Resonance Scattering Technique and break-up to study nuclear structure

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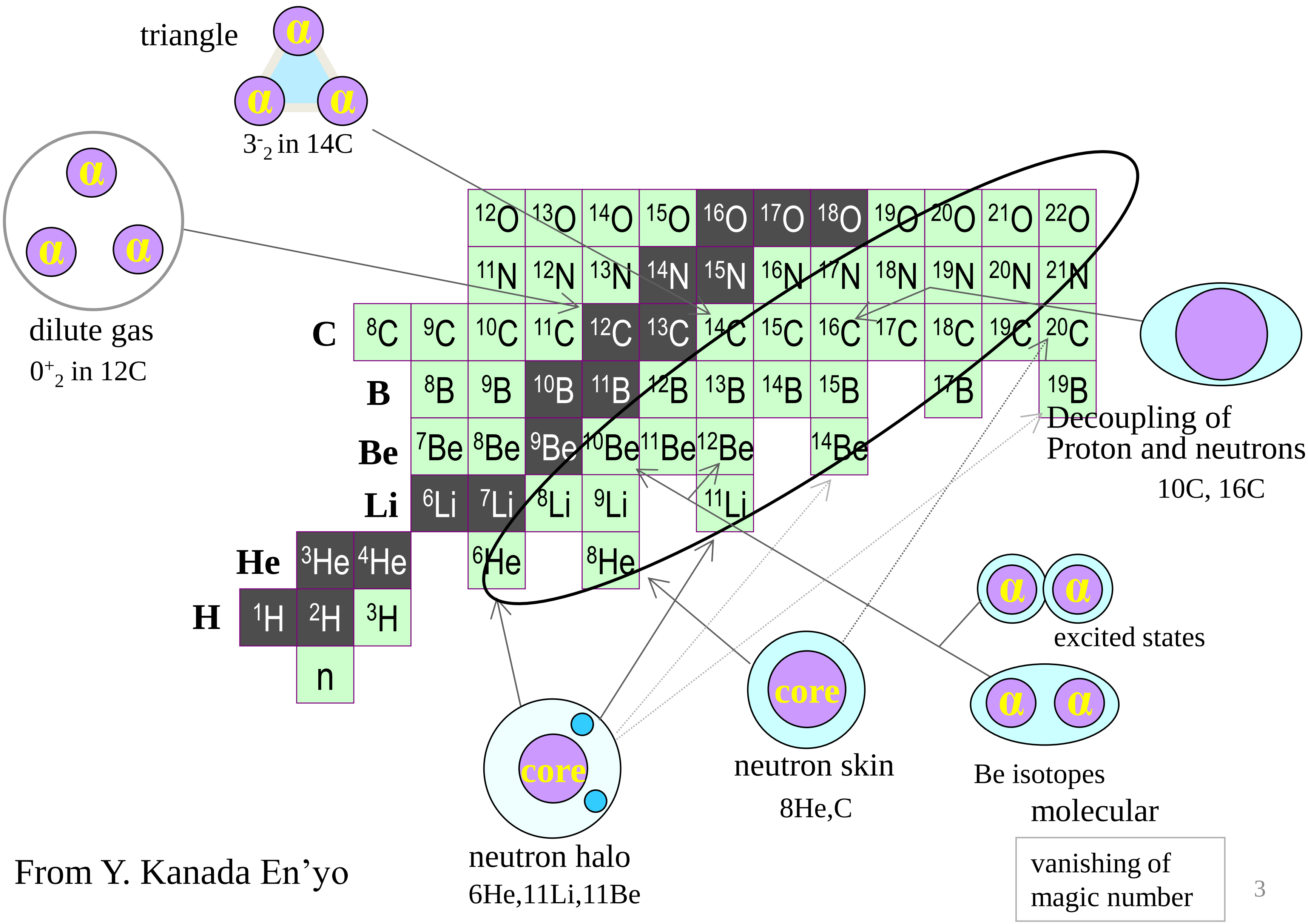
Outline of the lecture:

- **Resonance scattering method in reverse kinematics.**
- **Advantages of the technique.**
- **Resolution. Discrimination of different processes and energy reconstruction.**
- **Resonant break-up**
- **3-body kinematics**

Exotic structures in light nuclei



From Y. Kanada En'yo

Conventional cluster structure

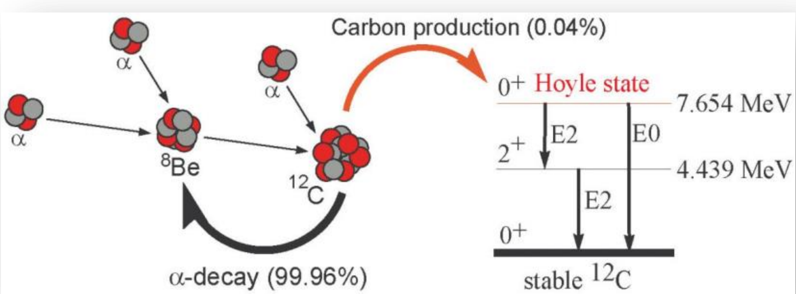
Cluster structure is a well established feature of many light N≈Z nuclei both in their ground and excited states.

Weak coupling picture:

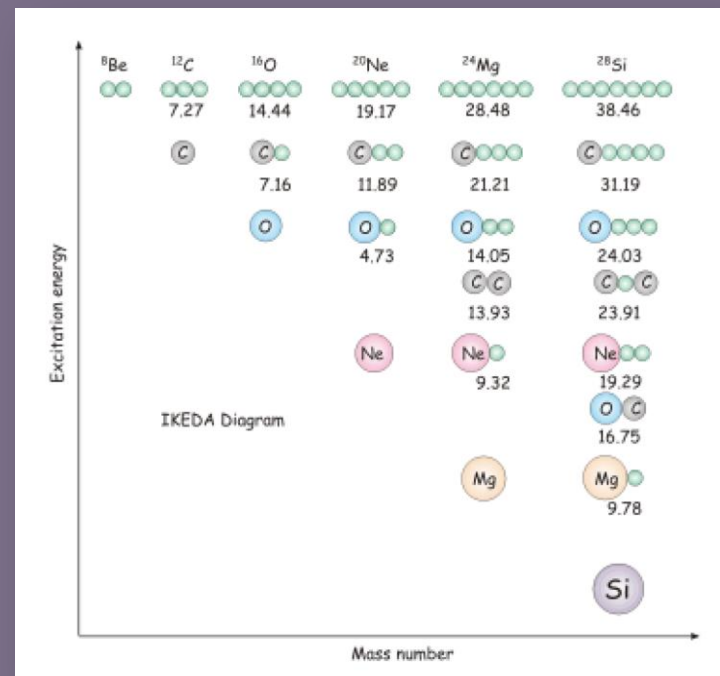
1. Clusters are formed by tightly bound nucleons (cluster is stiff, i.e. not easy to excite);
2. Weakly coupled inter-cluster motion is considered.

Threshold rule: i.e. these states appear close to the threshold for breaking-up into the cluster constituents.

Ex. Hoyle state in ^{12}C



Ikeda diagram



K. Ikeda et al. Supp.Progr.Theo.Phys. 68(1980)1

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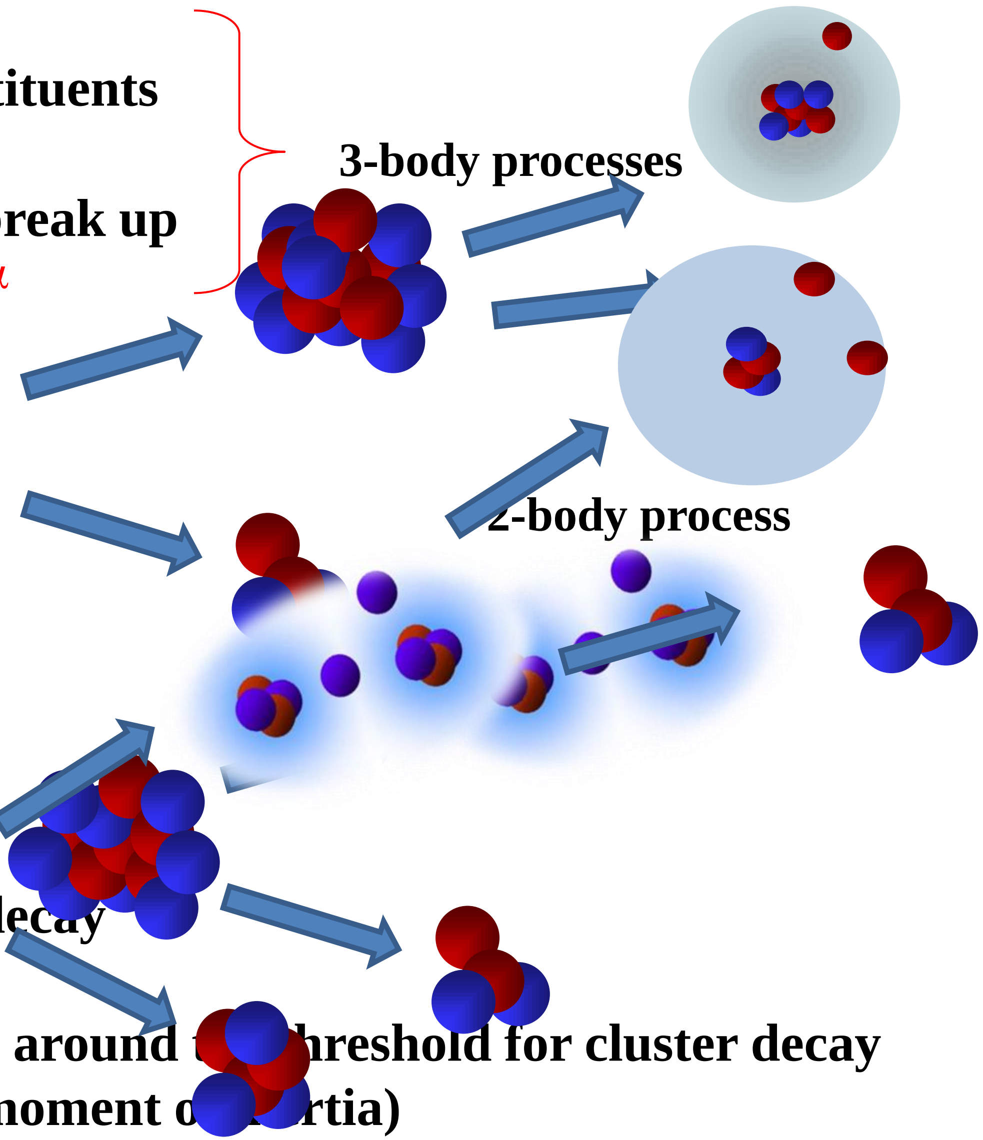
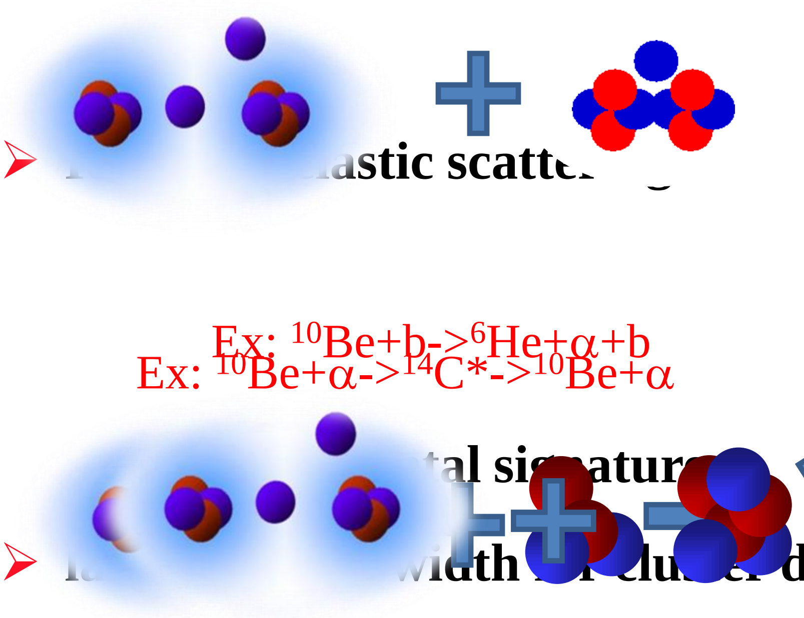
Possible ways to study cluster structures:

- **transfer and decay into the constituents**
- **inelastic scattering followed by break up**

  Ex: $^{10}Be+^{9}Be \rightarrow ^{15}C^{*}+\alpha \rightarrow ^{11}Be+\alpha+\alpha$





- **…astic scatte…**

  Ex: $^{10}Be+b \rightarrow ^{6}He+\alpha+b$

  Ex: $^{10}Be+\alpha \rightarrow ^{14}C^{*} \rightarrow ^{10}Be+\alpha$

- **…tal si…atur…**
- **…idth … clu…er decay**
- **rotational bands with band head around t…hreshold for cluster decay (measurement of E_{exc} and $J^{\pi} \rightarrow$ moment o…rtia)**

