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Study of fusion mechanisms induced by weakly bound nuclei

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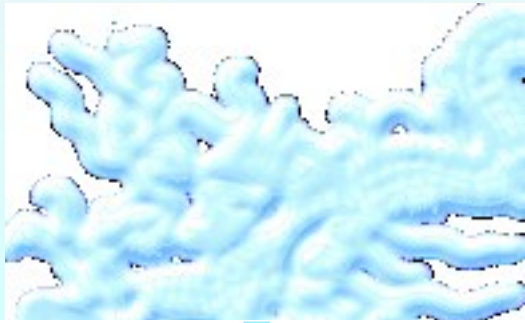
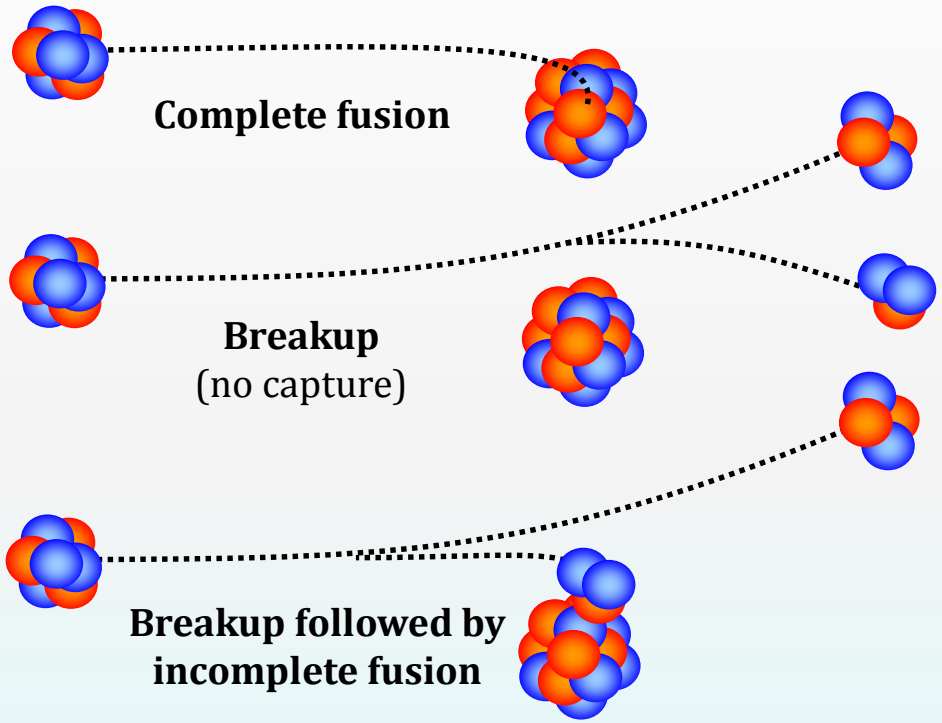
Outline

- Introduction
- Experiment and experimental results
- Summary



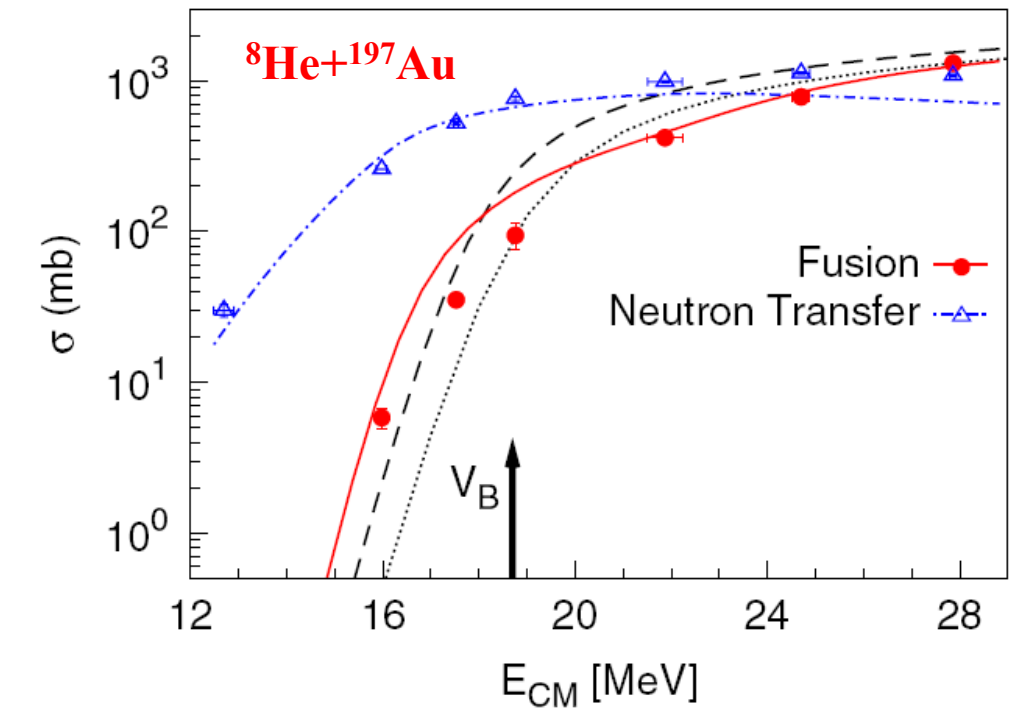
Introduction

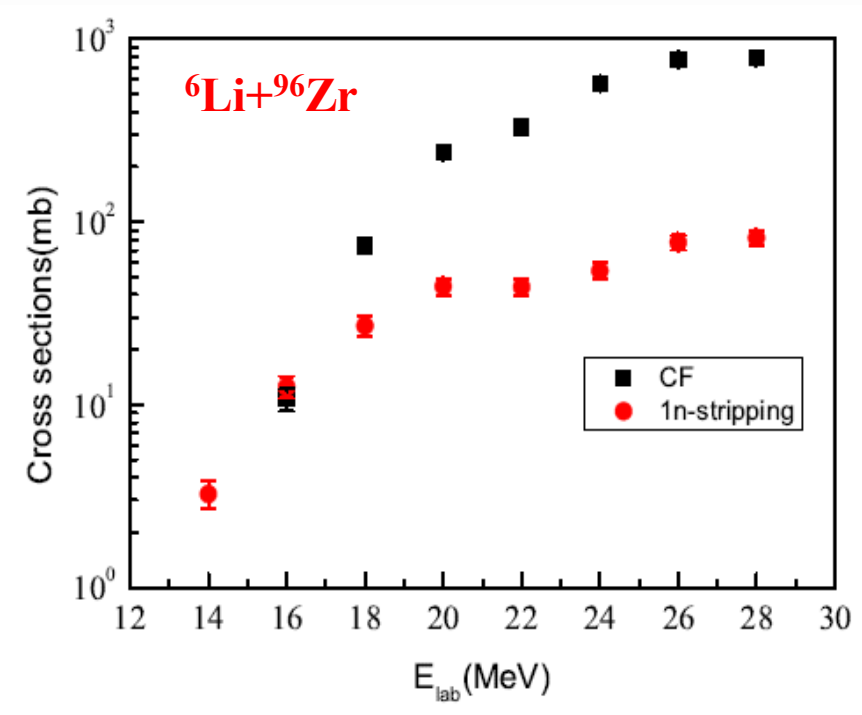
^{6}Li, ^{7}Li, ^{9}Be



The same residues

Transfer: direct transfer (1n stripping and 1n pickup) and breakup transfer



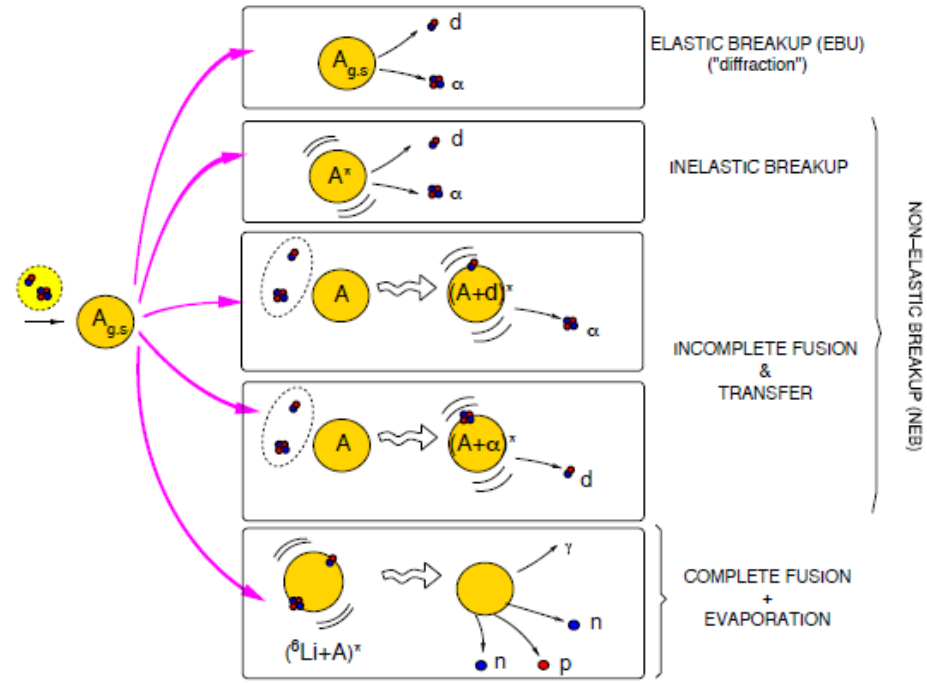


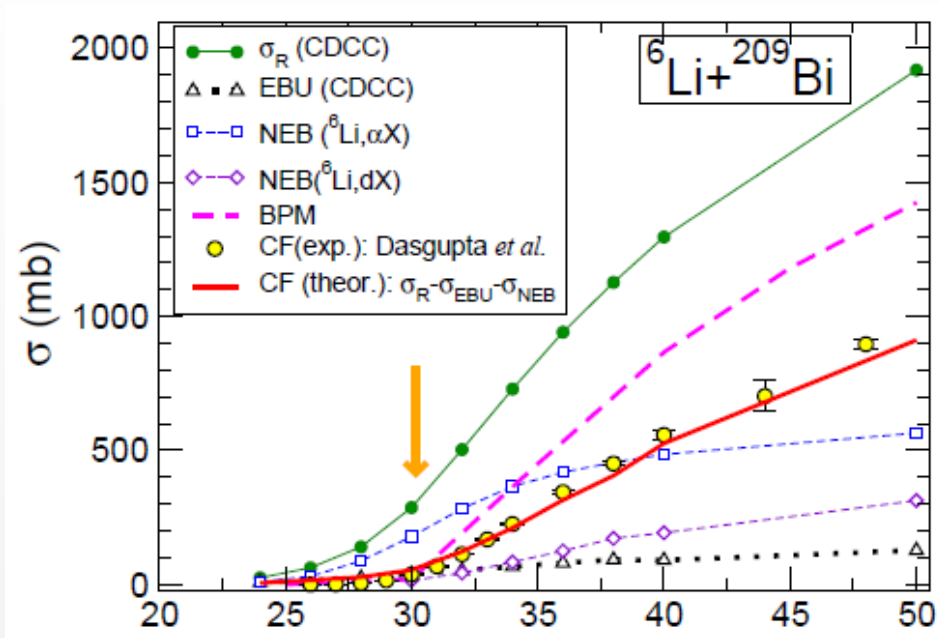
It is indicated that the sub-barrier total reaction cross section is dominantly by one and two neutron stripping. In the case of reactions with neutron-rich radioactive ion beams, the coupling to transfer is also found to be important.

