Cluster-transfer reactions with radioactive beams: a spectroscopic tool for neutron-rich nuclei

Simone Bottoni

University of Milano and INFN
KU Leuven - Instituut voor Kern- en Stralingsfysica

Introduction:

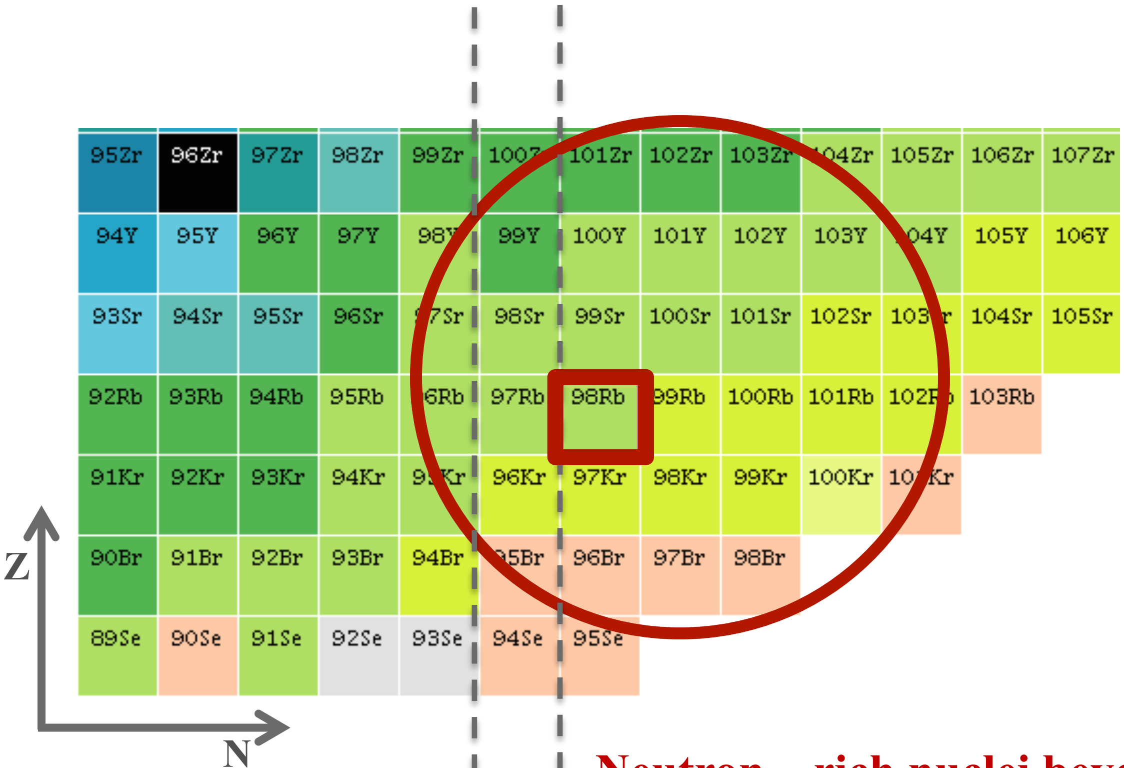
- Cluster-transfer reactions with RIB's

The ISOLDE pilot experiment

- $^{98}Rb/^{98}Sr+^{7}Li$
- The experiment
- Gamma spectroscopy
- Reaction dynamics

Conclusions and future perspectives

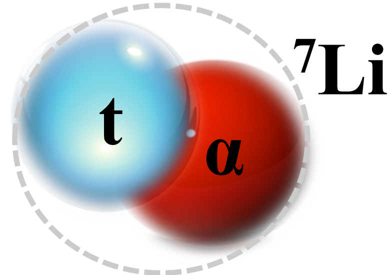
Test of a new reaction mechanism with RIB’s to populate neutron-rich nuclei at medium-high energy and spin