Resonant scattering method (RSM) in invese kinematics

K.P.Artemov et al. Sov.J.Nucl.Phys. 52(1990)408

Elastic scattering of heavy projectiles **B** on a light targets **b** (protons or αs) in order to study properties of the compound nucleus C resulting from

$$\mathbf{B+b \rightarrow C \rightarrow B+b}$$

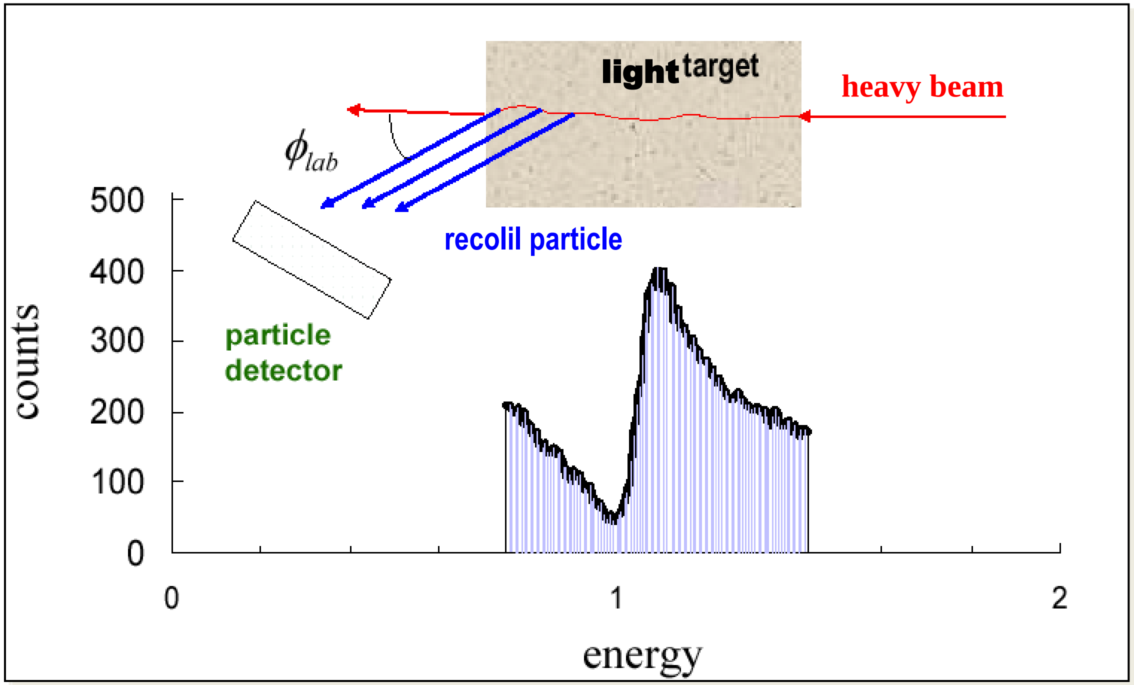
Excitation function measured at $\theta_{cm} \approx 180^o \Rightarrow$ enhanced visibility of resonances with respect to potential and Coulomb scattering.

- thick solid or gasous target
- gaseous target (H, He)

easy to change target thickness (changing gas pressure)

more homogeneous target

Used in the last ten years to measure excitation functions with radioactive beams.



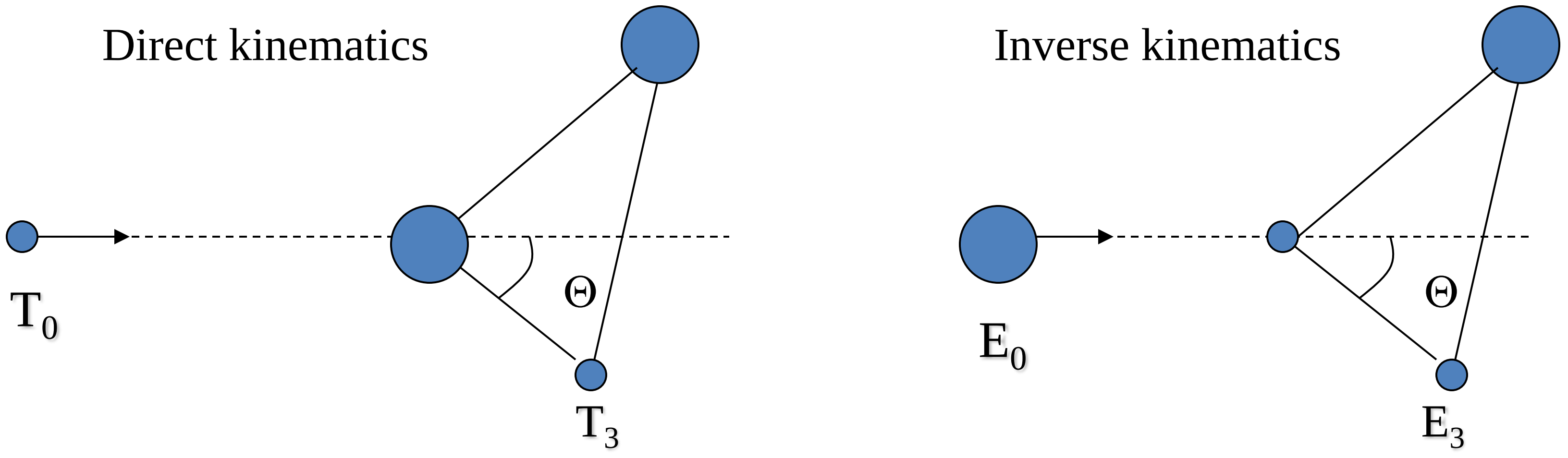
- Very useful in experiments with low intensity beams ($10^4 \div 10^6$ pps).

  ➡ Allows to measure excitation function in a wide energy range without changing beam energy ➔ reduces running time of the experiment

  ➡ Allows precise measurement of resonance properties: **E_r, J^π, Γ_{tot}, Γ_p, Γ_α**

  ➡ Allows to measure recoil particles around $\theta_{c.m.}$~180°

Advantages of using inverse kinematics



E_0 e T_0 = laboratory projectile energy in direct and reverse kinematics respectively

E_0' e T_0' = c.m. energy in direct and reverse kinematics respectively

Θ =laboratory scattering angle of light particle

E_3 e T_3 = light particle laboratory energy in direct and reverse kinematics respectively

Some trivial equations (see previous lecture)

$$T_0' = T_0 \frac{M}{m+M}$$ direct

$$E_0' = E_0 \frac{m}{m+M}$$ inverse

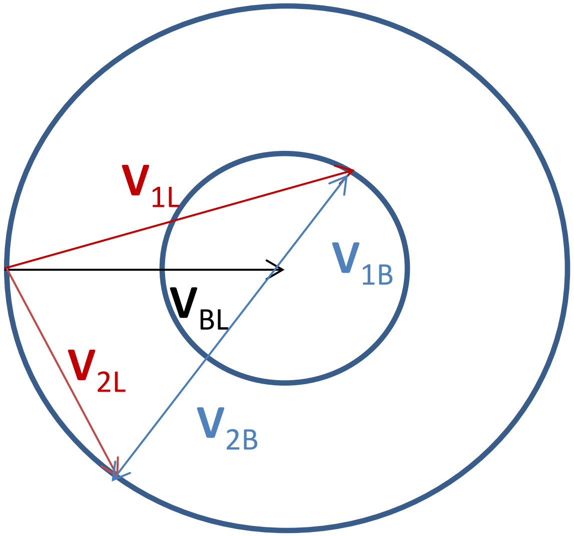
For the same c.m. energy:

$T_0' = E_0'$ ⟶ $$\frac{E_0}{T_0} = \frac{M}{m} \equiv k$$

For: $\theta_{lab} = 0°$ (= 180° in the c.m.)$\Rightarrow$ light particle enrgy is:

$$T_3 = T_0 \left(\frac{m}{m+M} \right)^2 (k+1)^2$$

$$E_3 = 4E_0 \frac{mM}{(m+M)^2}$$



In the current notation :

$E_3 = E_{2L}$ recoil energy in the Lab system
$E_{1L} = E_0$ projectile energy

$$E_3 = E_{2L} = \frac{1}{2} m V_{2L}^2 = \frac{1}{2} m (V_{BL}^2 + V_{2B}^2 - 2 V_{BL} V_{2L} \cos\theta_{1B}) =$$

$$= \frac{1}{2} m 4 V_{BL}^2 = 4 \frac{1}{2} m V_{BL}^2 \qquad \text{at } \theta_{1B} = 180°$$

$$E_{cm} = \frac{m}{M+m} E_{1L}$$

$$E_{cm} = \frac{1}{2} \frac{mM}{m+M} V_{BL}^2 = \frac{m}{m+M} E_{1L} \Rightarrow \frac{1}{2} m V_{BL}^2 = \frac{mM}{(m+M)^2} E_{1L} \Rightarrow \boxed{E_3 = 4 \frac{mM}{(m+M)^2} E_{1L}}$$

Excitation function from measured recoil energy:

B+b→ C*→B+b

$$E_{ex} = E_{c.m.} + Q = E_0 \frac{m}{M+m} + Q$$

$$\Downarrow$$

$$E_{ex} = \frac{M+m}{4M\cos^2(\theta_{lab})} E_3 + Q$$

Laboratory energy resolution for light recoil particles in inverse kinematics.

$$\varepsilon = \Delta E \frac{\left(\dfrac{dE}{dx}\right)_{li}}{\left(\dfrac{dE}{dx}\right)_{HI}} \approx \frac{\Delta E}{4} \frac{z^2}{Z^2}$$

ΔE=beam energy straggling in the laboratory

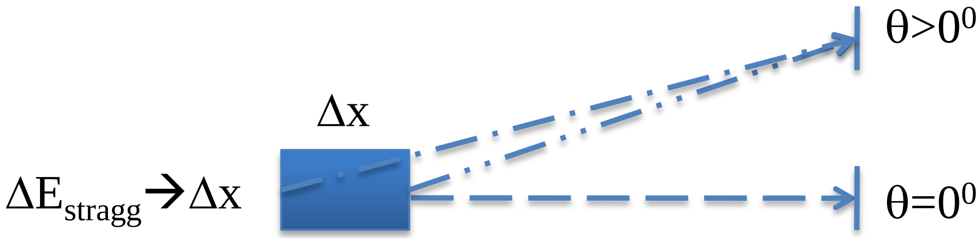
$(dE/dx)_{li}$= stopping power for light particles

$(dE/dx)_{HI}$= stopping power for beam particles

z= charge of light recoil particles

Z=charge of beam particles

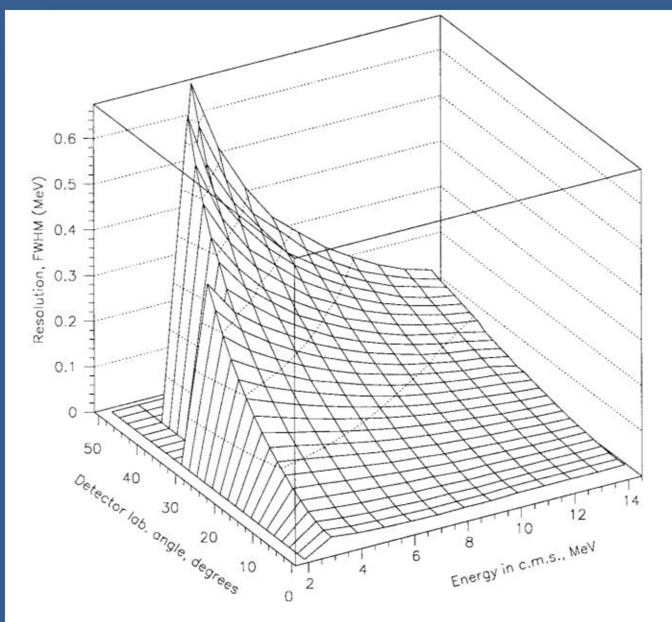
Dependence of energy resolution from energy straggling



Due to energy straggling, to the same $E_{c.m.}$ correspond different $E_{det.}$ due to different paths.
Effect larger at $\theta > 0^0$ due to additional contribution of different scattering angles.

$^{32}S + \alpha$

G. Rogachev Ph.D thesis. Moscow1999



Energy resolution depends also from:

- Beam spot size
- Detector energy resolution
- Detector angular resolution
- Kinematical spread within $\delta\theta$
- Beam angular straggling
- Recoil angular straggling (small)

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Problems of using this technique:

- Sources of background ⇒ inelastic scattering events

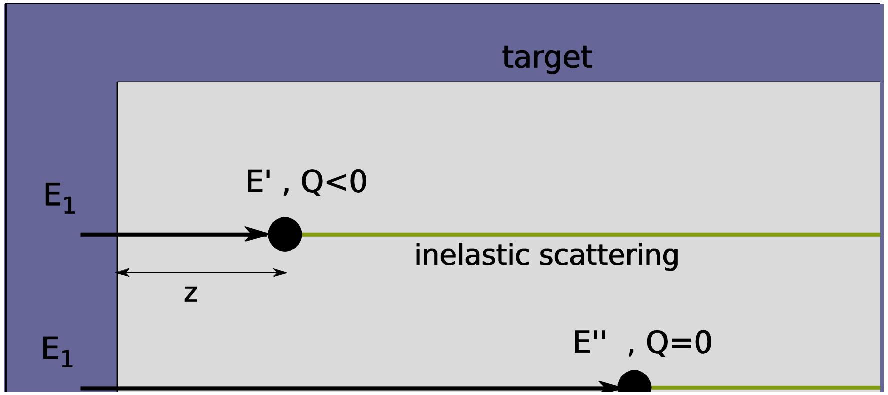
- Precise knowledge of stopping power to extract correctly the resonance parameters