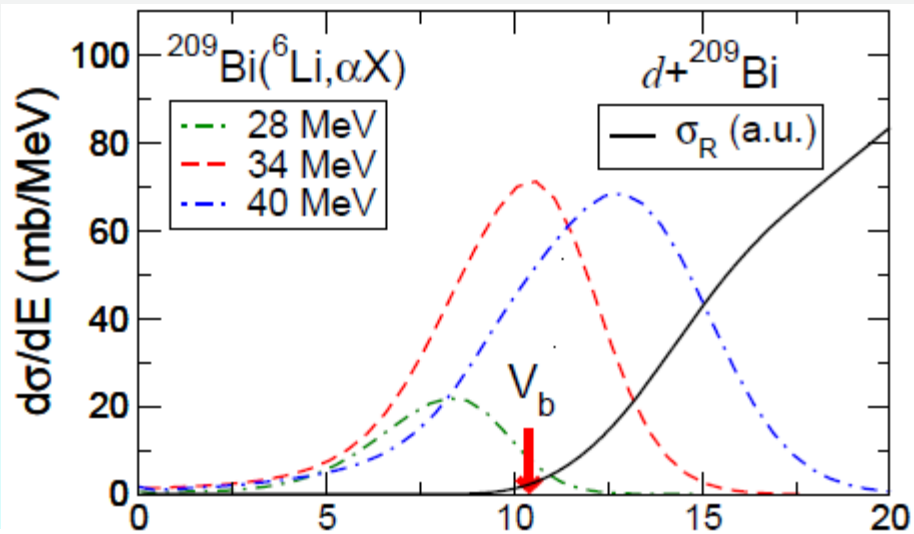
A. Lemasson *et al*., Phys. Rev. Lett. 103, 232701 (2009).

S. P. Hu *et al*., Phys. Rev. C 93, 014621 (2016).

$$\sigma_R \approx \sigma_{\rm CF} + \sigma_{\rm inel} + \sigma_{\rm EBU} + \sigma_{\rm NEB}^{(b)} + \sigma_{\rm NEB}^{(x)}.$$

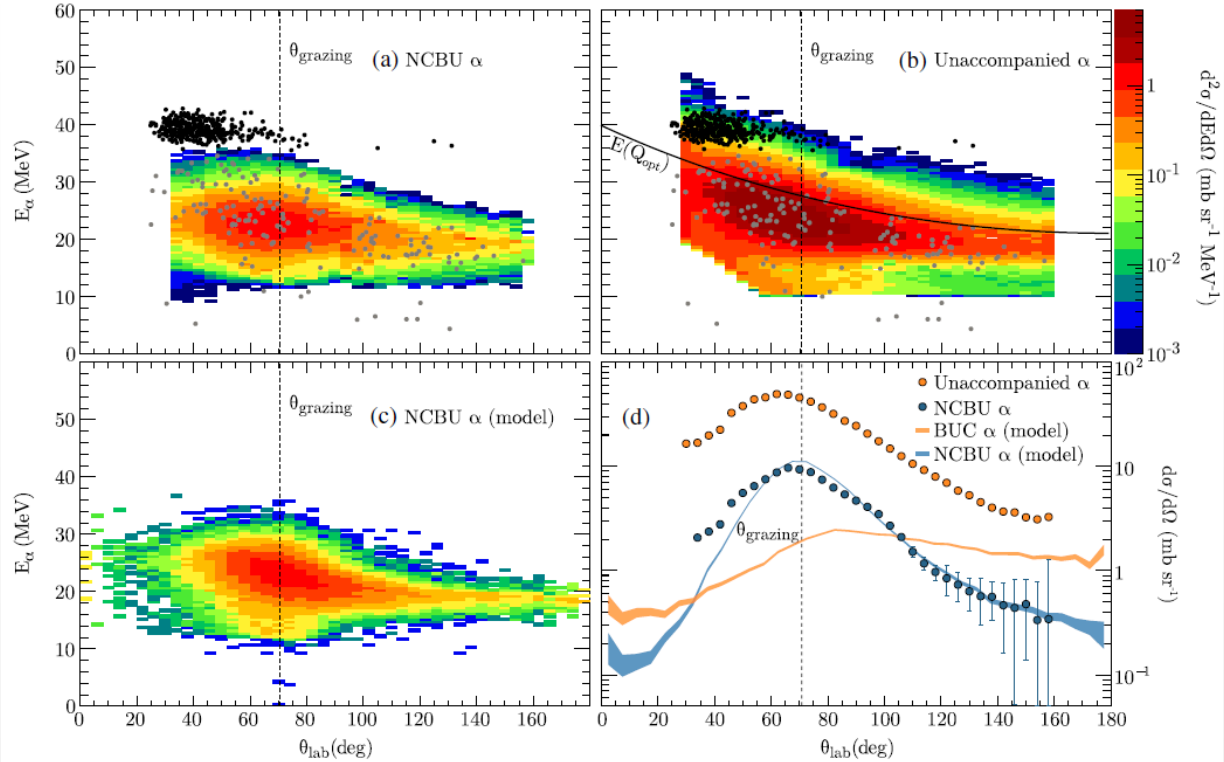






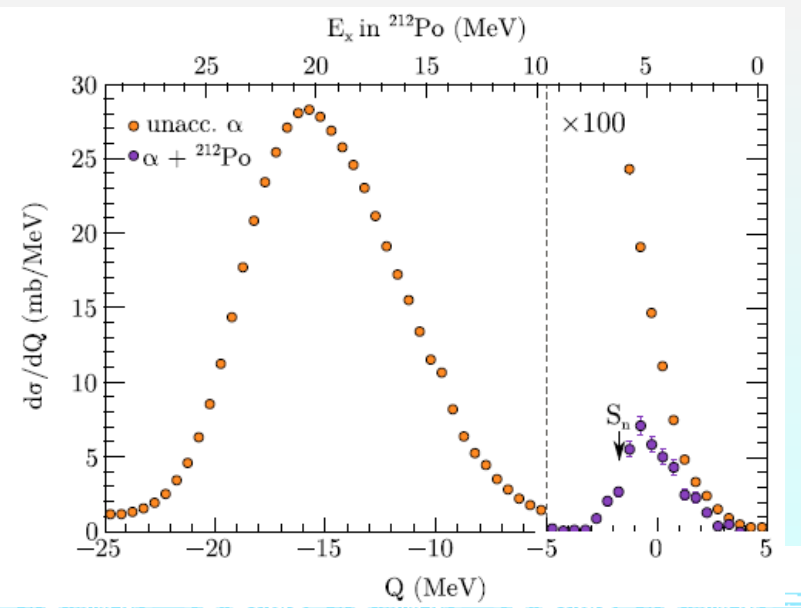
The CF suppression is mostly caused by NEB modes, EBU plays a minor role. The large α yields can be explained as a consequence of s Trojan Horse mechanism.

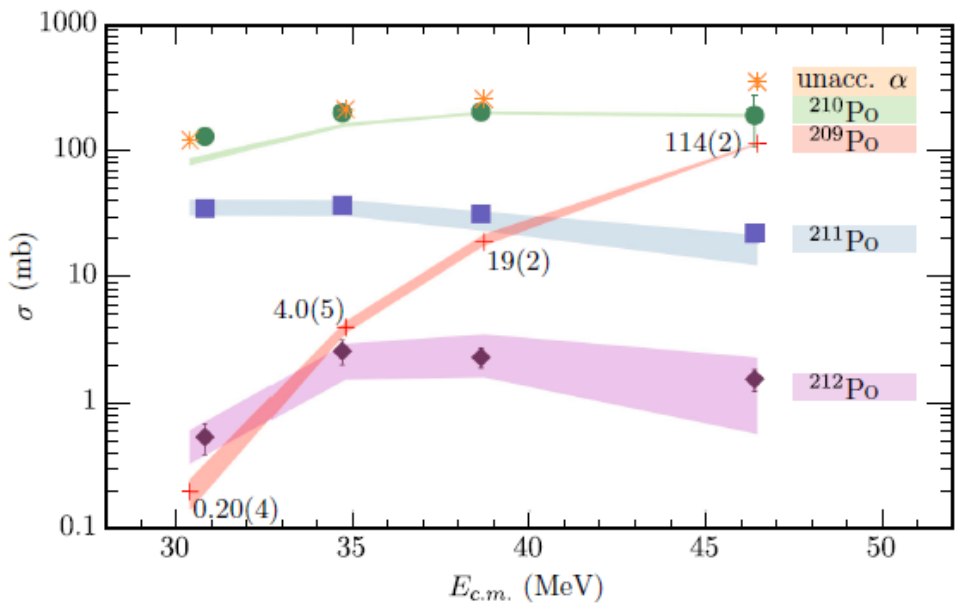
L. Jin and A. M. Moro, Phys. Rev. Lett. 122 (2019) 042503.