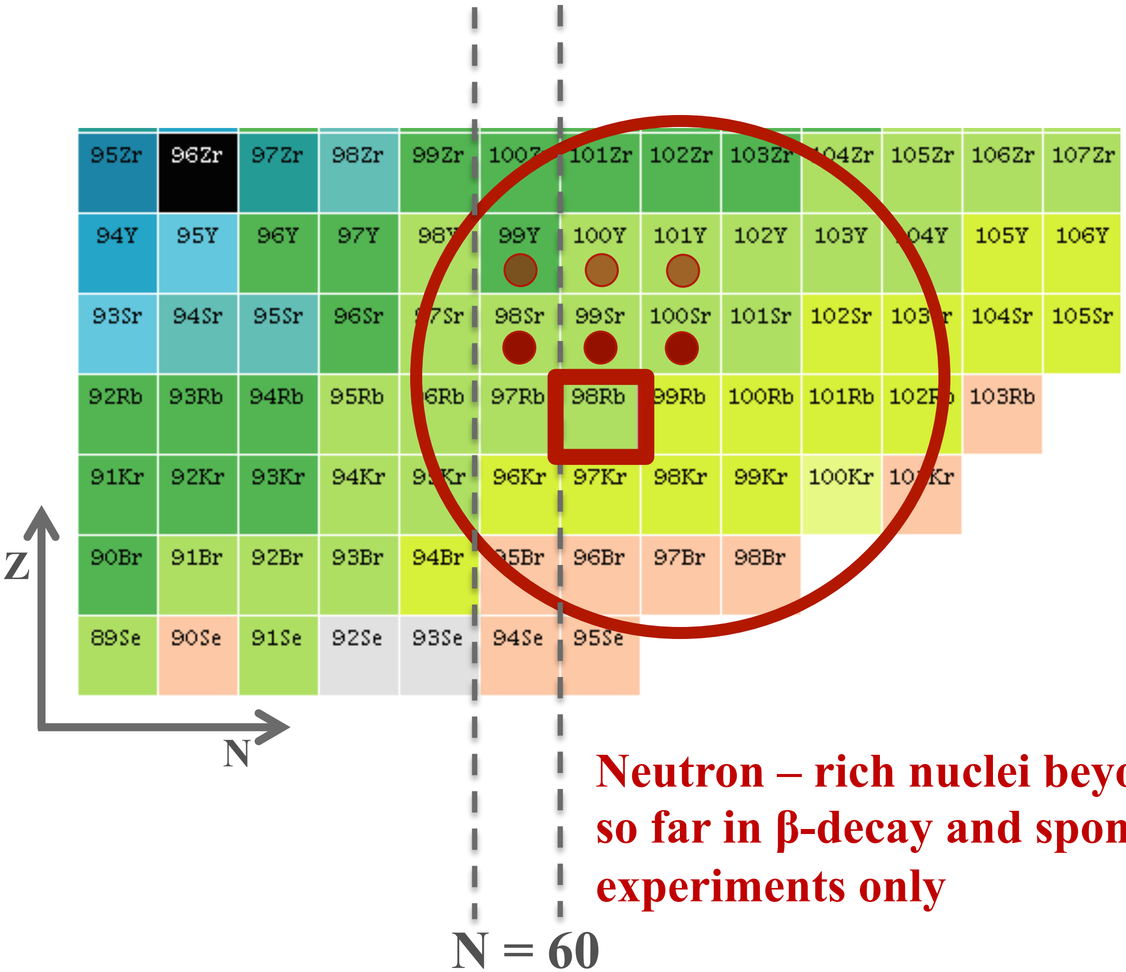


Neutron – rich nuclei beyond N = 60 studied so far in β-decay and spontaneous fission experiments only

N = 60

Test of a new reaction mechanism with RIB’s to populate neutron-rich nuclei at medium-high energy and spin