⤷ **Need to measure de/dx with radioactive beams (but not only!)**

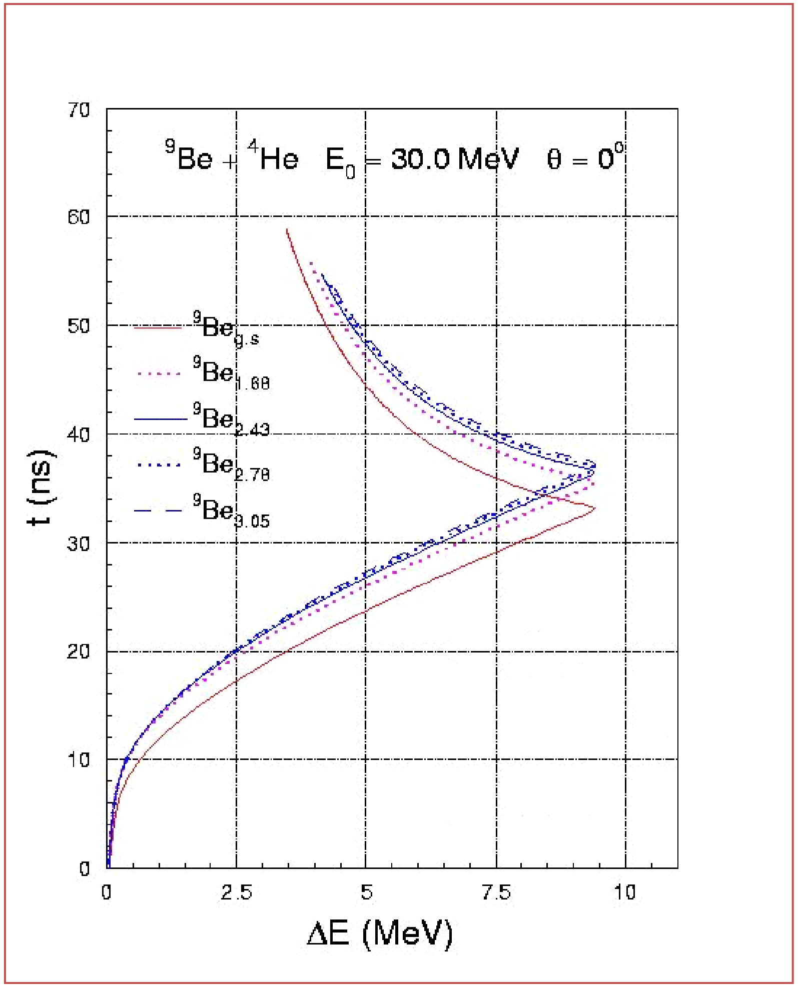
How to discriminate elastic from inelastic scattering events?

✓**From α or p spectrum no possibilities to discriminate the process which produces recoil particles.**

✓ **In experiment with a gasous extended target is possible to discriminate elastic from inelastic from time of flight measurement or tracking (active targets).**



Example: $^{9}Be + ^{4}He$



Calculated T_{tOF}- ΔE 2d-spectrum

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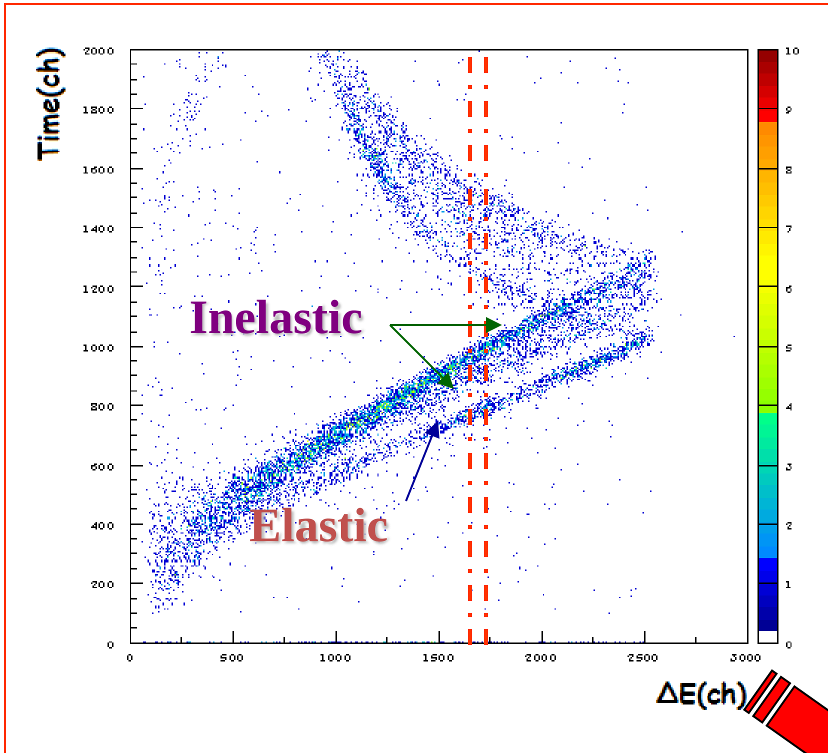
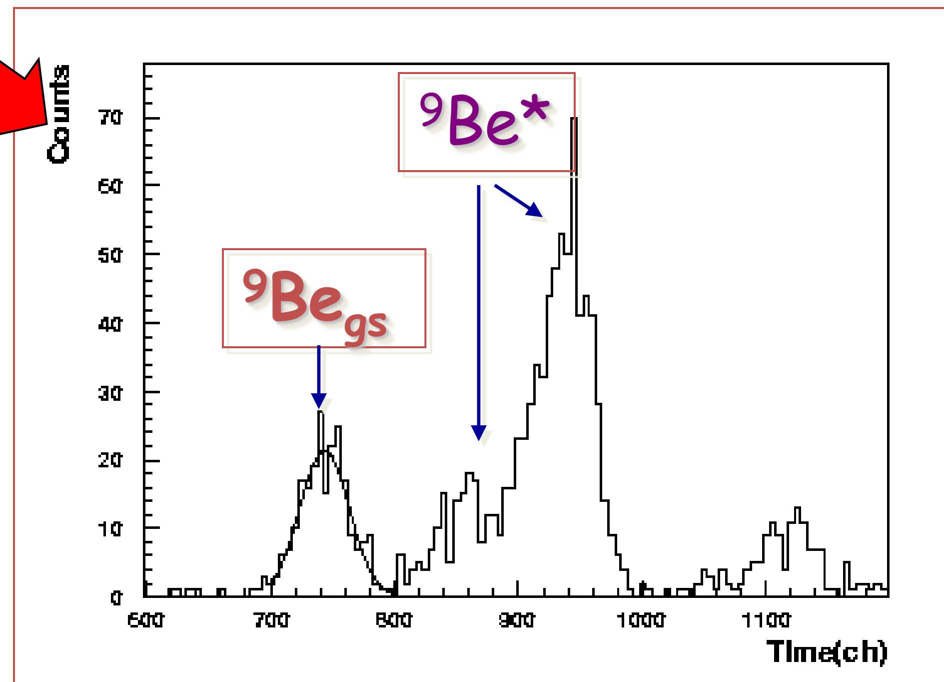


Experimental Ttof-ΔE
2d-spectrum

Projecting on time axis



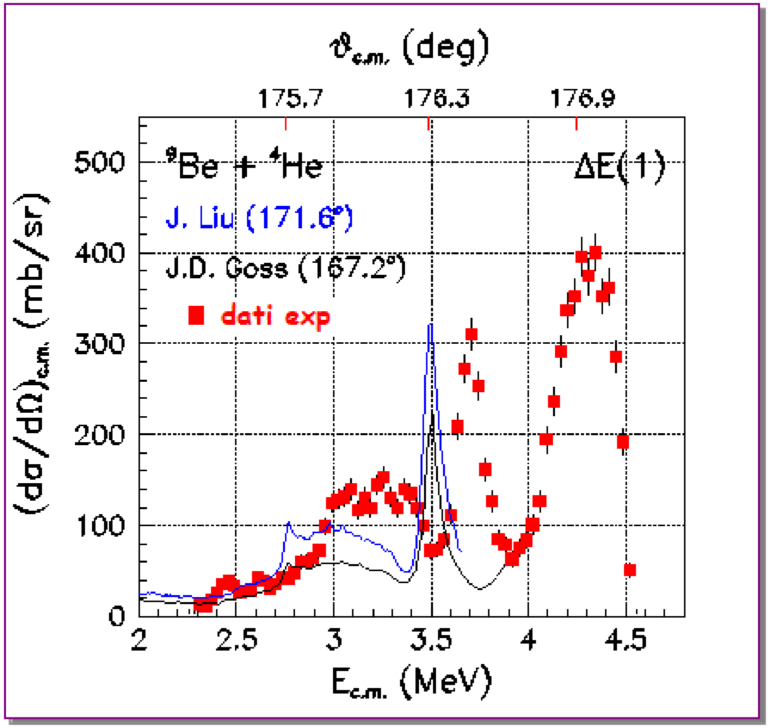
Time resolution ΔT~1 ns

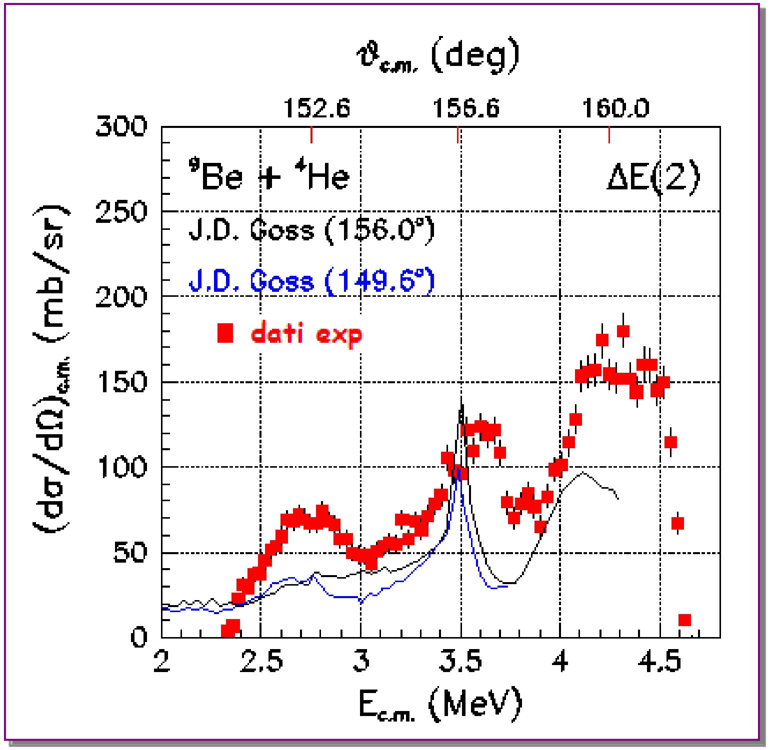
Problems with stopping power calculations.

Excitation function $^{9}Be+^{4}He$ at E_{cm}<4.5MeV

■ **Excitation function <u>$^{9}Be + \alpha$</u> with RSM on infinite target and energy loss calculated using Monte Carlo code SRIM** M. Zadro et al, NIM B259 (2007).

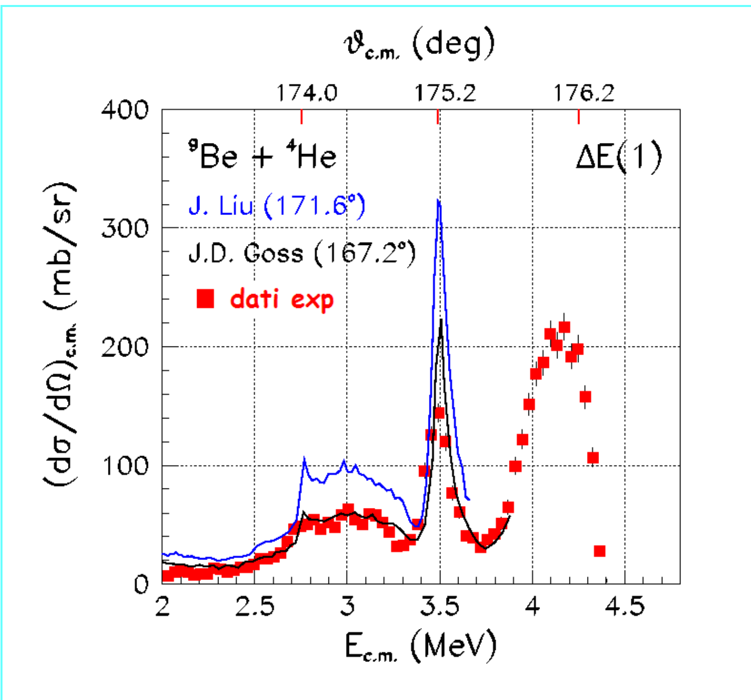
— **Excitation function <u>$\alpha+^{9}Be$</u> measured with thin target method varying beam energy at small streps** **J. Liu [NIM B 108,(1996) 247] , J.D. Goss [PRC 7,(1973) 247]**

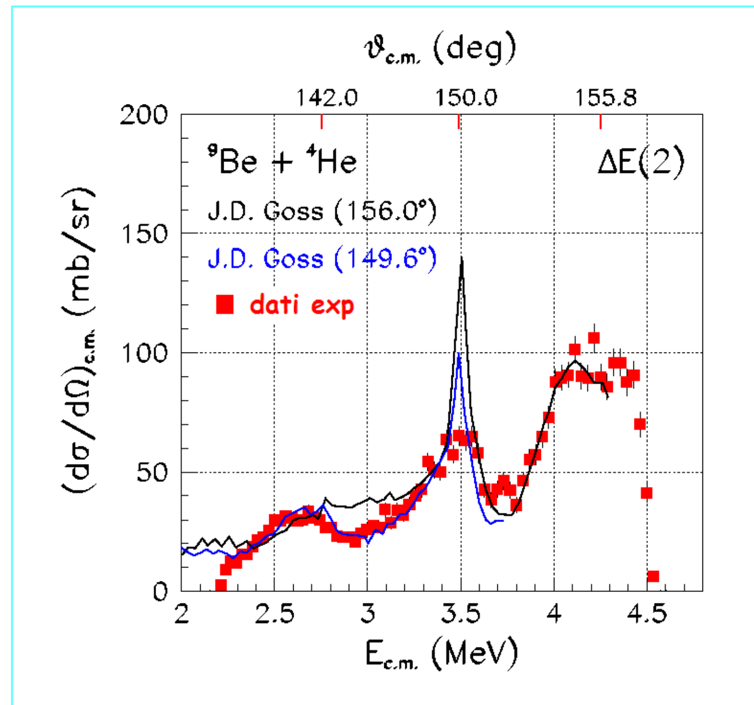




Different energy resonance with the two techniques !