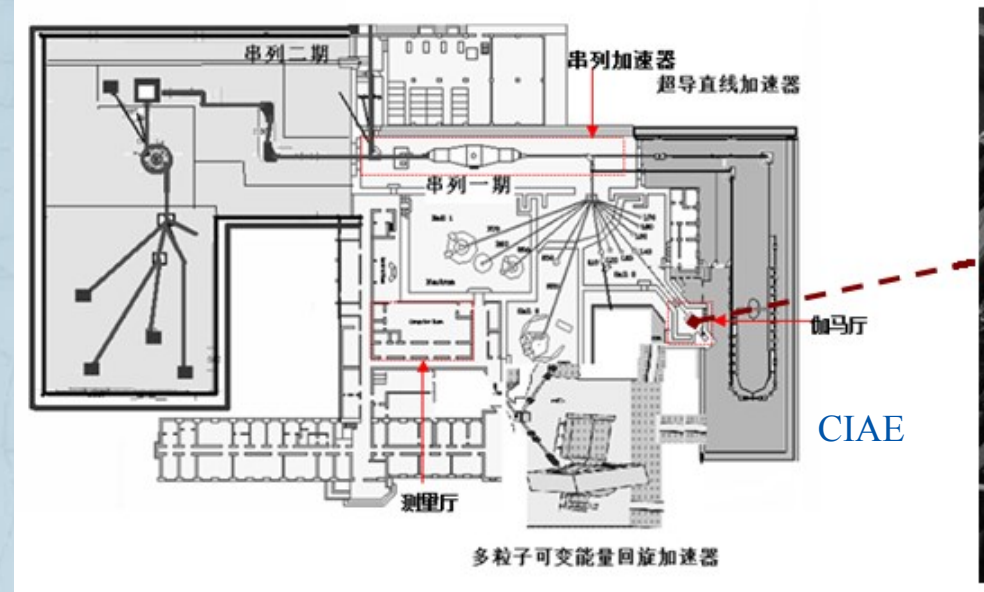
$^{7}Li+^{209}Bi$ at $E_{c.m.}$=38.72MeV

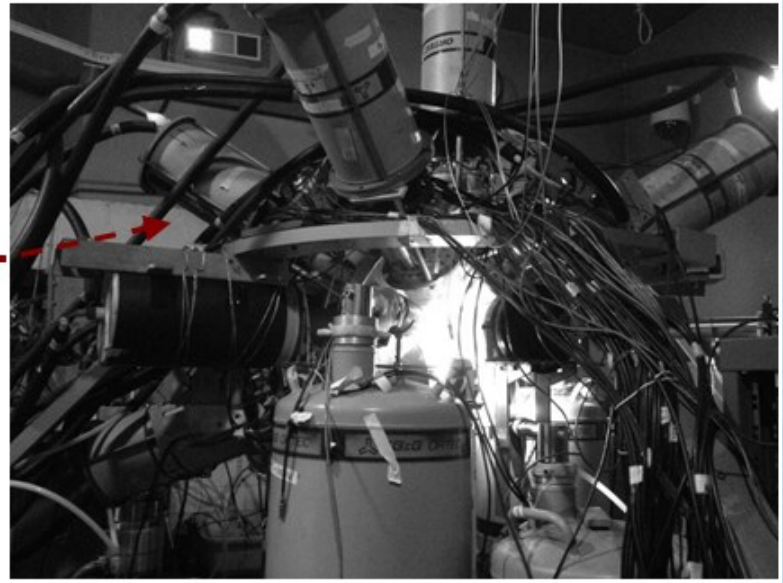
K. J. Cook, et al., Phys. Rev. Lett. 122 (2019) 102501.

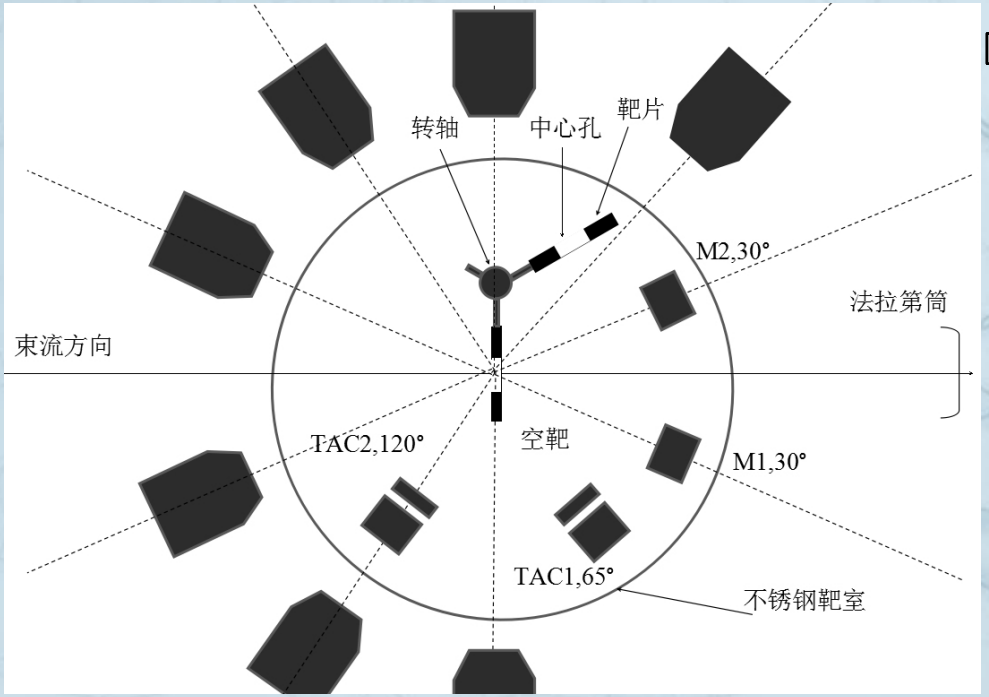


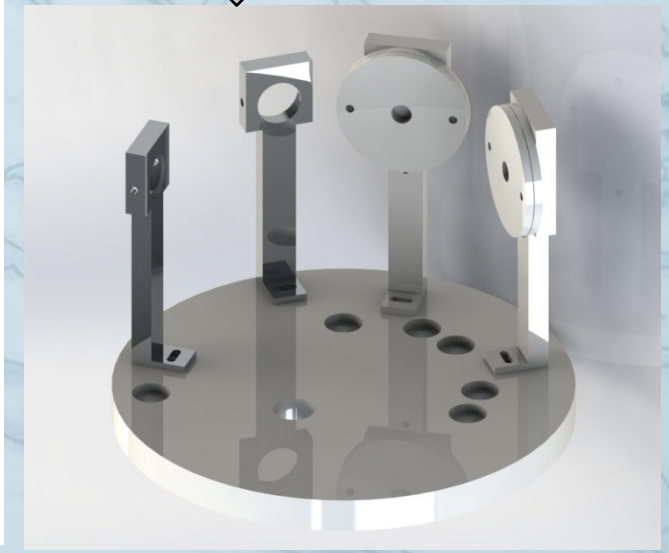


Experimental setup and results

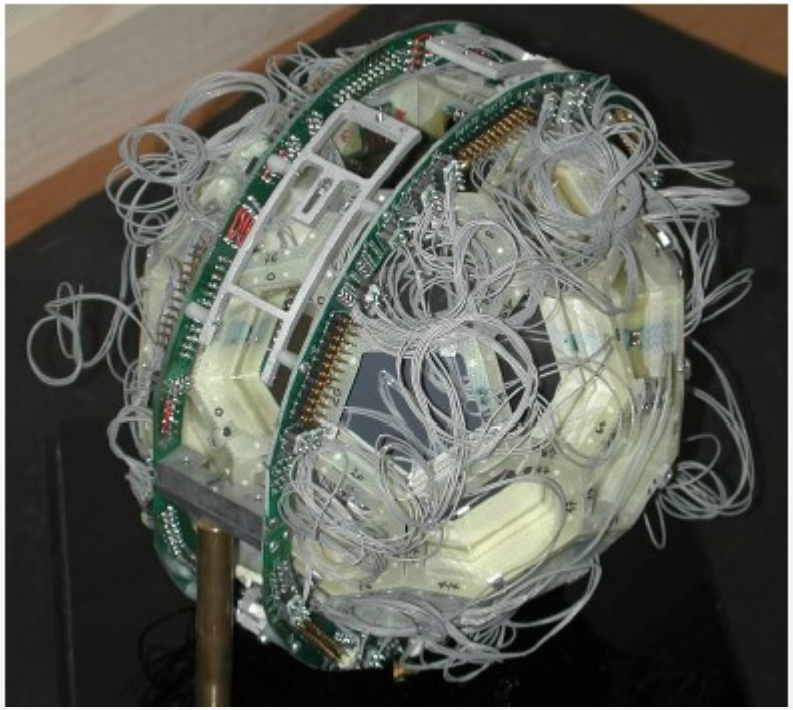


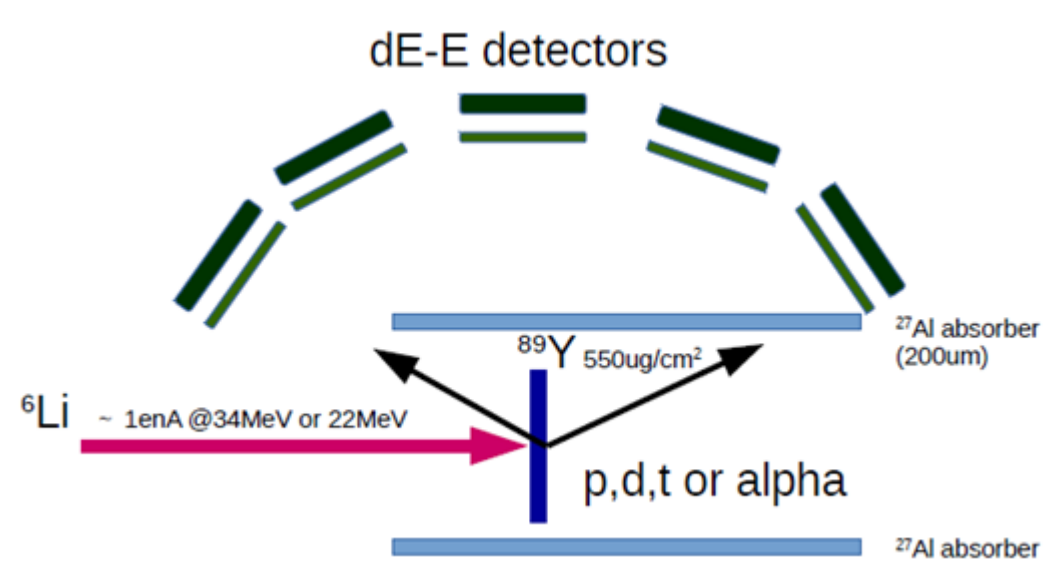


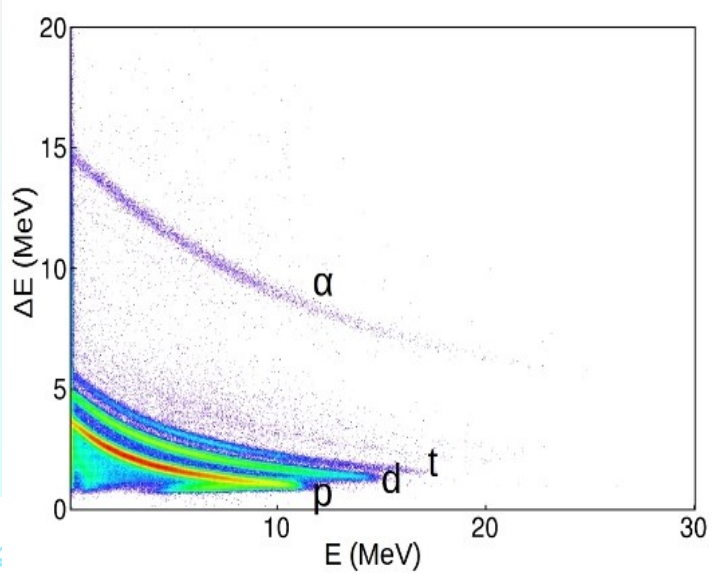




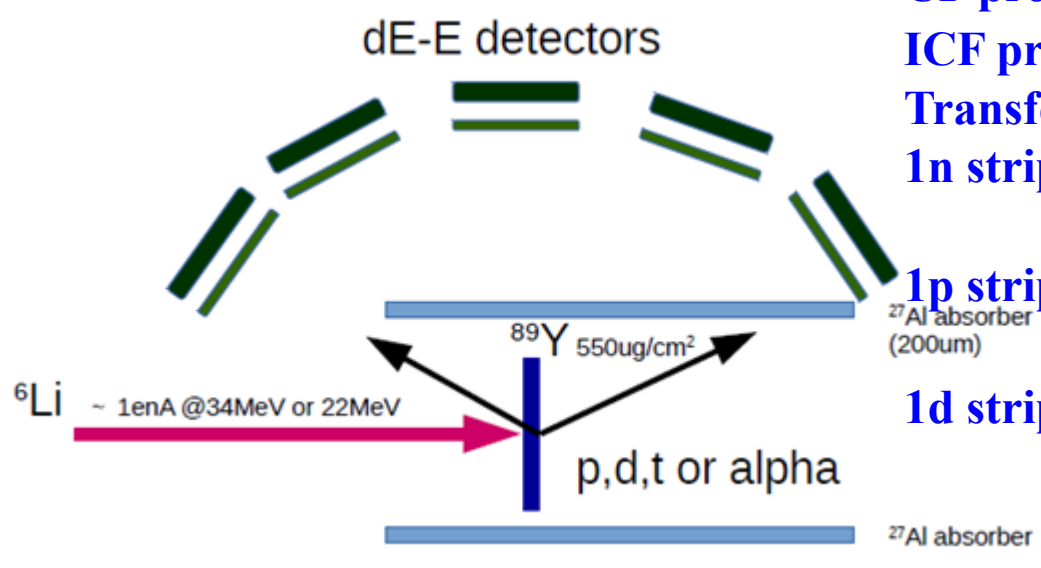
$^{6}Li+^{89}Y$ experiment at INFN-LNL in Italy