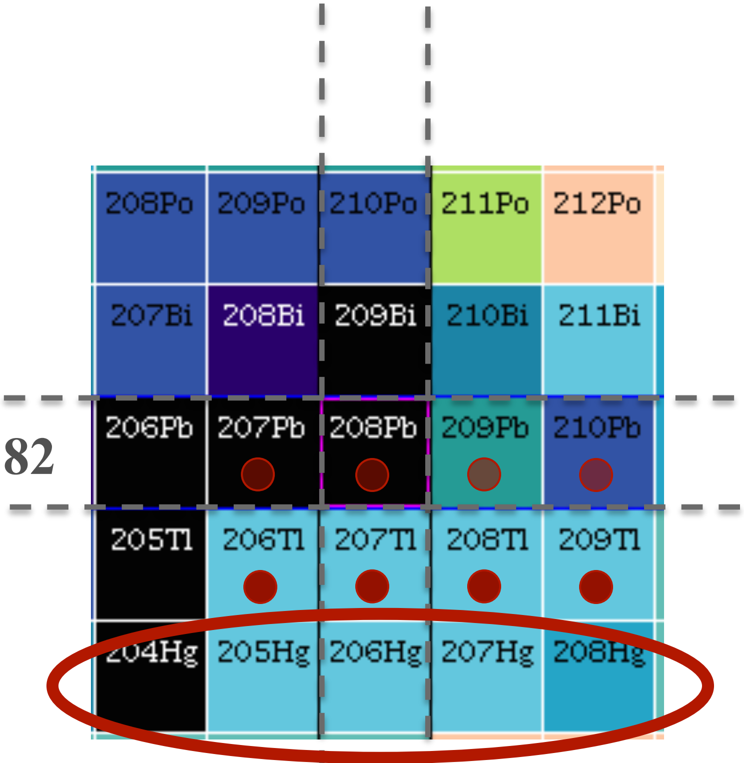
CLUSTER – TRANSFER WITH A ^{7}Li TARGET @ ISOLDE

^{7}Li(^{98}Rb,αxn)

^{7}Li(^{98}Rb,txn)

Neutron – rich nuclei beyond N = 60 studied so far in β-decay and spontaneous fission experiments only

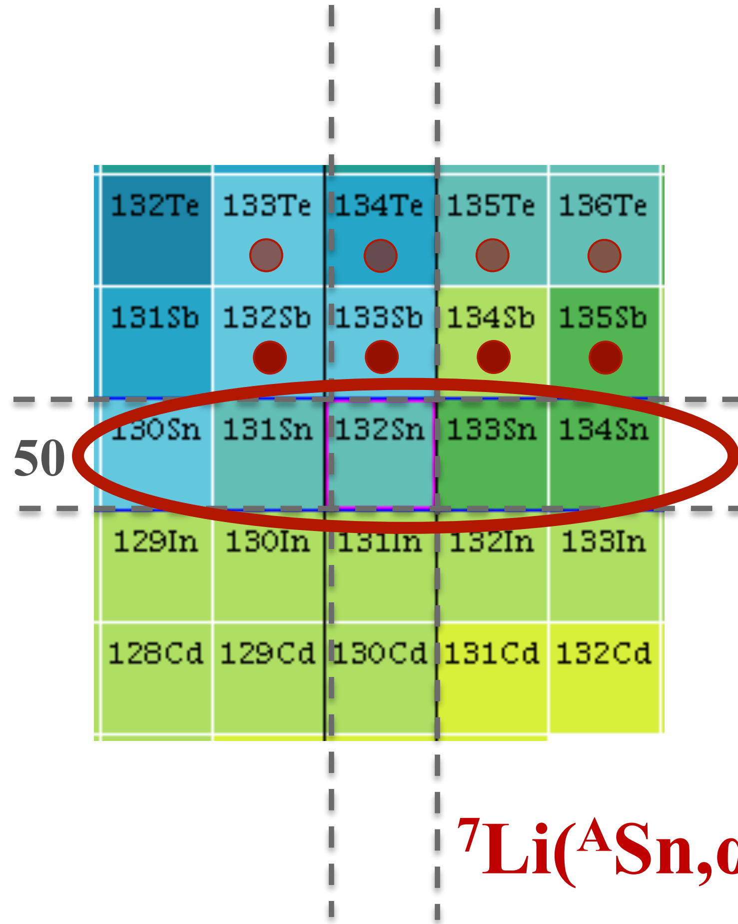
A possible mechanism to populate low-lying medium spin states around closed shells