Using measured energy loss data

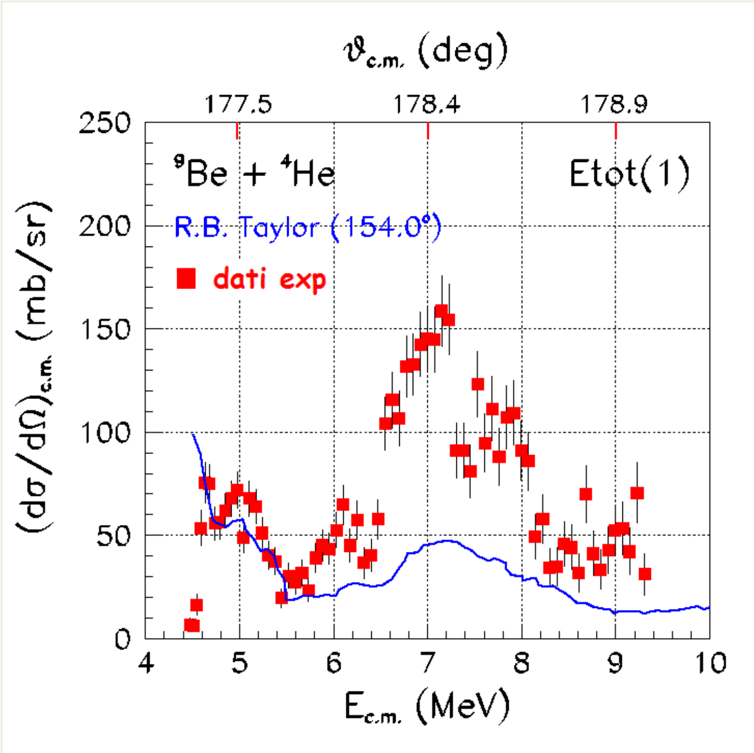


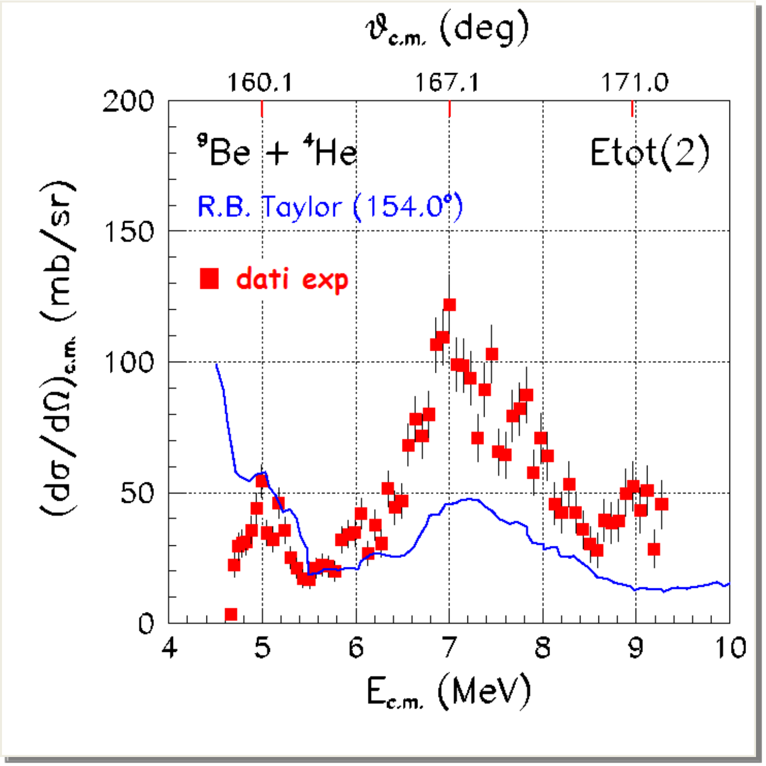


Note: changing stopping power date changes also extracted resonance cross-section

Excitation function $^{9}Be+\alpha$ at $E_{cm}>4.5$ MeV

Using measured energy loss data





■ **Excitation function $^{9}Be + \alpha$ with RSM on infinite target** M. Zadro et al, NIM B259 (2007).

— **Excitation function $\alpha + ^{9}Be$ measured with thin target method varying beam energy at small streps** R.B.Taylor [NP 65,(1965) 318]

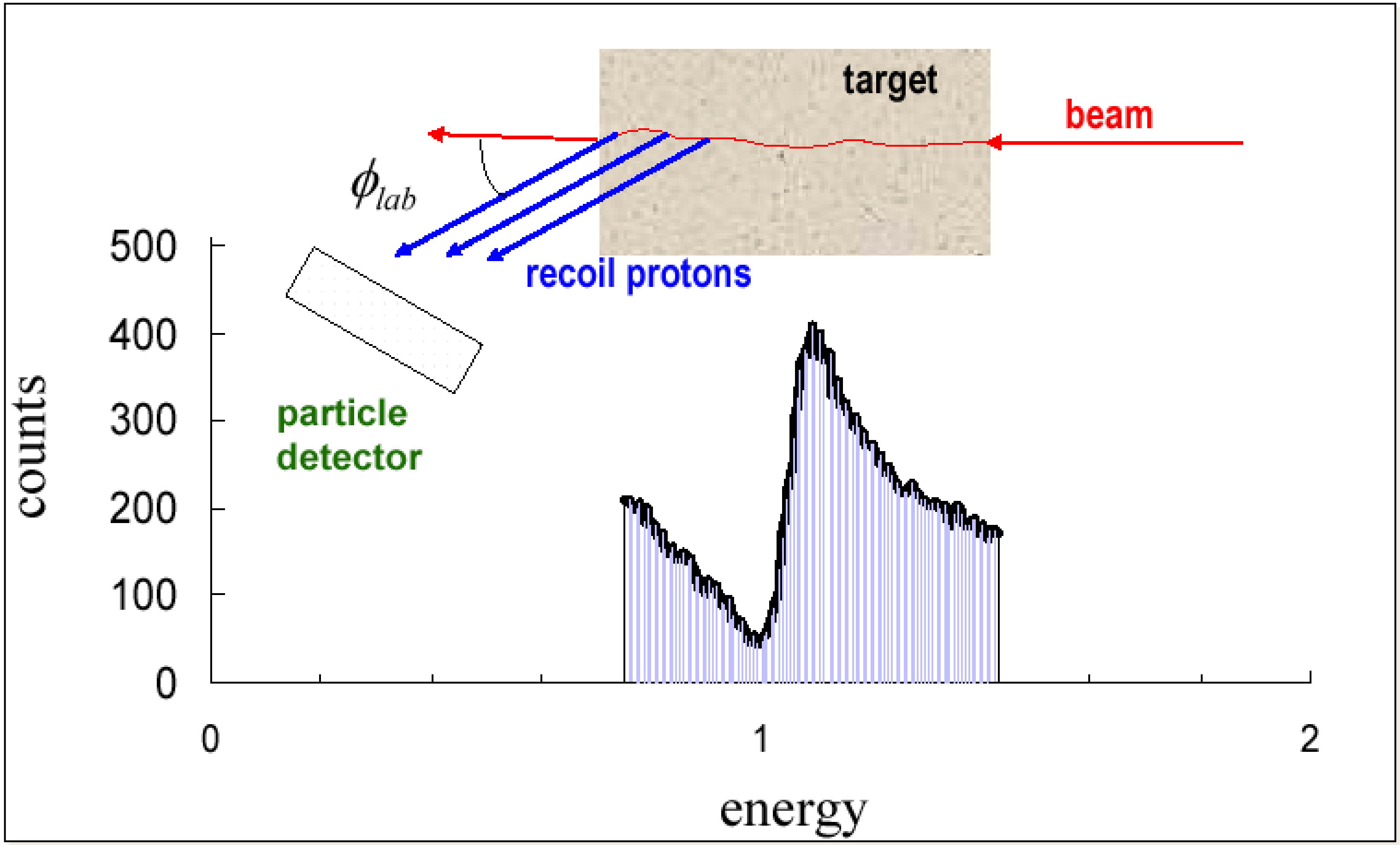
Need to measure stopping power with RIBs but not only!

Some example of experiments performed using RIBs and RSM technique.

Level scheme of p-rich nuclei unknown for many species.

By bombarding a ^{1}H enriched target with a p-rich radioactive beam ⇒ possibility to study levels in the p-rich compound nucleus which are proton unbound.

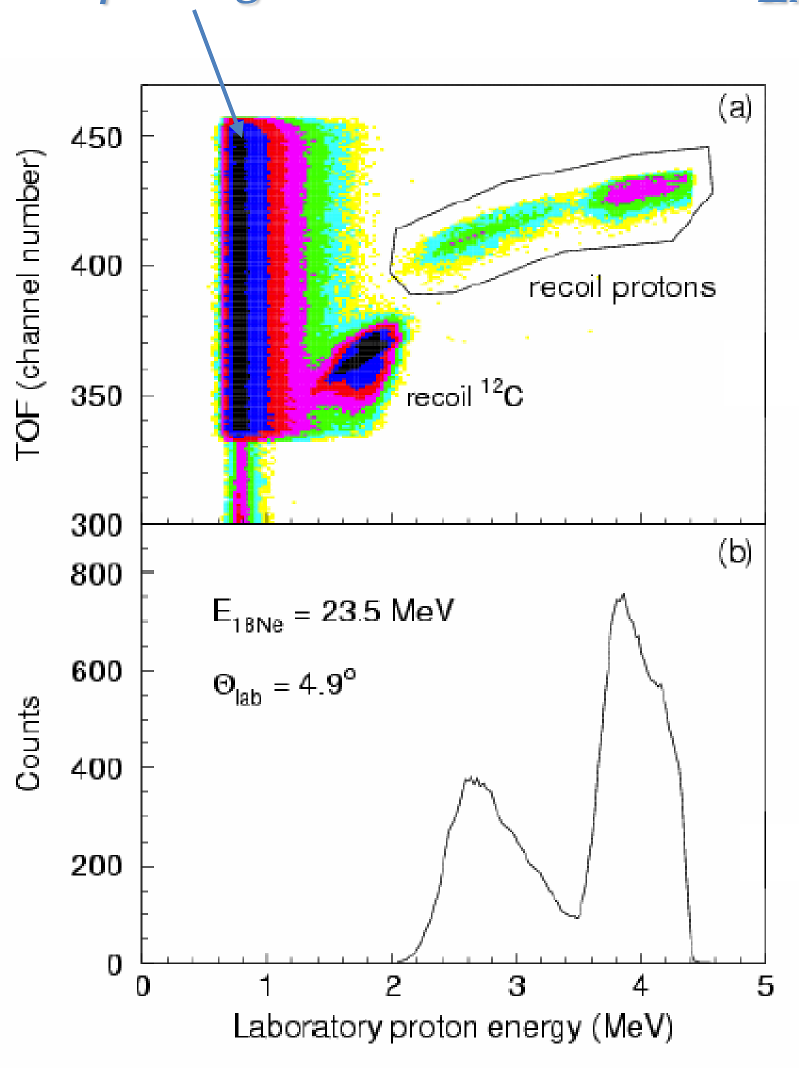
RSM on thick target



Curtsy of C. Angulo

β background

Experiment performed at CRC Louvain-la Neuve



$^{18}Ne+p$ @ E_{lab}=21, 23.5 and 28 MeV

Average beam intensity ~4 × 10^6 pps
Target 0.5 mg/cm^2 polyethylene

Detection set-up

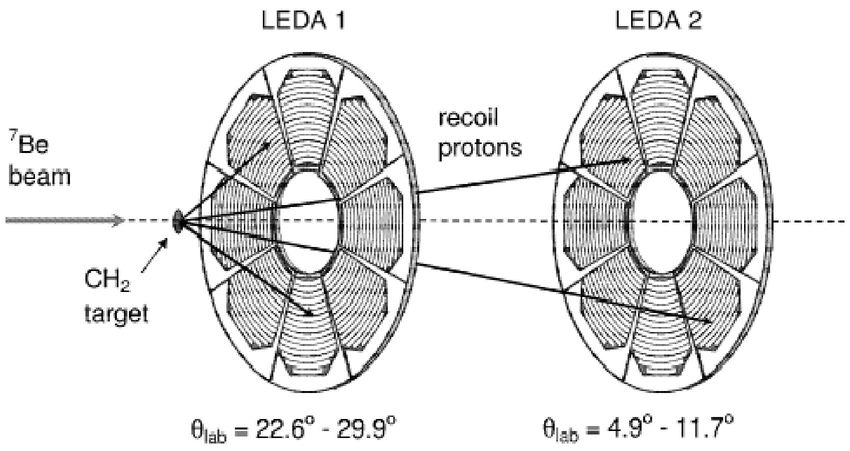


Fig. 1. Schematic drawing of the experimental set-up (see text).