■ Gamma coincidence with α particles



CF process $^6Li + {}^{89}Y \rightarrow {}^{95}Mo \rightarrow {}^{90}Zr + \alpha + n,$

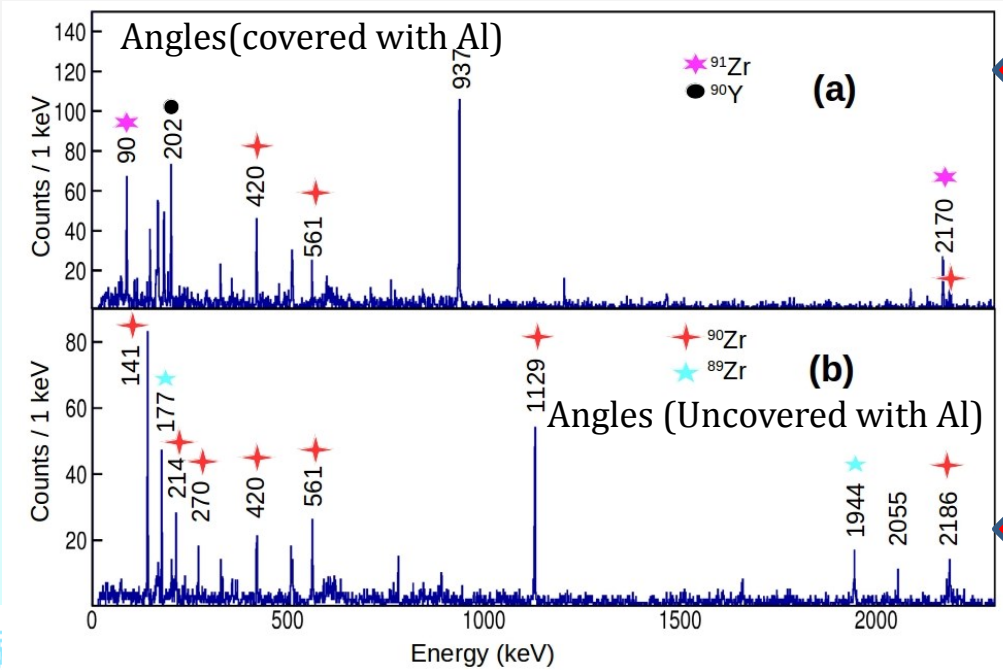
ICF process $^2H + {}^{89}Y \rightarrow {}^{91}Zr \rightarrow {}^{90}Zr + n, \alpha$

Transfer process:

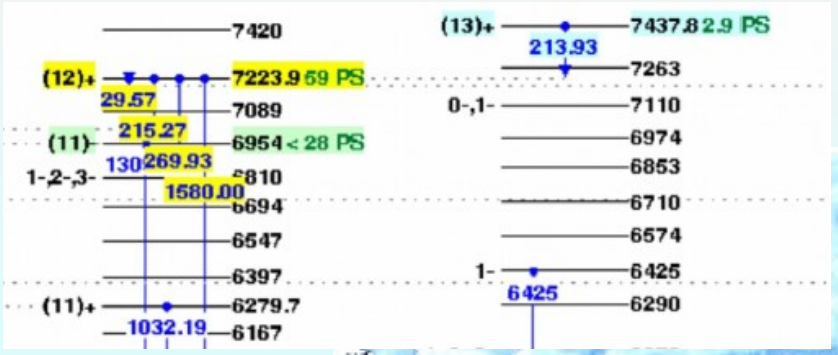
1n stripping: ^{6}Li+^{89}Y→^{90}Y+^{5}Li+1.19MeV;
^{5}Li→α+p

1p stripping: $^6Li + {}^{89}Y \rightarrow {}^{90}Zr + \alpha + n$+3.92MeV

1d stripping: ^6Li+^{89}Y→^{91}Zr+ α+11.85MeV



Transfer process



CF: ^{6}Li+^{89}Y→^{95}Mo→^{90}Zr+α+n
→^{89}Zr+α+2n

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

A powerful combination measurement for exploring the fusion reaction mechanisms induced by weakly bound nuclei

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■ Gamma coincidence with proton particles

CF:

$^{6}Li + ^{89}Y \longrightarrow (^{95}Mo)^{*} \longrightarrow ^{93}Nb + n + p$

$^{6}Li + ^{89}Y \longrightarrow (^{95}Mo)^{*} \longrightarrow ^{92}Nb + 2n + p$

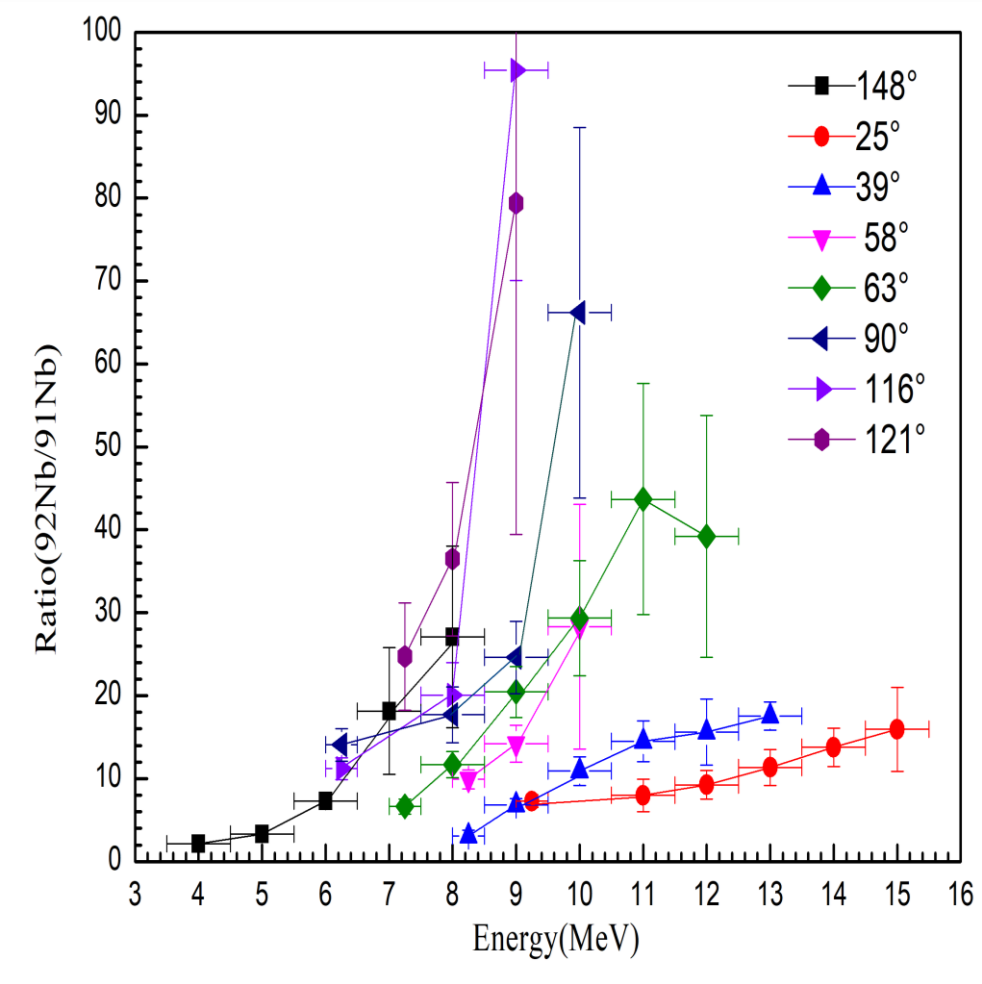
$^{6}Li + ^{89}Y \longrightarrow (^{95}Mo)^{*} \longrightarrow ^{91}Nb + 3n + p$

If ICF? May come from the breakup of ^{6}Li ✗

breakup	Separation energy (MeV)
$^{6}Li \longrightarrow d+\alpha$	-1.47
$^{6}Li \longrightarrow p+^{5}He(n+\alpha)$	-4.43
$^{6}Li \longrightarrow n+^{5}Li(\alpha+p)$	-5.66
$d \longrightarrow p+n$	-2.224

According to estimation, protons from breakup cannot go through Al and ΔE detector.

So, ^{91}Nb, ^{92}Nb and ^{93}Nb are from CF process.