Z = 82

N = 126

$^{7}Li(^{A}Hg,\alpha xn)$



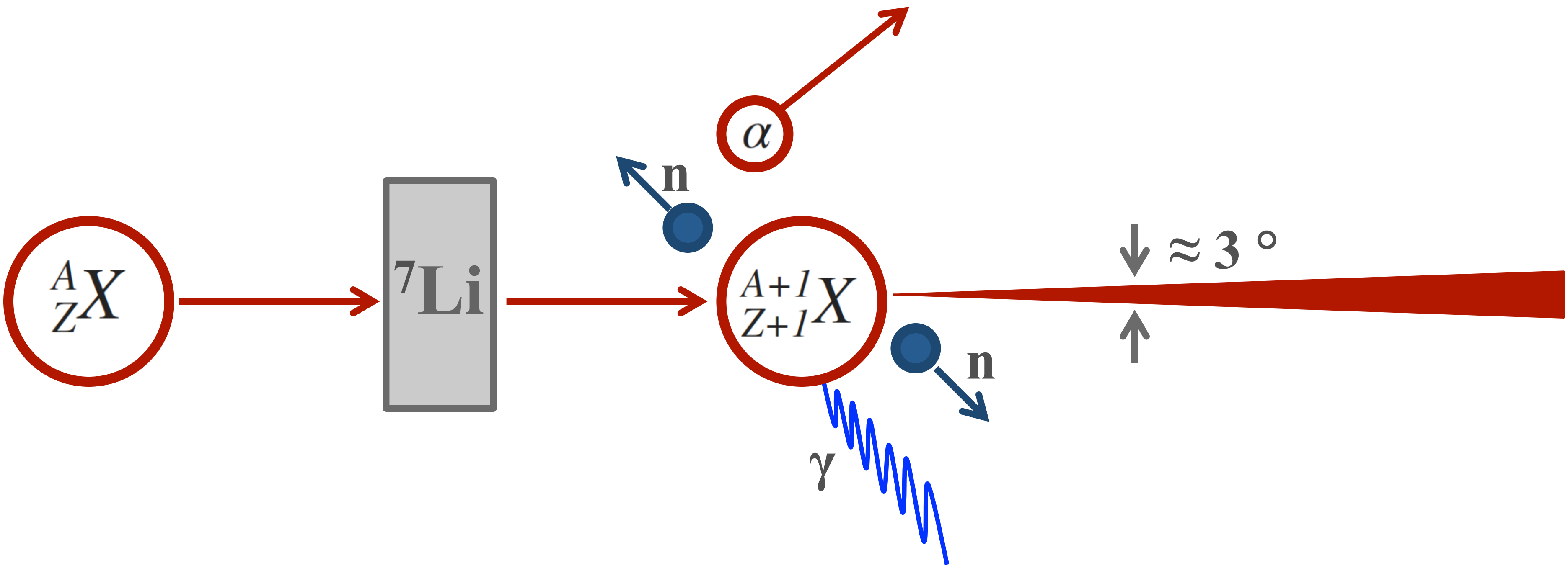
Z = 50

N = 82

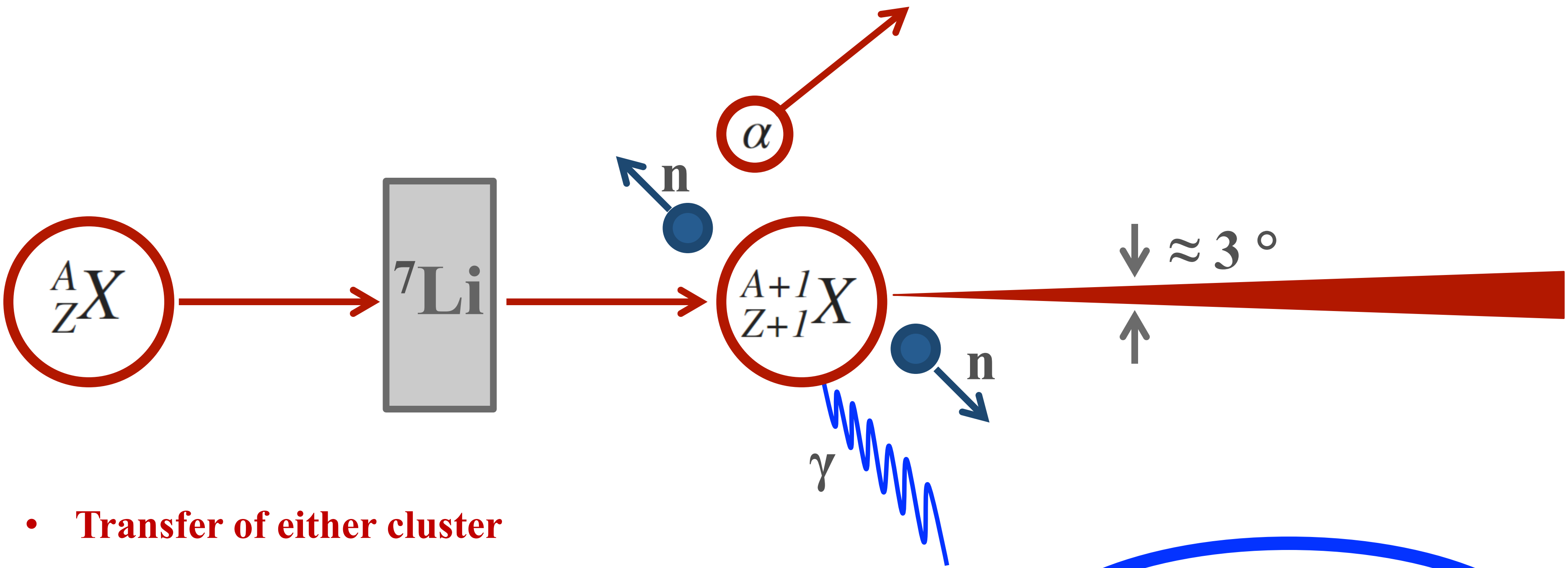
$^{7}Li(^{A}Sn,\alpha xn)$