C. Angulo et al. Nucl. Phys. A 716(2003)211

R-matrix analysis

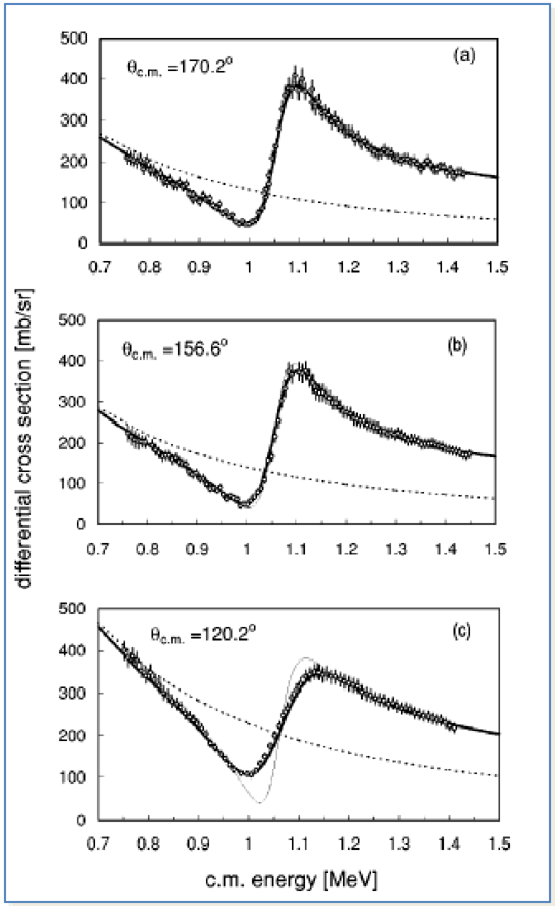
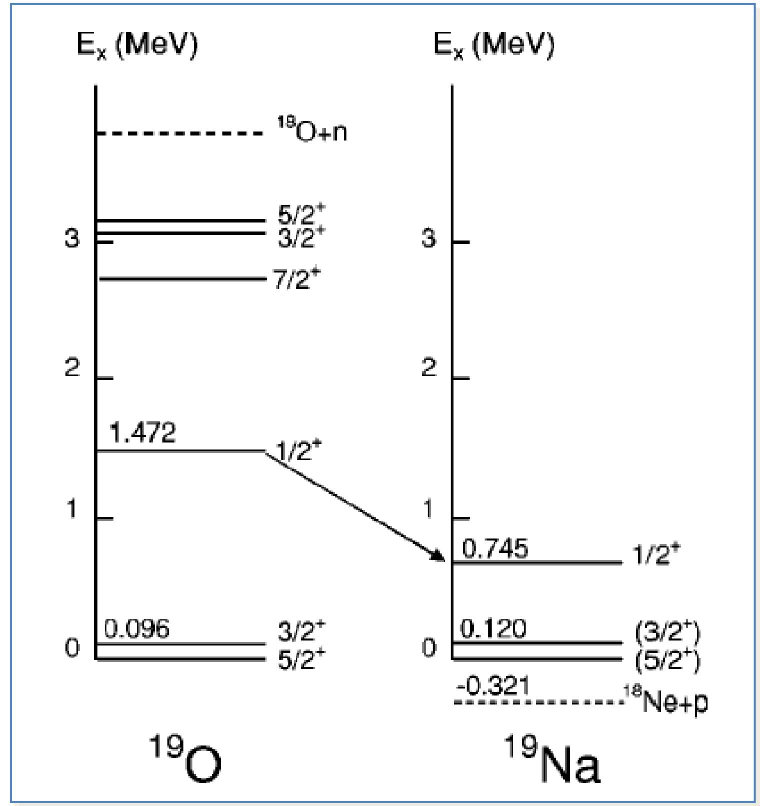


TABLE I. Results of the *R*-matrix fits ($N=367$).

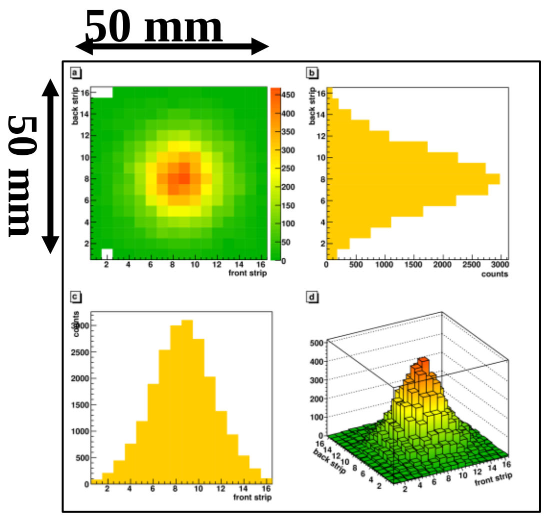
	$a=4$ fm	$a=5$ fm	$a=6$ fm
E_R (MeV)	1.067 ± 0.003	1.066 ± 0.003	1.064 ± 0.003
Γ_p (keV)	104 ± 3	101 ± 3	95 ± 3
χ^2/N	0.53	0.44	0.49
θ_p^2 (%)	29.8	22.9	21.6

Level scheme



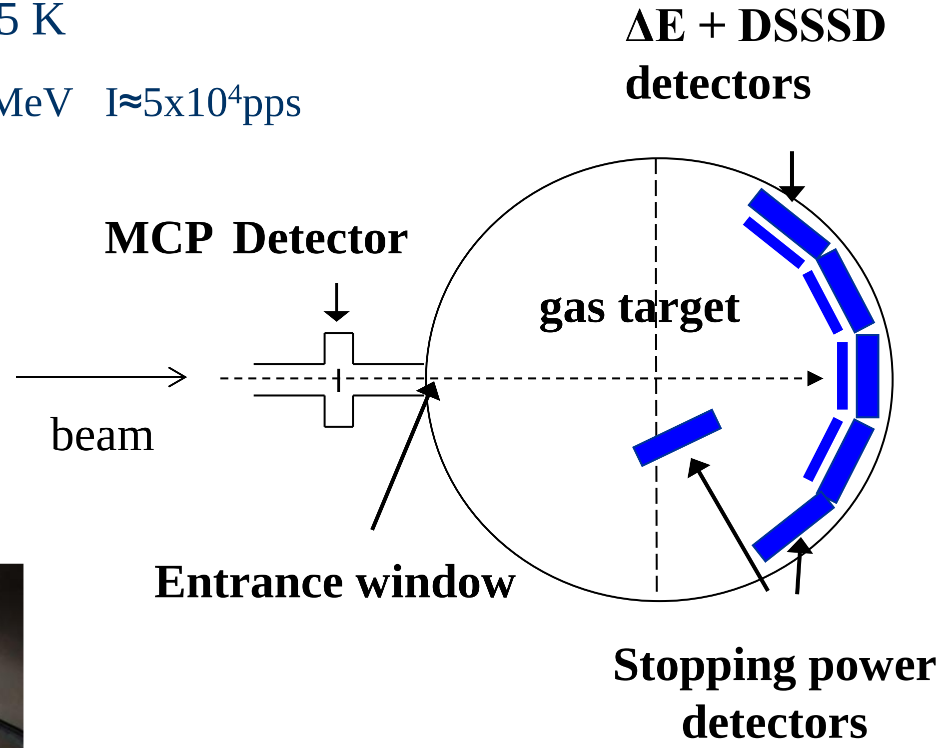
Very large Coulomb shift (~0.73 MeV) typical of deformed states in nuclei near the drip-line.

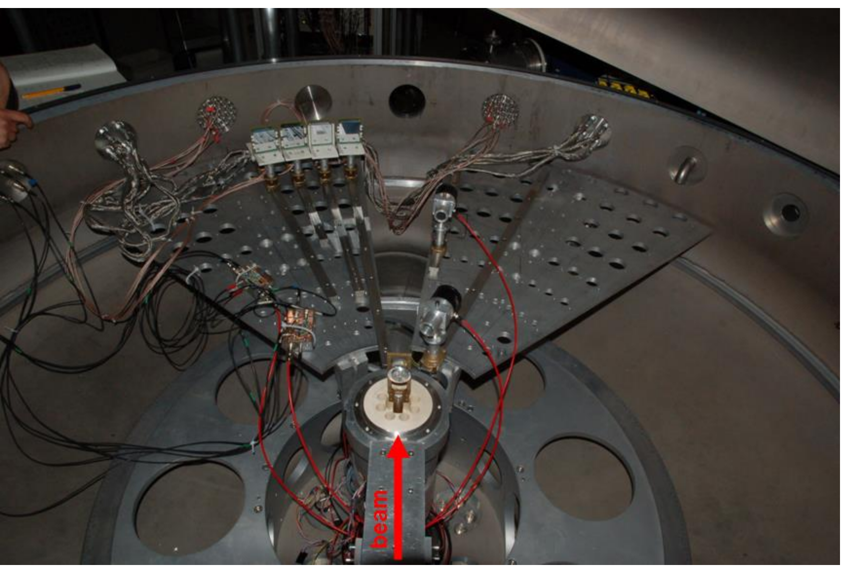
Beam profile



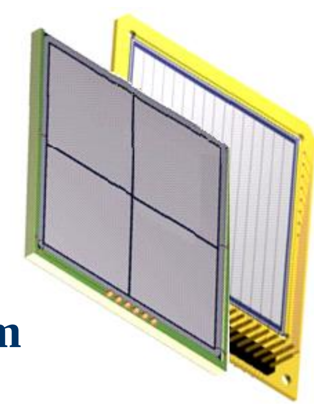
P=700 mbar
T=295 K

E_{8Li}=30.6 MeV   I≈$5x10^4$pps





^{8}Li+^{4}He→^{12}B

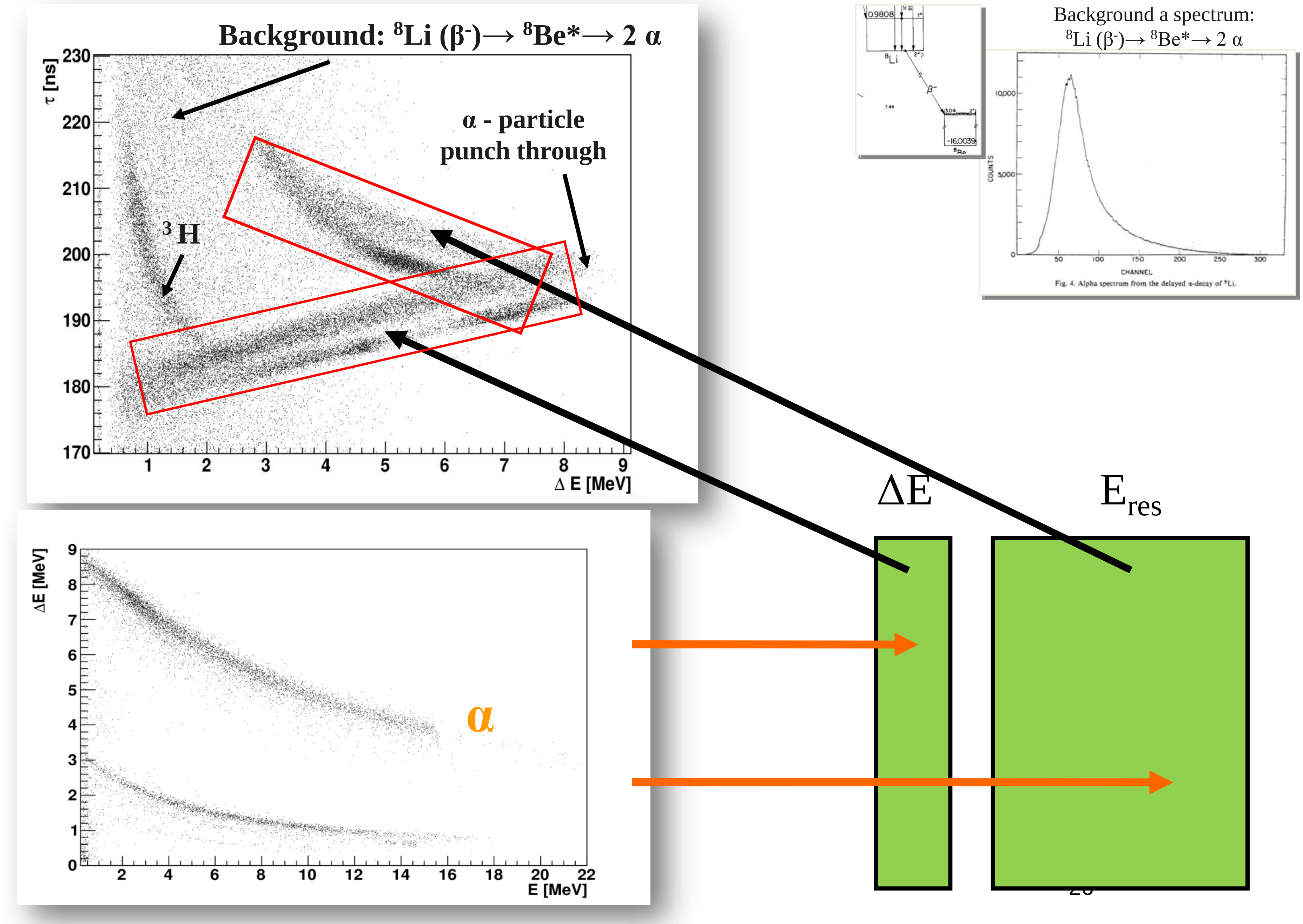


α

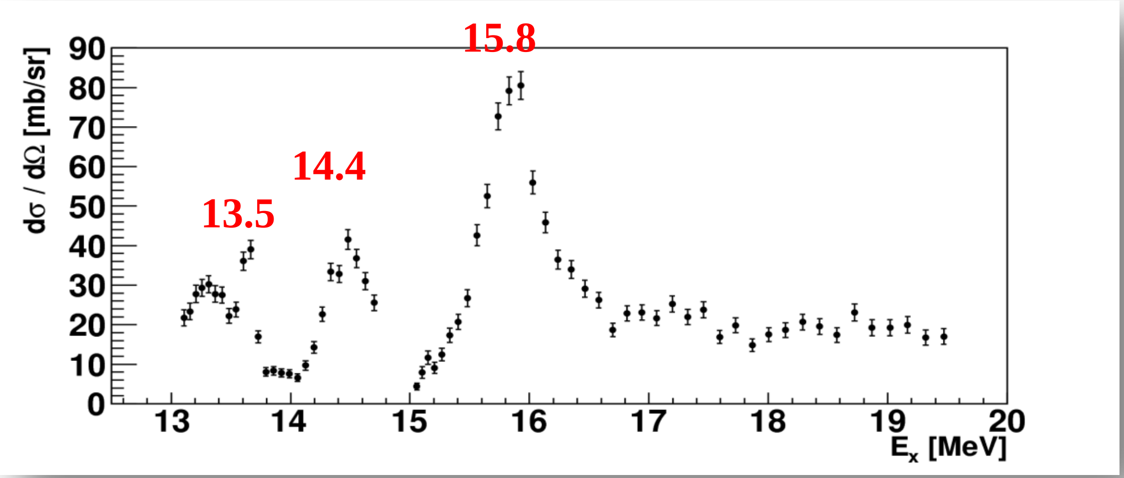
✓**ΔE : quadrants 50x50 mm^2 quadrants Si detectors 50 μm thick.**