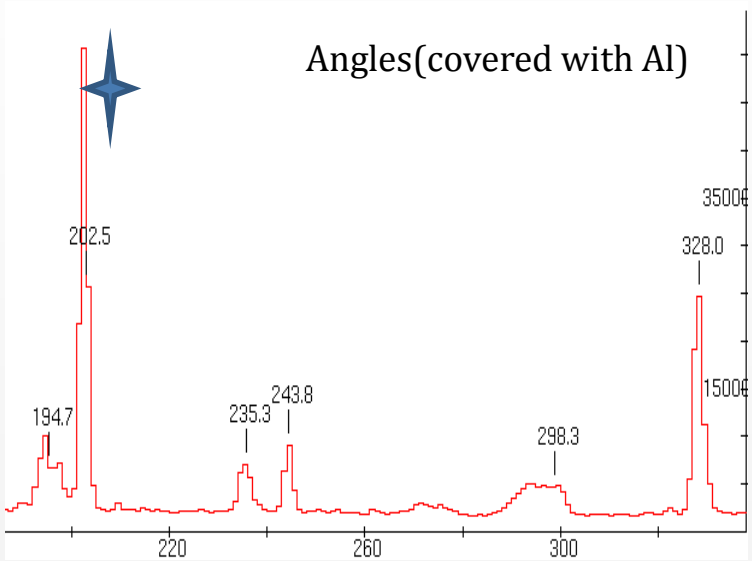


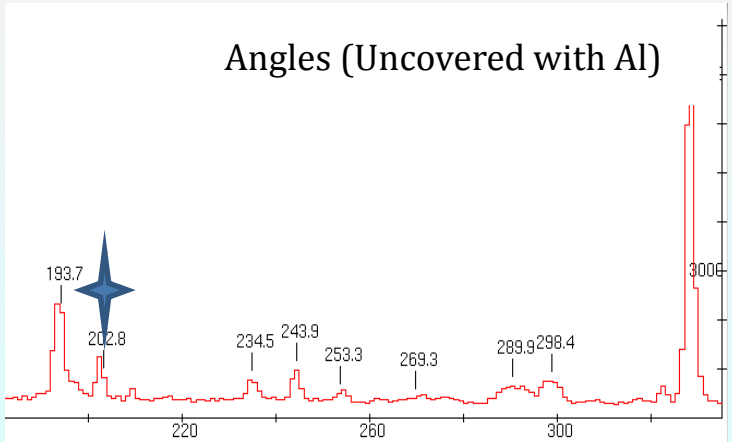
(1)The energies of protons detected by detector in the angles covered by Al are much higher than that of the other angles.

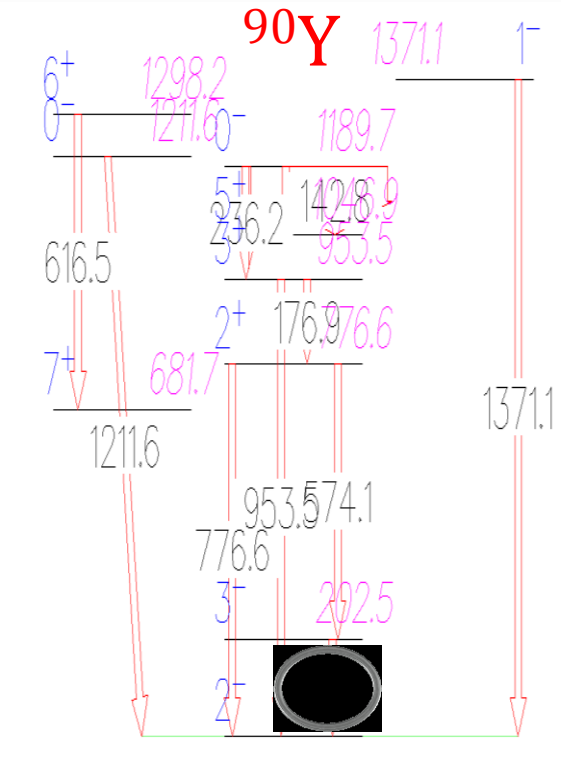
(2)The ratio of $^{92}Nb/^{91}Nb$ increases with energy at the same angle.

(3)The experimental results are consistent with that of (statistical evaporation model)

$^{89}Y + ^{6}Li \longrightarrow ^{90}Y + (^{5}Li)^{*} \longrightarrow ^{90}Y + \alpha + p + 3158\ keV$







^{90}Y at angles covered with Al foil comes from the 1n stripping reaction.

G. L. Zhang *et al*., Phys. Rev. C 97, 044618 (2018).

■ Gamma coincidence with deuteron particles

$^{6}Li \longrightarrow \alpha + d$

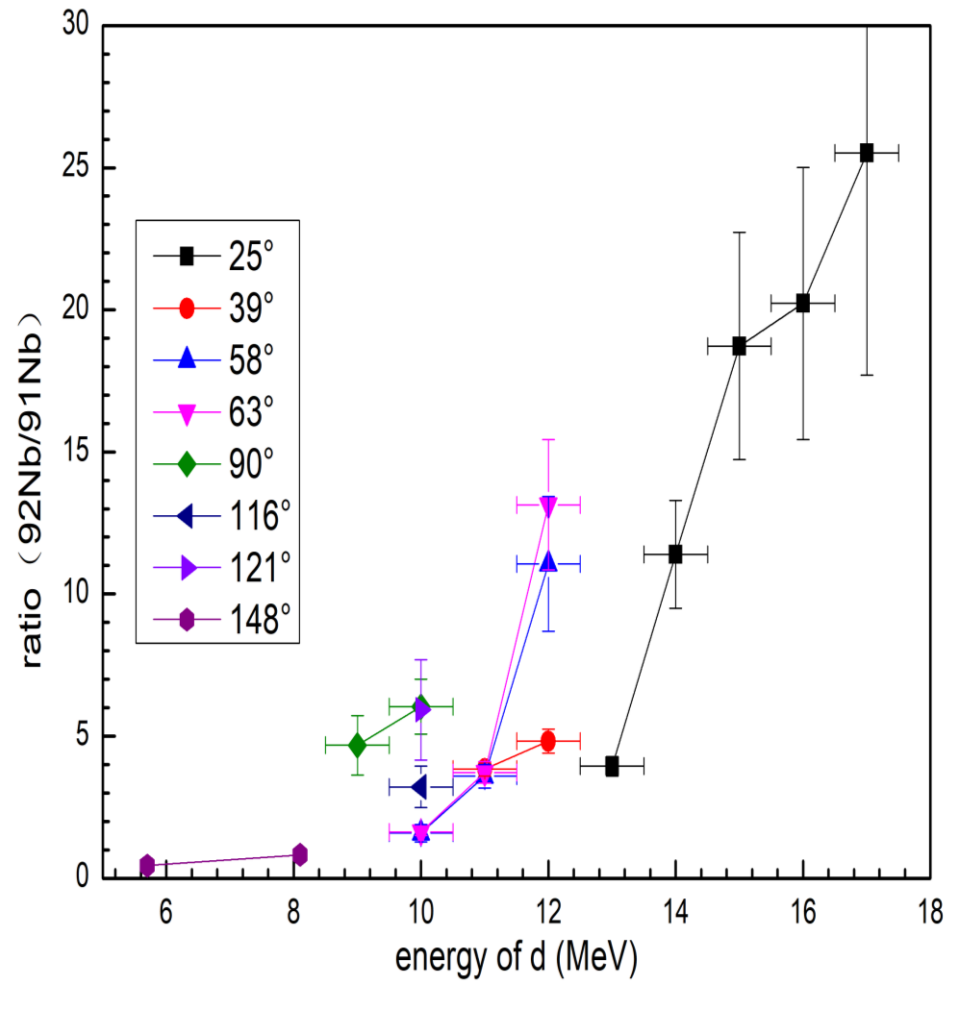
ICF:

$\alpha + {}^{89}Y \longrightarrow ({}^{93}Nb)^{*} \longrightarrow {}^{92}Nb + n$

$\alpha + {}^{89}Y \longrightarrow ({}^{93}Nb)^{*} \longrightarrow {}^{91}Nb + 2n$

breakup	Separation energy (MeV)
$^{6}Li \longrightarrow d+\alpha$	-1.47
$^{6}Li \longrightarrow p+{}^{5}He(n+\alpha)$	-4.43
$^{6}Li \longrightarrow n+{}^{5}Li(\alpha+p)$	-5.66
$d \longrightarrow p+n$	-2.224

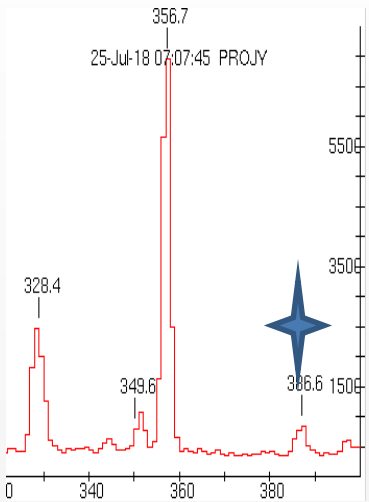
According to the calculations, a part of the deuterons from breakup can pass through the Al foil and ΔE detector

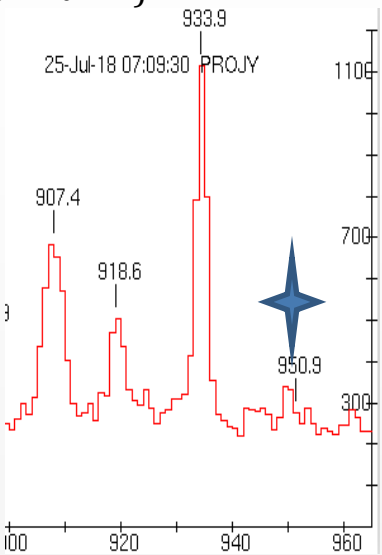


(1) The ratio of $^{92}Nb/^{91}Nb$ increases with energy at the same angle.

(2) By the calculation of statistical evaporation model, $^{92}Nb/^{91}Nb$ <1, which is the same as that at 148°(uncovered with Al), but at angles with covered by Al, since the deuteron must pass through Al, it is asked for higher energy, so $^{92}Nb/^{91}Nb$ >1

Angles(covered with Al)

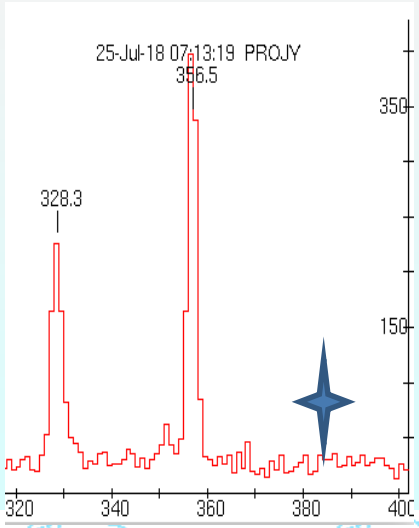


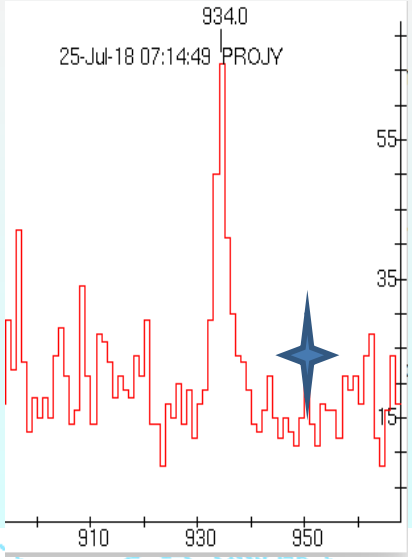


$^{89}Y+^{6}Li$——>$^{93}Nb+d+455.65$ keV

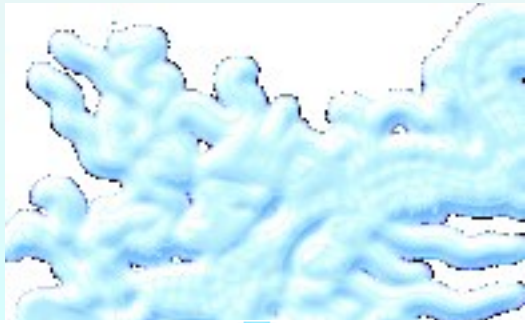
(1) The typical γ rays (385, 949) of ^{93}Nb are different at angles (covered and uncovered with Al foils)

Angles (Uncovered with Al)





(2) In α stripping reaction channel, the energy of d is higher than 11.5 MeV, through dynamical model calculation, the energy range of d is 28~34 MeV.