at least 4-5 MeV /A

$$^{A}_{Z}X + {}^{7}Li = {}^{A+3}_{Z+1}X + \alpha + xn$$



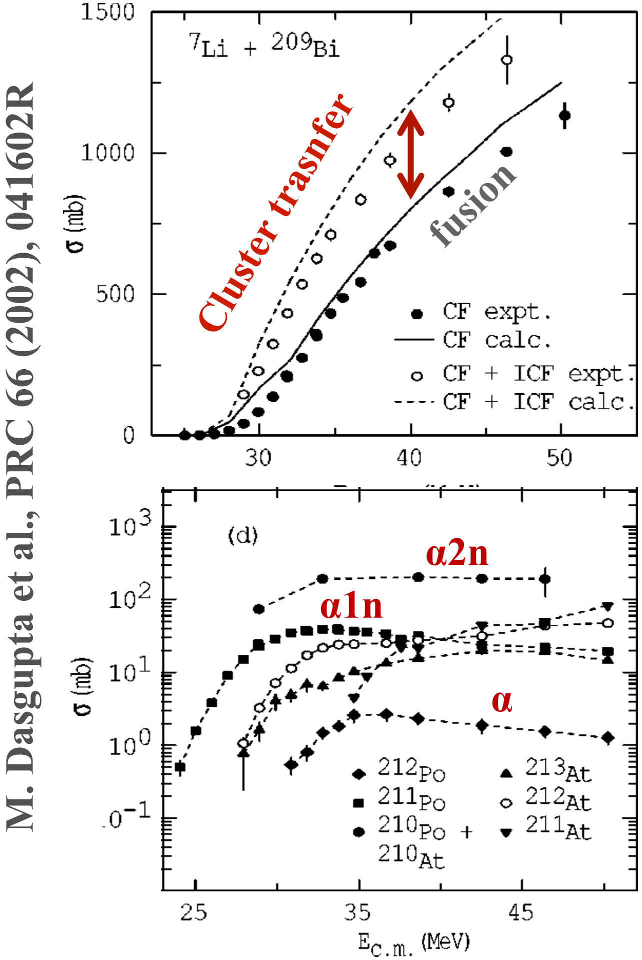
$$ {}^{A}_{Z}X + {}^{7}Li = {}^{A+3}_{Z+1}X + \alpha + xn $$