✓**E Double Sided Silicon Strip Detectors, 50x50 mm^2 16+16 strip, 1000 μm**

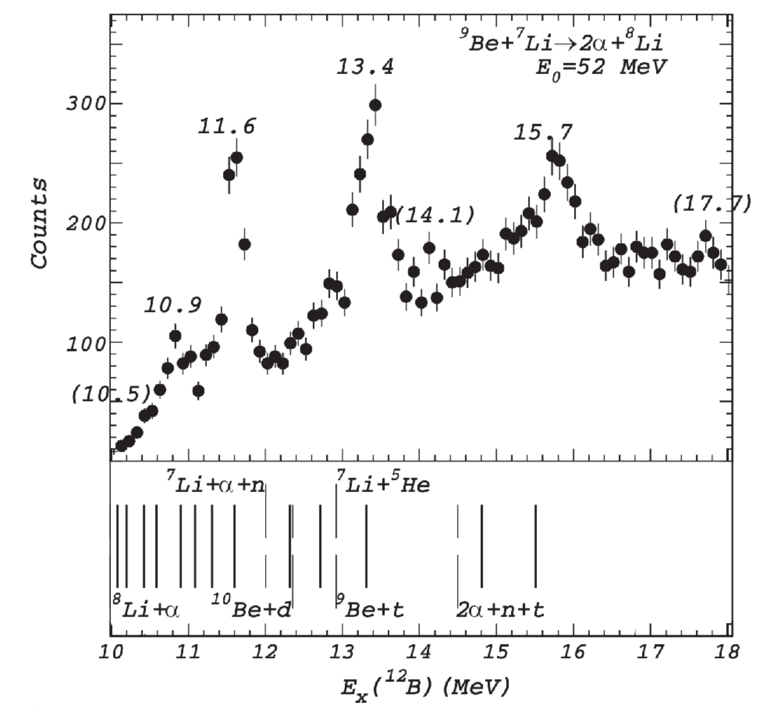
Elastic scattering α particle discrimination



Comparison with literature



$^{9}Be+^{7}Li \rightarrow 2\alpha+^{8}Li$



Soic N., Europhys. Lett.,63 (2003), 524

^{12}B states.

α particle threshold 10.0 MeV

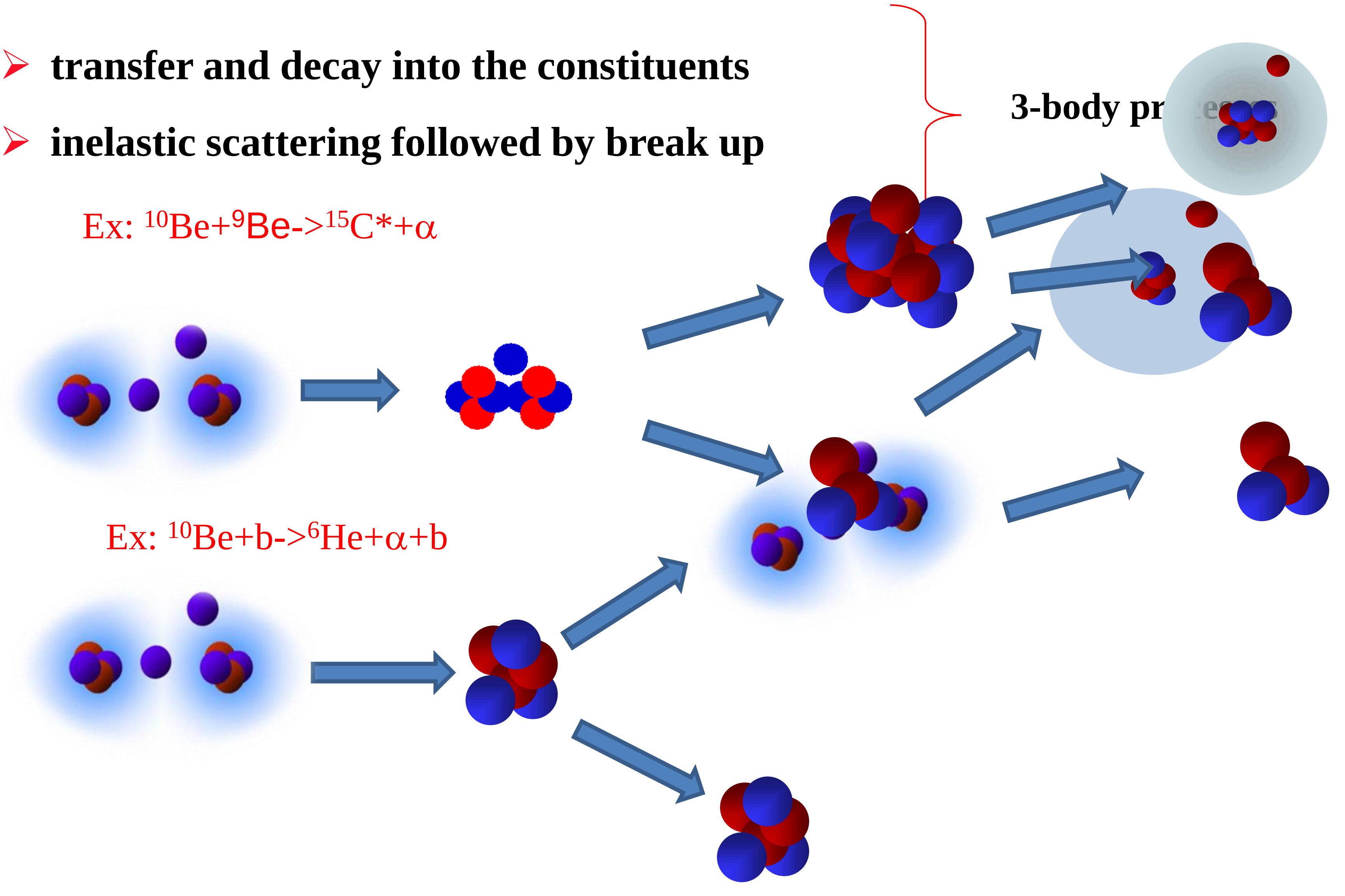
E MeV	Err keV	Width keV	J^{π};T	reazione
13.33	30	50±20		$^{9}Be(^{7}Li,\alpha)$
13.40	100	Broad		$^{10}B(t,p)$
13.4				$^{9}Be(^{7}Li,2\alpha)$
14.1				$^{9}Be(^{7}Li,2\alpha)$
14.80	100	<200	2+;2	$^{14}C(p,^{3}He)$
15.50				$^{9}Be(^{7}Li,\alpha)$
15.7				$^{9}Be(^{7}Li,2\alpha)$
17.7				$^{9}Be(^{7}Li,2\alpha)$

Resonant particle spectroscopy:

- transfer and decay into the constituents
- inelastic scattering followed by break up

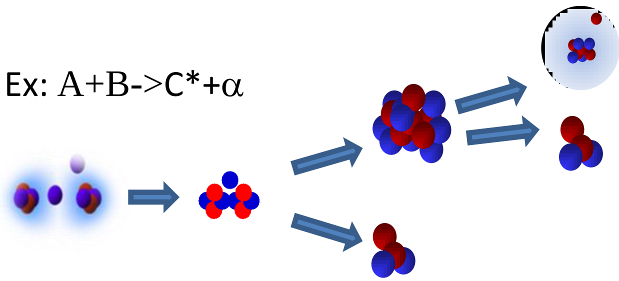
Ex: $^{10}Be+^{9}Be \to ^{15}C^{*}+\alpha$