■ Gamma coincidence with triton particles

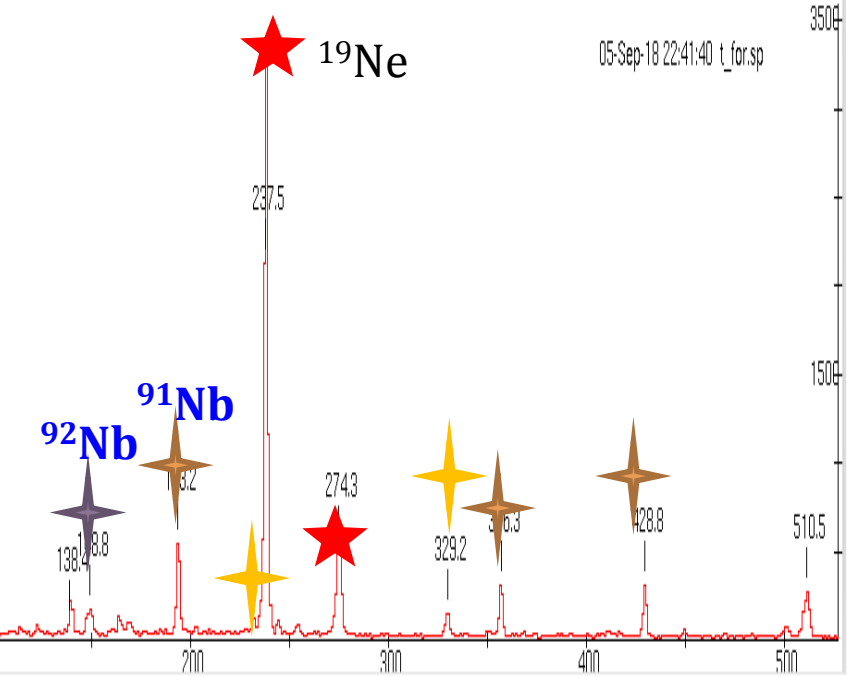
^{3}He stripping :

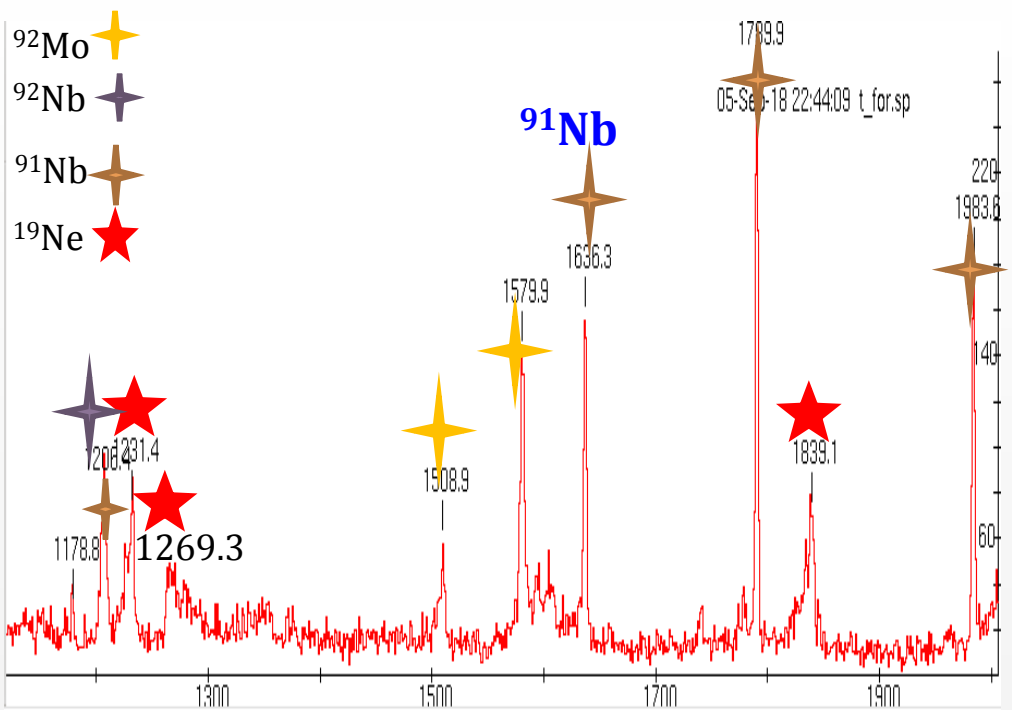
$^{6}Li + ^{89}Y \longrightarrow t + ^{92}Nb + (-2.12\ MeV)$

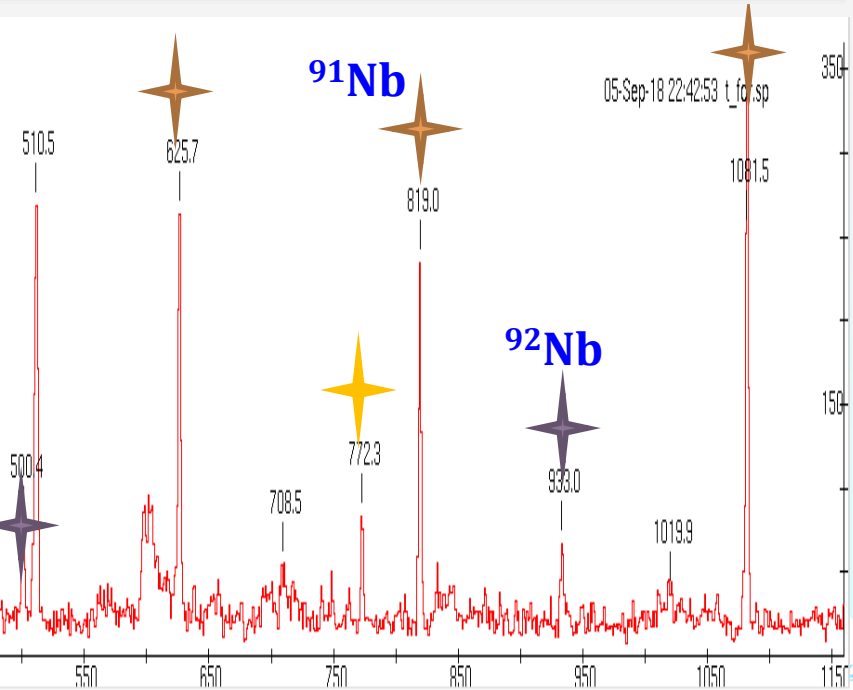
(1) $E_t \approx$ 25~30.5 MeV by dynamic model calculation.

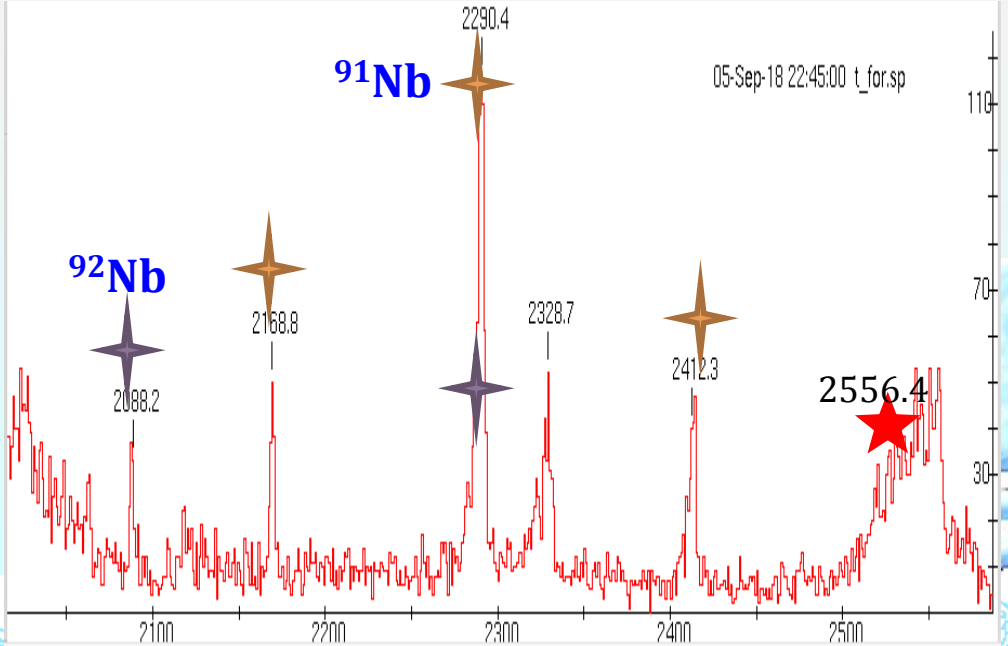
$^{6}Li + ^{16}O \longrightarrow ^{19}Ne + t + (-7.35\ MeV)$

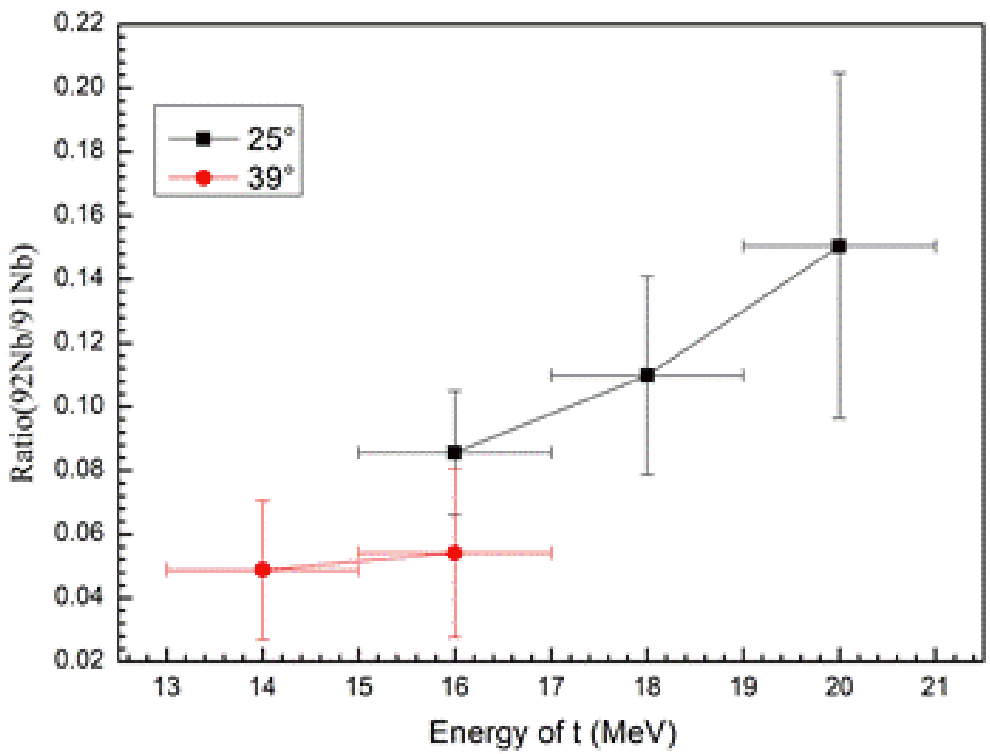
(2) $E_t \approx$ 8~24 MeV by dynamic model calculation.