- **Transfer of either cluster**
- **Evaporation of few neutrons**
- **Detection of complementary charged particle**
- **Detection of γ-rays in coincidence**

NO recoil detection nedeed for Doppler correction

FROM DIRECT KINEMATICS
^{7}Li + STABLE TARGETS

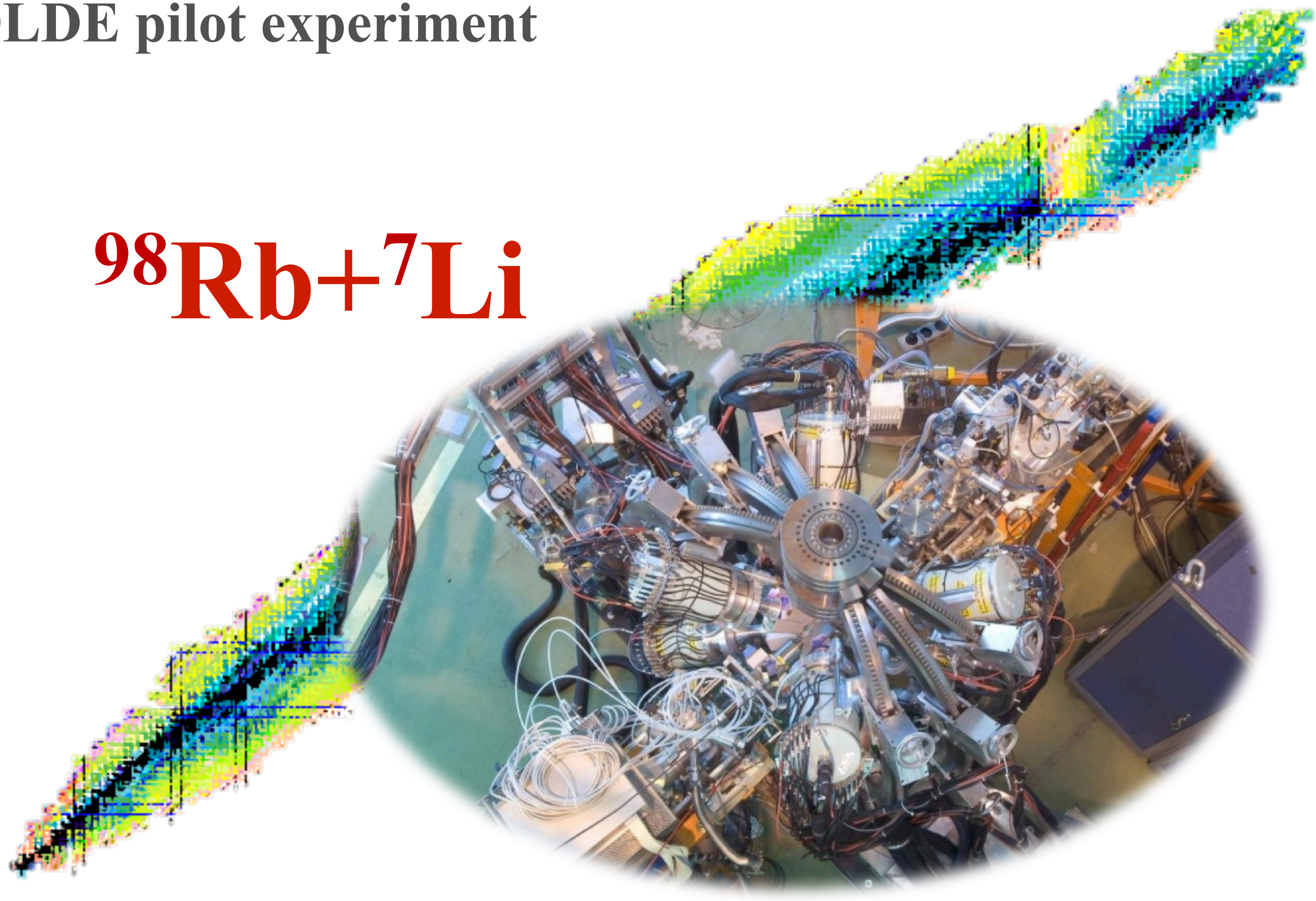


- **Sizable cross section of cluster-transfer**
- **Favorable capture of t and emission of α**
- **Evaporation of 1-2n**
- **Population of neutron – rich systems**