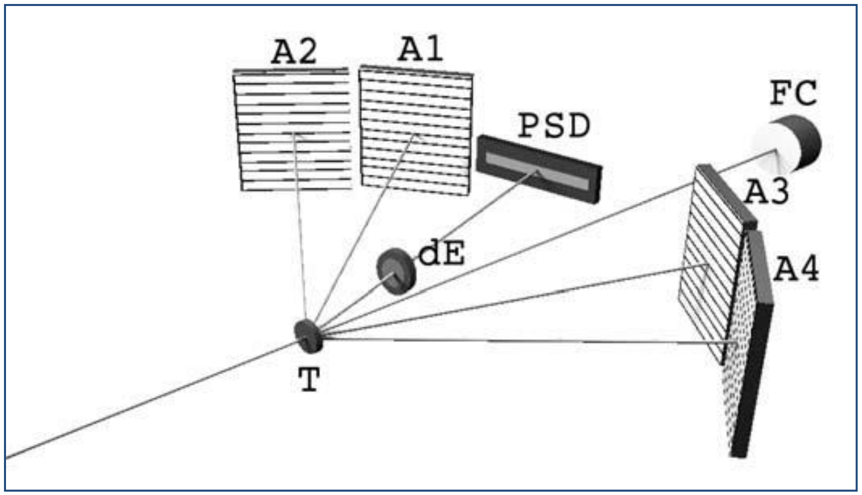
Ex: $^{10}Be+b \to ^{6}He+\alpha+b$

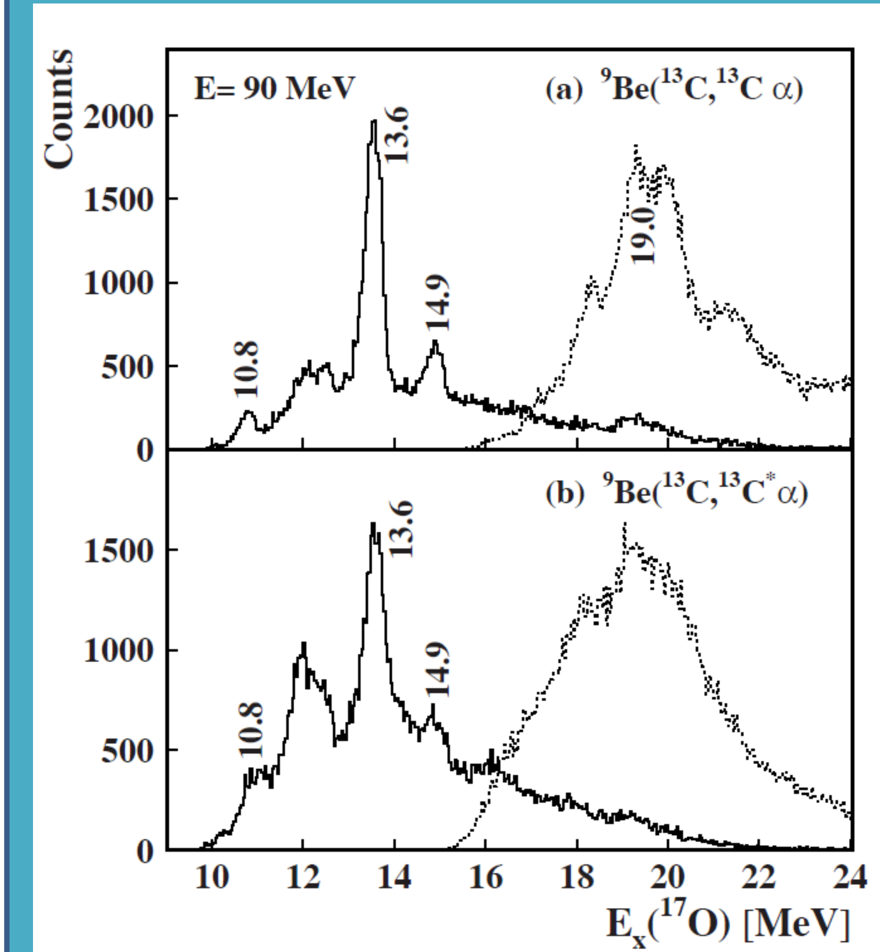


Resonant particle spectroscopy

Ex: A+B->C*+α



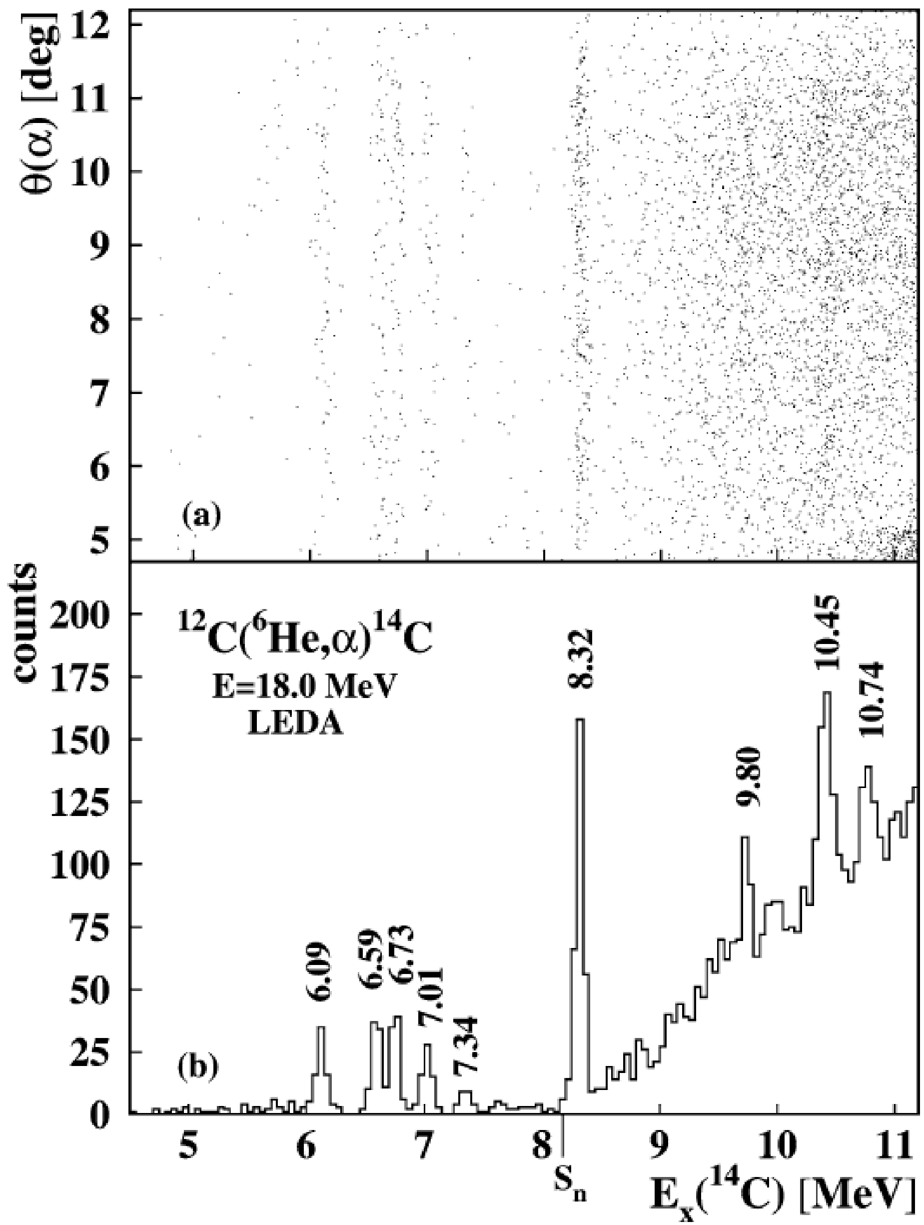




M. Milin at al. EPJ A41(2009)335

The detection of break-up products select states with large partial widths for decaying into a chosen channel thus enabling the selection of states with well-developed cluster structure.
High segmentation of the detection system allows for high resolution measurement.

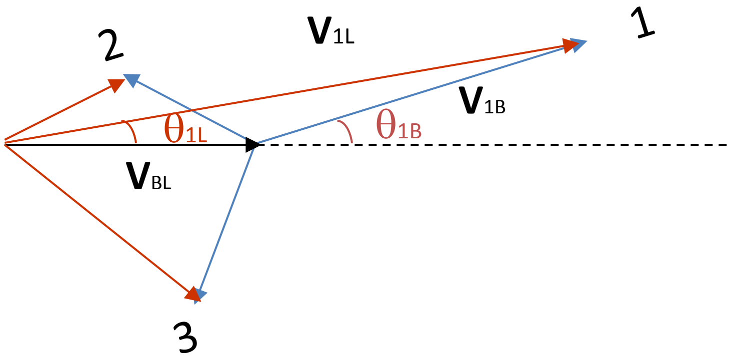
$^{6}He+^{12}C \rightarrow ^{4}He+^{14}C^{*} \rightarrow ^{4}He+^{4}He+^{10}Be$



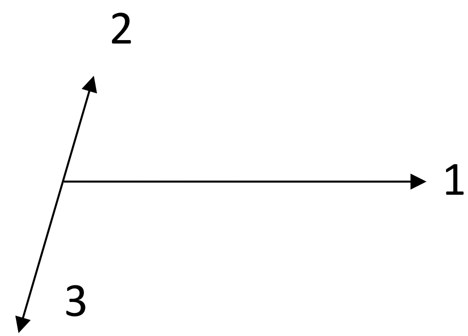
Three body kinematics

Three body kinematics

Reaction: P+T→1+2+3



Center of mass system



Sequential decay relative coordinate system

$$V_{BL}=(2m_P E_{PL})^{1/2}/(m_P+m_T)$$

$$V_{1B}^2=V_{1L}^2+V_{BL}^2-2V_{1L}V_{BL}\cos\theta_{1L}$$

$$E_{1B}=\tfrac{1}{2}m_1V_{1L}^2+\underbrace{m_1(m_P E_{PL})/(m_P+m_T)^2}_{a_1^2}-m_1V_{1L}(2m_P E_{PL})^{1/2}/(m_P+m_T)\cos\theta_{1L}$$

$$E_{1B}=E_{1L}-2a_1E_{1L}\cos\theta_{1L}+a_1^2$$

$$\cos\theta_{1B} = \frac{\sqrt{E_{1L}}\cos\theta_{1L} - a_1}{\left[E_{1L} - 2a_1\sqrt{E_{1L}}\cos\theta_{1L} + a_1^2\right]^{\frac{1}{2}}}$$

$\phi_{1B}=\phi_{1L}$

$$E_{1L} = E_{1B} + 2a_1\sqrt{E_{1B}}\cos\theta_{1B} + a_1^2$$

$$\sin\theta_{BB} = \sqrt{\left(\frac{m_b E_{bL}}{m_A E_{AL}}\right)}\sin\theta_{bL}$$

$$\sin\theta_{bB} = \left(\frac{E_{bL}/E_T}{D}\right)\sin\theta_{bL}$$

$$\cos\theta_{1L} = \frac{\sqrt{E_{1B}}\cos\theta_{1B} + a_1}{\left[E_{1B} + 2a_1\sqrt{E_{1B}}\cos\theta_{1B} + a_1^2\right]^{\frac{1}{2}}}$$

$\phi_{1B}=\phi_{1L}$

If we detect particle one the kinematics is completely determined by the two body (particle 1 and 23) kinematics.

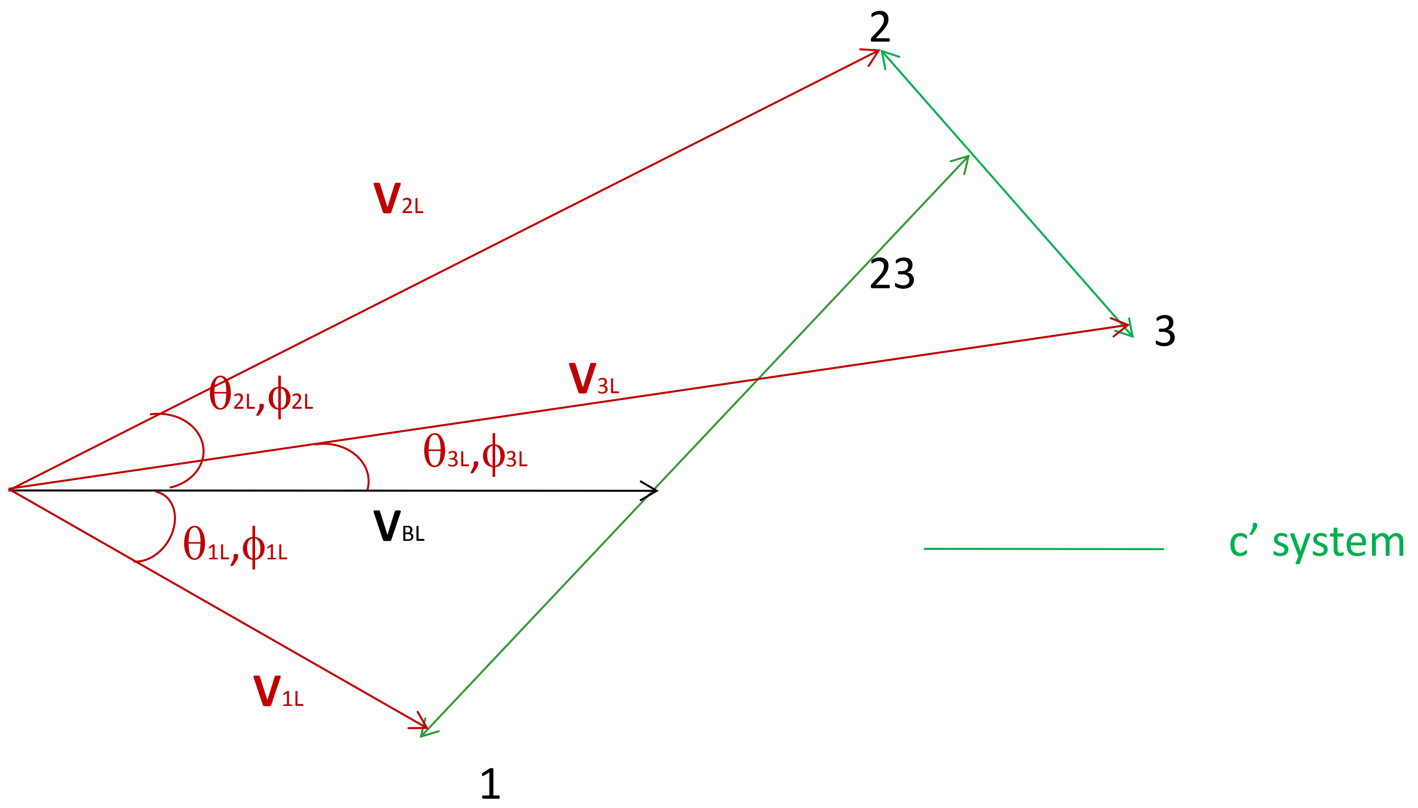
If we detect particle 2 and 3 we have to reconstruct the excitation energy of particle 23.

$$E_{Tot} = Q_{3body} + \underbrace{\frac{m_T}{m_P + m_T} E_P^L}_{E_{cm}} = E_{1-23} + E_{2-3}$$

Total energy available in the cener of mass system

m1=mass of particle 1
m23=m2+m3= mass of particle 23
M=m1+m2+m3

We define the reduced masses:
μ1-23=m1m23/(m1+m23)=m1(m2+m3)/M
μ2-3=m2m3/m2+m3

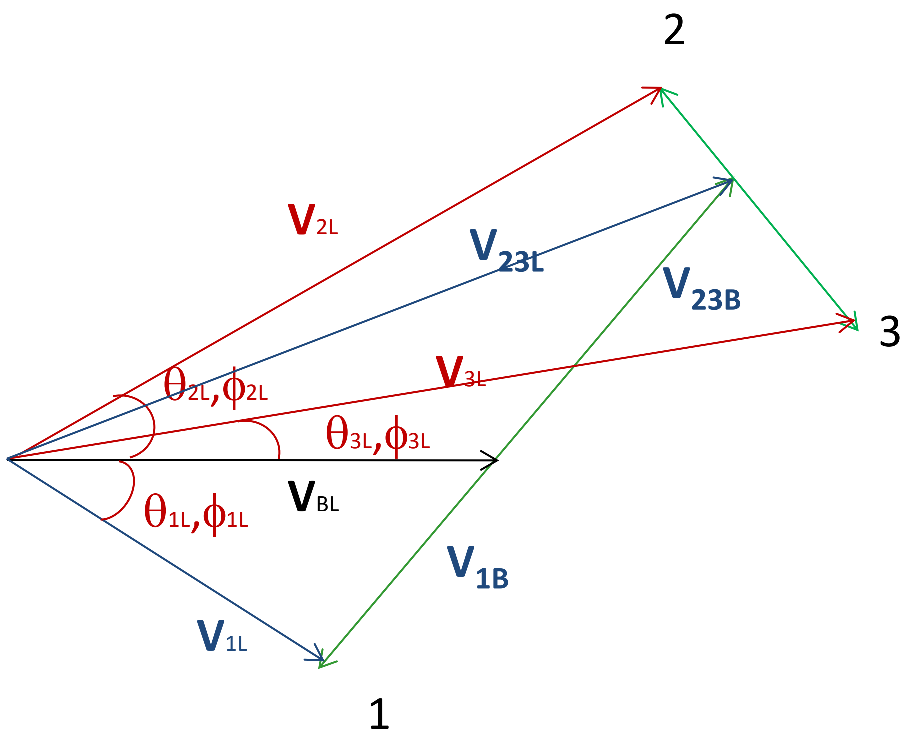


Measured quantities are $E_{1L},\theta_{1L},\phi_{1L}$ – $E_{2L},\theta_{2L},\phi_{2L}$- $E_{3L},\theta_{3L},\phi_{3L}$ of one, two or even three particles

NB: we note that the velocity vectors are in the 3 dimentional space not in plane and both θ and ϕ angles are important.