^{19}Ne
05-Sep-18 22:41:40 t_for.sp
^{92}Nb
^{91}Nb
297.5
274.3
329.2
428.8
510.5
138.4
200
300
400
500


^{92}Mo
^{92}Nb
^{91}Nb
^{19}Ne
^{91}Nb
05-Sep-18 22:44:09 t_for.sp
1789.9
1636.3
1579.9
1508.9
1231.4
1269.3
1178.8
1839.1
1983.6
1300
1500
1700
1900

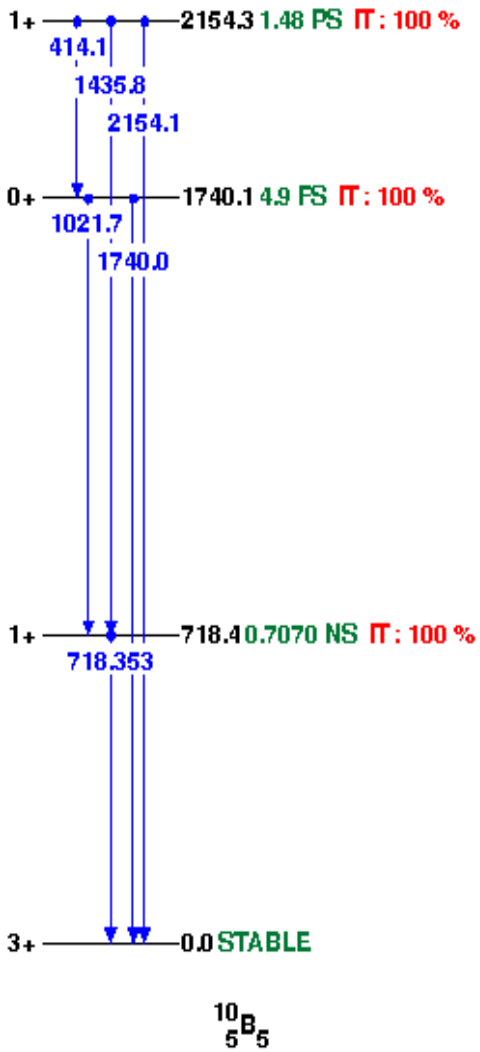

^{91}Nb
05-Sep-18 22:42:53 t_for.sp
510.5
625.7
819.0
1081.5
^{92}Nb
772.3
933.0
500.4
708.5
1019.9
550
650
750
850
950
1050

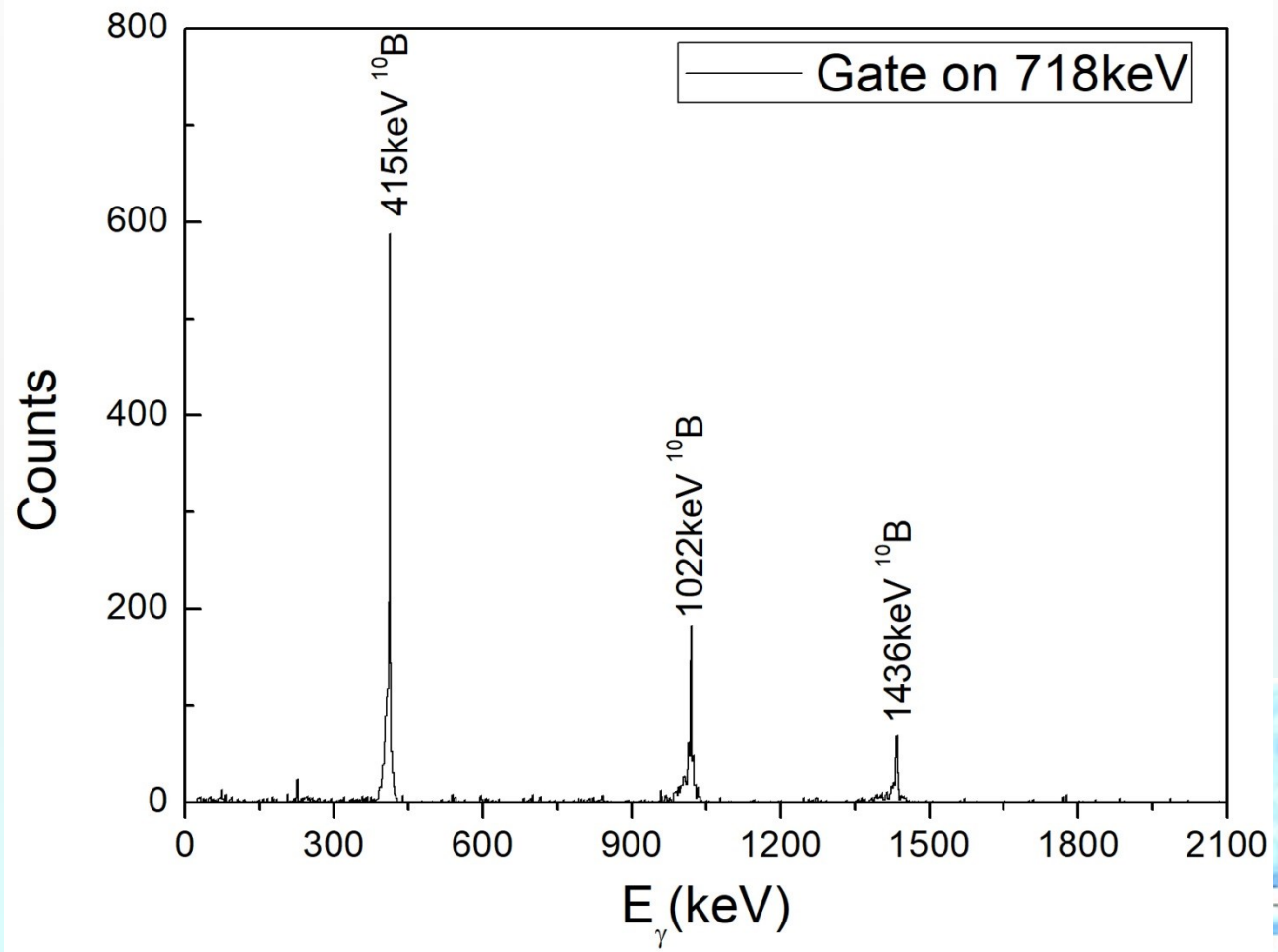

2290.4
^{91}Nb
05-Sep-18 22:45:00 t_for.sp
^{92}Nb
2168.8
2328.7
2412.3
2088.2
2556.4
2100
2200
2300
2400
2500



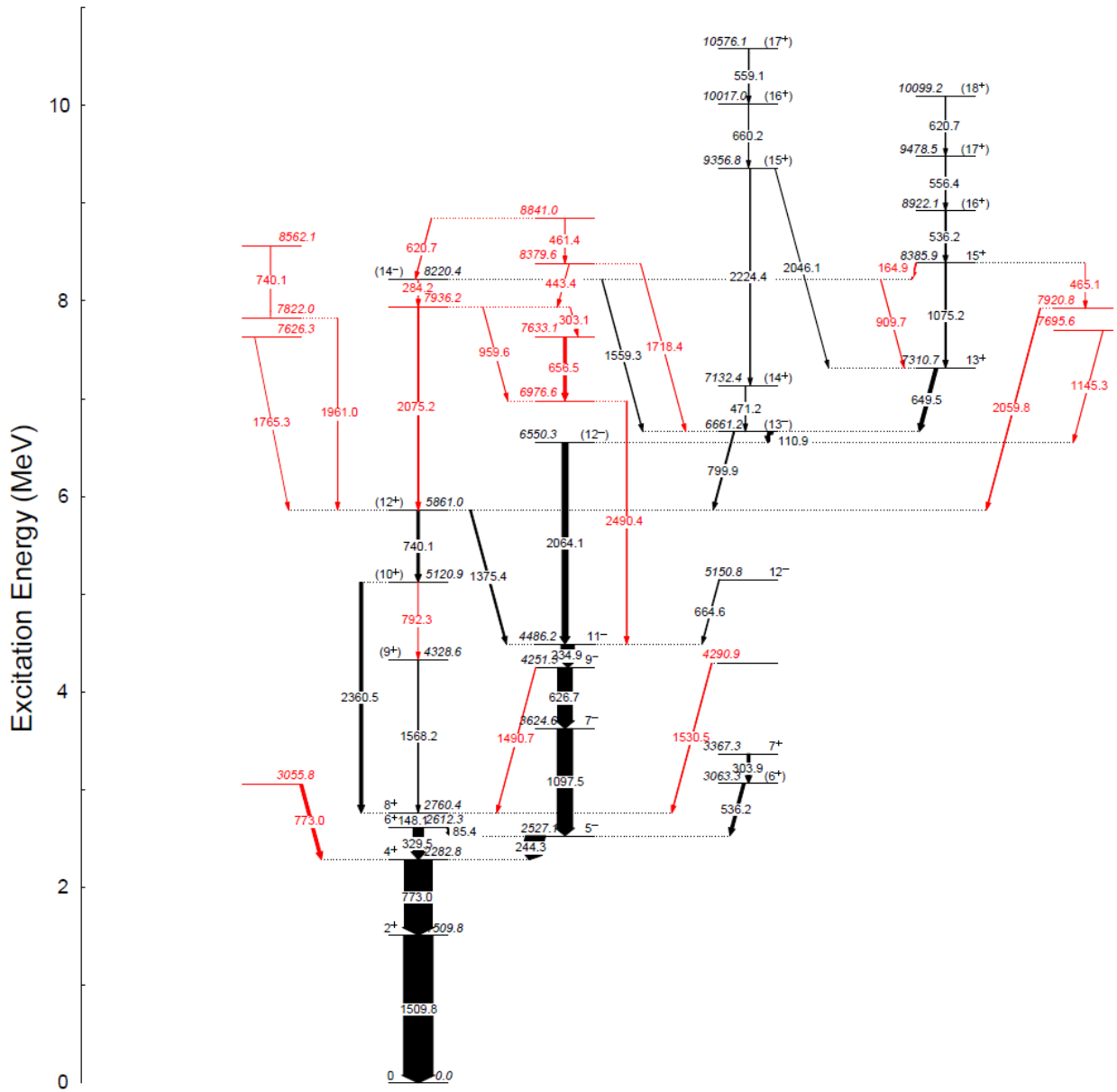
(1) The energies of triton are different at different angles, it is much higher at smallest angle.
(2) The ratio at smallest angle is larger than that at the other angles.

