\right]$$

$$= \frac{m}{2}\left[v_0{}^2 \cos^2\theta_{cm} + V_{cm}^2 + 2 v_0 V_{cm} \cos\theta_{cm} + v_0{}^2 \sin^2\theta_{cm}\right]$$

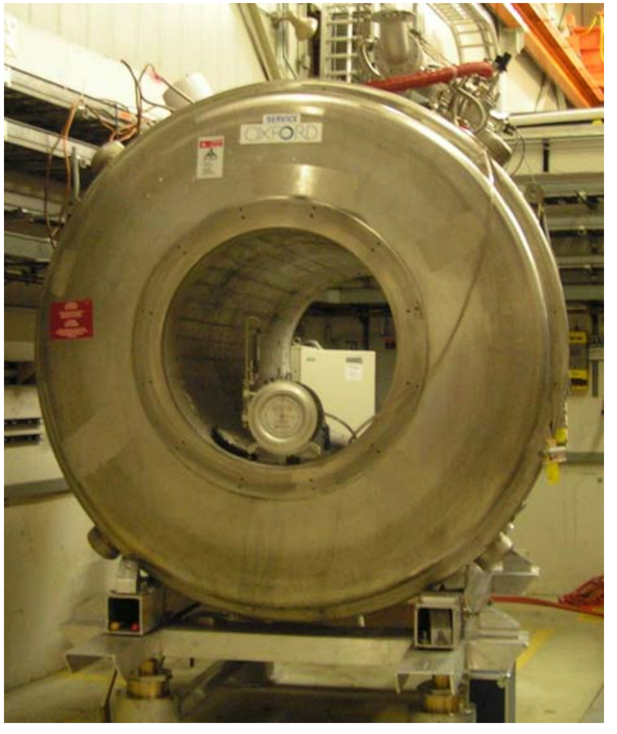
$$= E_{cm} - \frac{m}{2} V_{cm}^2 + \frac{m V_{cm} z}{T_{cyc}}$$

$p(^{44}Ti,p')^{44}Ti$ kinematics





High Efficiency Spectrometers



Superconducting Solenoid (Transfer Reactions in inverse Kinematics)

$^{132}Sn(d,p)^{133}Sn$ kinematics