Eg. One wants to reconstruct excitation energy of particle 23

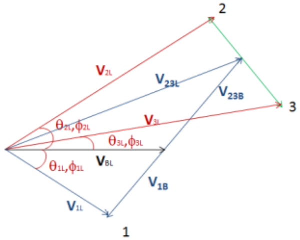
Reaction p+T→1+23*→1+2+3
e.g. : $\alpha+^{6}Li\rightarrow\alpha+^{6}Li^{*}\rightarrow\alpha+\alpha+d$



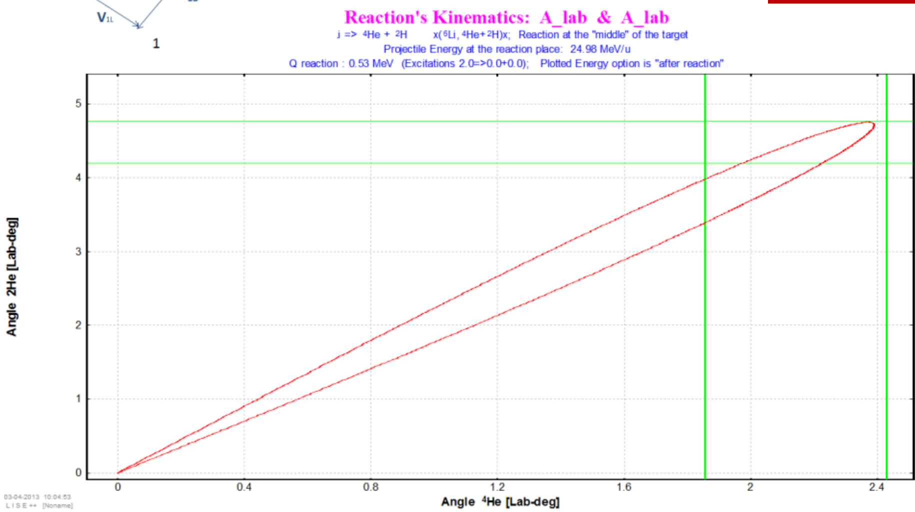
From two body kinematics one can reconstruct the excitation energy of the intermediate 23 system.
See equations for two body kinematics

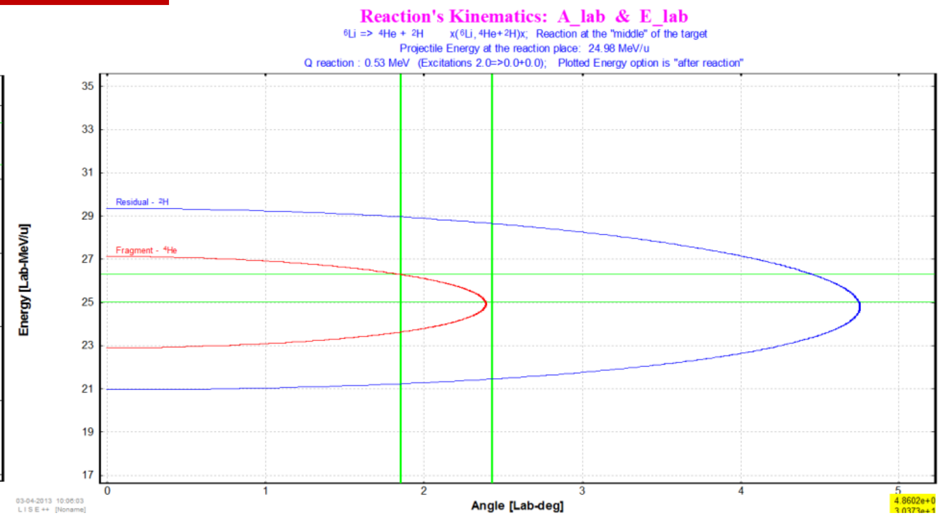
$$E_{\alpha B}+E_{6LiB}=E_{cm}-E^{*}_{6Li}+Q_{2body(\alpha-6Li)}$$

$^{6}Li+\alpha \rightarrow {}^{6}Li^{*}+\alpha \rightarrow \alpha+d+\alpha$

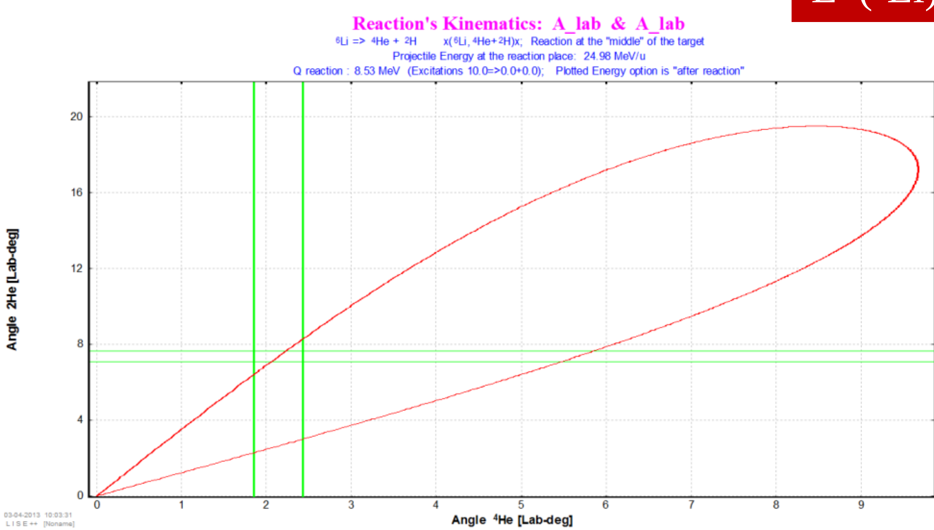


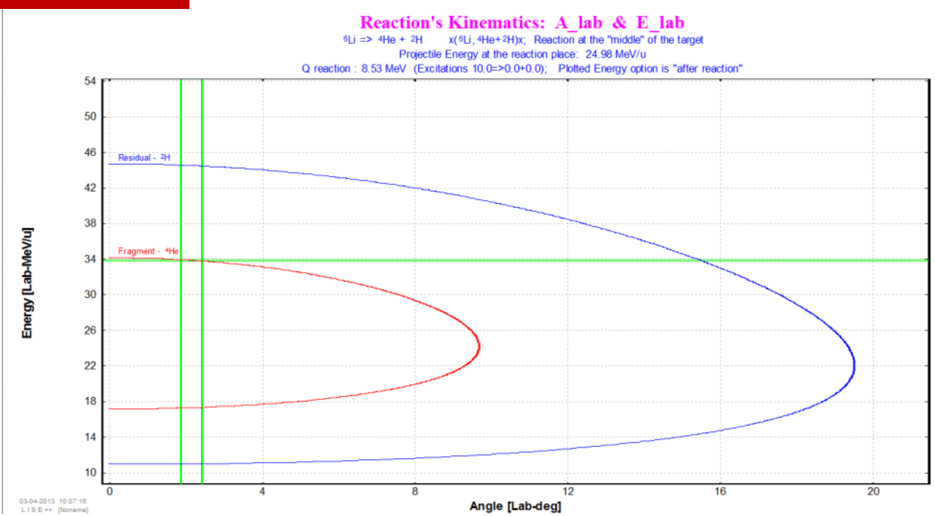
E*(^{6}Li)=2 MeV



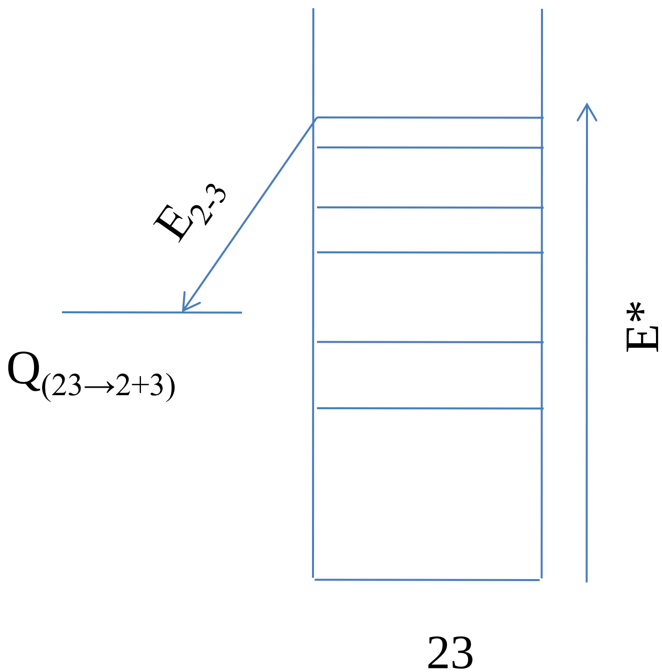


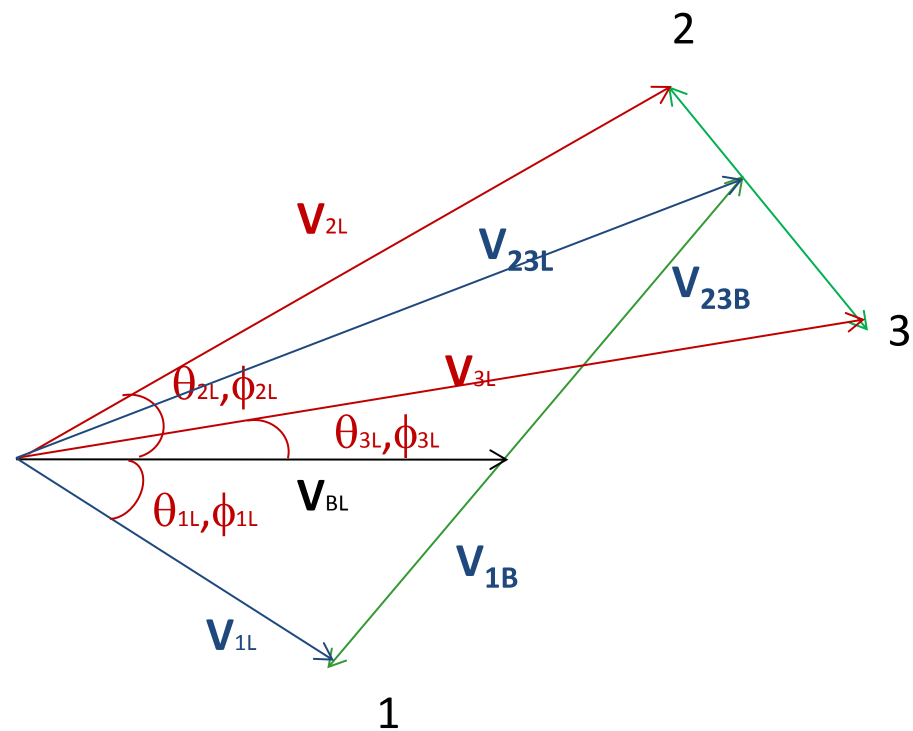
E*(^{6}Li)=10 MeV





Reaction $p+T \rightarrow 1+23^* \rightarrow 1+2+3$





$$E_{2\text{-}3}=E_{23}^{*}+Q_{(23\rightarrow 2+3)}=1/2\mu v_{rel(2\text{-}3)}^{2}=1/2\mu(\mathbf{V}_{2L}\text{-}\mathbf{V}_{3L})^{2}$$

quantities to be measured

quantity we want to extract from the experiment

$\mathbf{V}_{2L} \rightarrow V_{2L}, \theta_{2L}, \phi_{2L}$ $\quad$ $\mathbf{V}_{3L} \rightarrow V_{3L}, \theta_{3L}, \phi_{3L}$

$$\begin{cases} V_{2Lx} = V_{2L} \sin\theta_{2L} \cos\phi_{2L} \\ V_{2Ly} = V_{2L} \sin\theta_{2L} \sin\phi_{2L} \\ V_{2Lz} = V_{2L} \cos\theta_{2L} \end{cases}$$

$$V^2_{rel} = (\mathbf{V}_{2L} - \mathbf{V}_{3L})^2 = V_{2L}{}^2 + V_{3L}{}^2 - 2\, \mathbf{V}_{2L} \bullet \mathbf{V}_{3L}$$

$$V_{2L} = \sqrt{\frac{2E_{2L}}{m_2}} \qquad V_{3L} = \sqrt{\frac{2E_{3L}}{m_3}}$$

$$\begin{cases} V_{3Lx} = V_{3L} \sin\theta_{3L} \cos\phi_{3L} \\ V_{3Ly} = V_{3L} \sin\theta_{3L} \sin\phi_{3L} \\ V_{3Lz} = V_{3L} \cos\theta_{3L} \end{cases}$$

$\mathbf{V}_{2L} \bullet \mathbf{V}_{3L} = V_{2L} V_{3L} \cos\theta_{rel} =$

$V_{2Lx} V_{3Lx} + V_{2Ly} V_{3Ly} + V_{2Lz} V_{3Lz} =$

$V_{2L} \sin\theta_{2L} \cos\phi_{2L}\, V_{3L} \sin\theta_{3L} \cos\phi_{3L} + V_{2L} \sin\theta_{2L} \sin\phi_{2L}\, V_{3L} \sin\theta_{3L} \sin\phi_{3L} + V_{2L} \cos\theta_{2L}\, V_{3L} \cos\theta_{3L}$

$$V_{rel}^2 = \frac{2E_{2L}}{m_2} + \frac{2E_{3L}}{m_3} - 2\cos\theta_{rel} \qquad E^*_{2-3} = \frac{1}{2}\mu_{2-3} V_{rel}^2 - Q_{23\rightarrow 2-3}$$

measured quantities energies and angles

Summary and conclusions

Cluster structures can be measured in various way.

Resonant elastic scattering gives the possibility to measure the excitation function in a single run without changing beam energy. Particularly useful in RIB experiments.

With this technique only unbound states can be measured and the main limitation is the minimum resonance width that can be measured.

Both single particle and cluster states can be studied with RSM.

Resonant particle spectroscopy is the most commonly used technique to study cluster structure.

Good energy and angular resolution is required.