$^{6}Li+^{12}C=^{10}B+^{8}Be$? / $^{10}B = ^{6}Li+^{4}He$?





New energy levels of ^{92}Mo

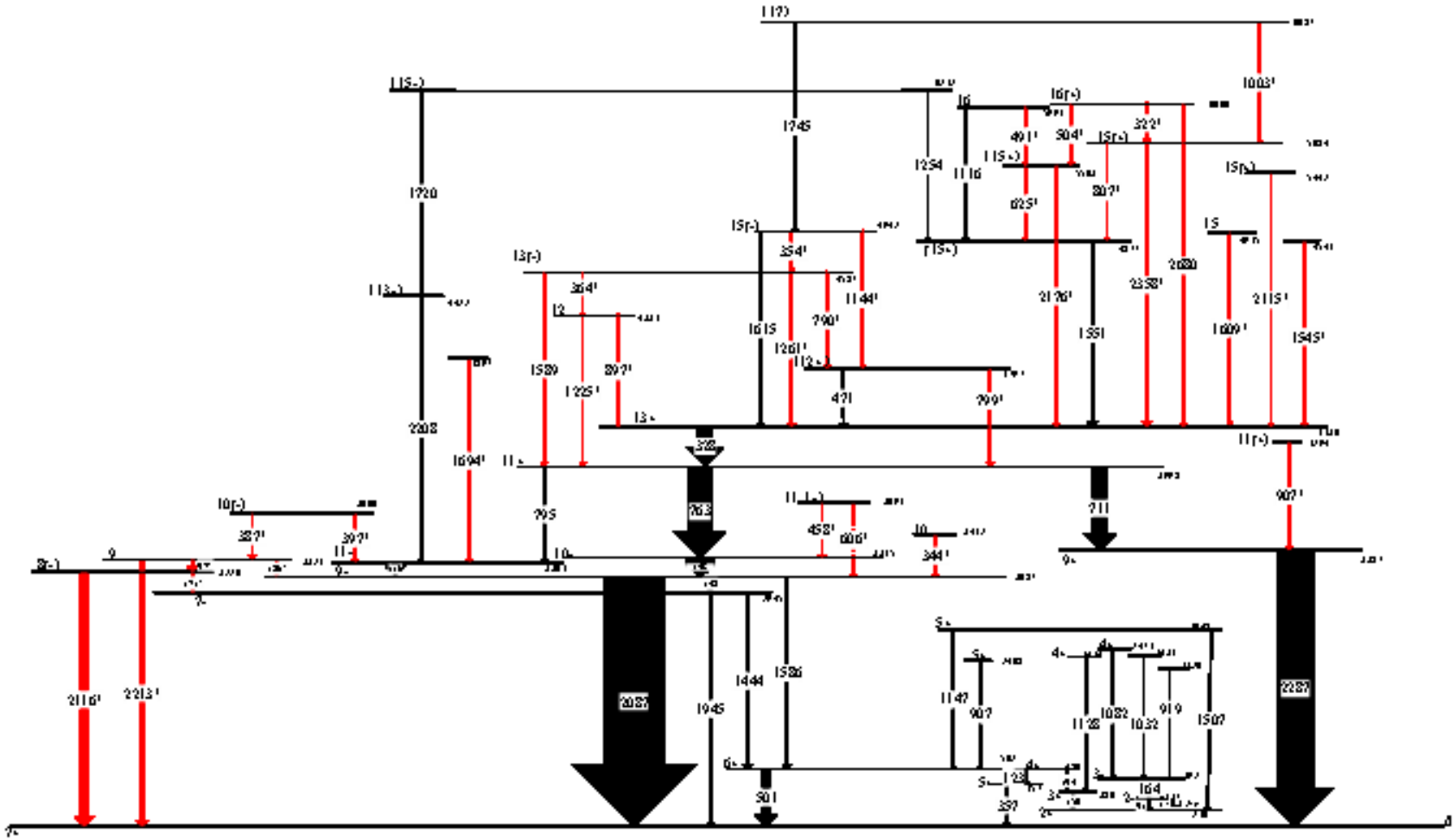


From 92mo.gls

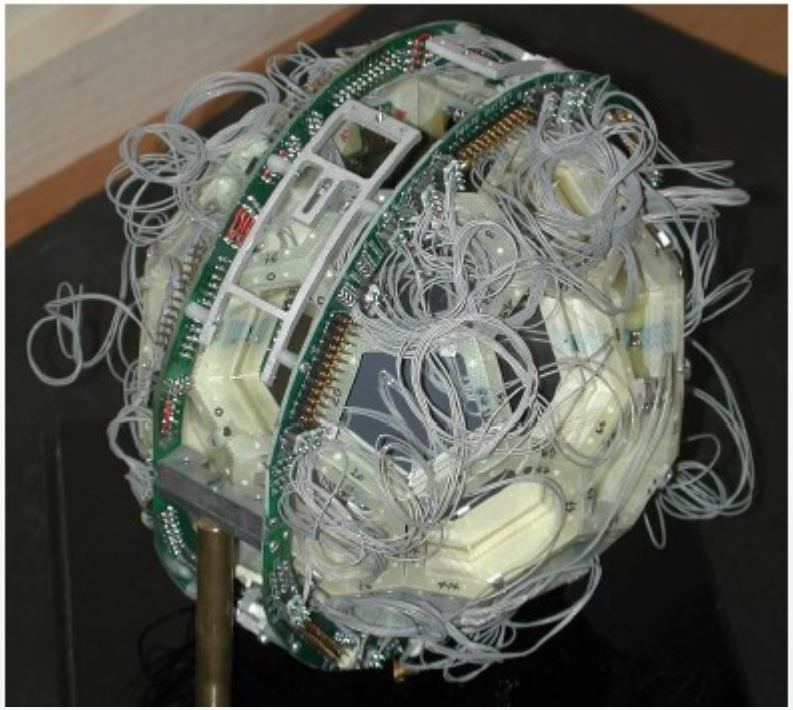
92mo-6.27.eps, created 27-Jun-18 20:19:07

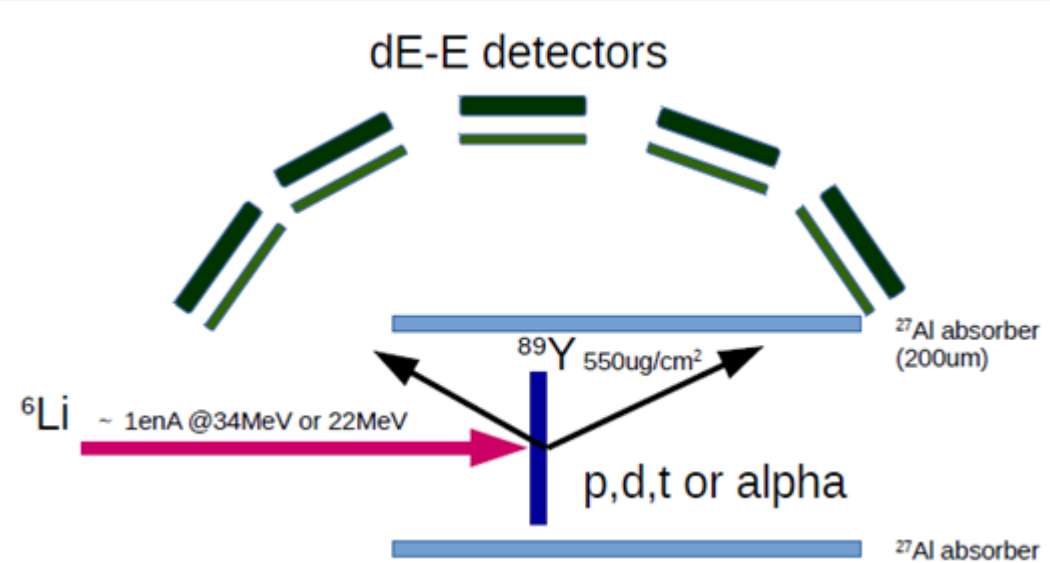
Rad Ware

New energy levels of ^{92}Nb



$^{6}Li+^{209}Bi$ experiment at INFN-LNL in Italy



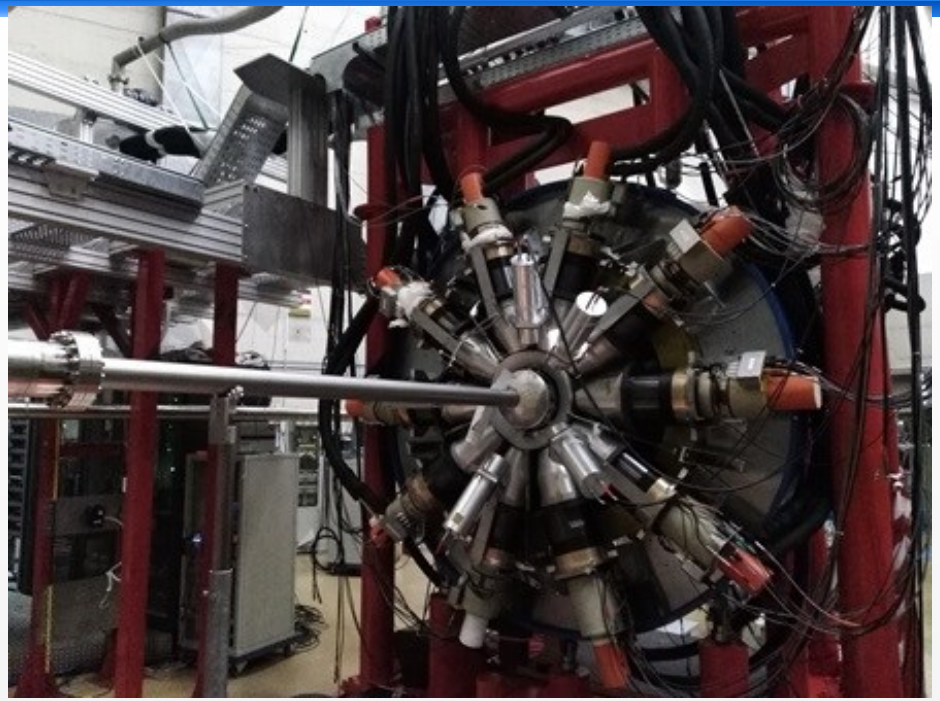


5 days beam time

34MeV 6Li, 166μm Al foil

30MeV 6Li, 138 μm Al foil

28MeV 6Li, 124μm Al foil



Summary

- ✓ A powerful combination of gamma and light charged particles can **distinguish the various reaction channels** **and** **separate the different reaction processes** **including CF, ICF and transfer**.
- ✓ A powerful combination of gamma and light charged particles can correct and give new energy levels for many nuclei in the future.
- ✓ Particle-particle coincidence can explore the different reaction processes to study the reaction mechanisms in the future.

Not only explore the reaction dynamics of weakly bound nuclei at low energies, but also study the nuclear structure!!!

Thank you for your attention