- **Population of off – Yrast states**
- **Intermediate spins up to 12 ℏ**

G.D. Draculis et al., JPG 23 (1997), 1191
D.S. Judson et al., PRC 76 (2007), 054306
R.M. Clark et al., PRC 72 (2005), 054605

CLUSTER-TRANSFER REACTIONS WITH RIB's:
the ISOLDE pilot experiment

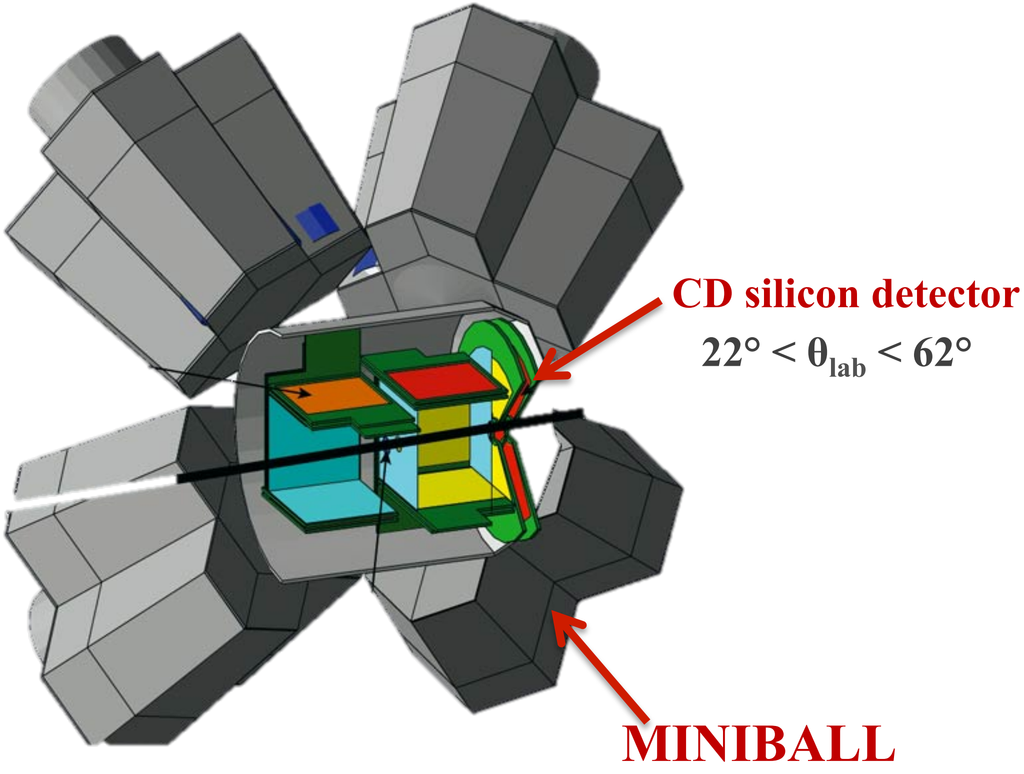
$^{98}Rb + ^{7}Li$



^{98}Rb/^{98}Sr+^{7}Li @ 2.5 MeV/A

@ the Coulomb Barrier

1.5 mg/cm^2 LiF



$^{98}Rb/^{98}Sr + ^{7}Li$ @ 2.5 MeV/A

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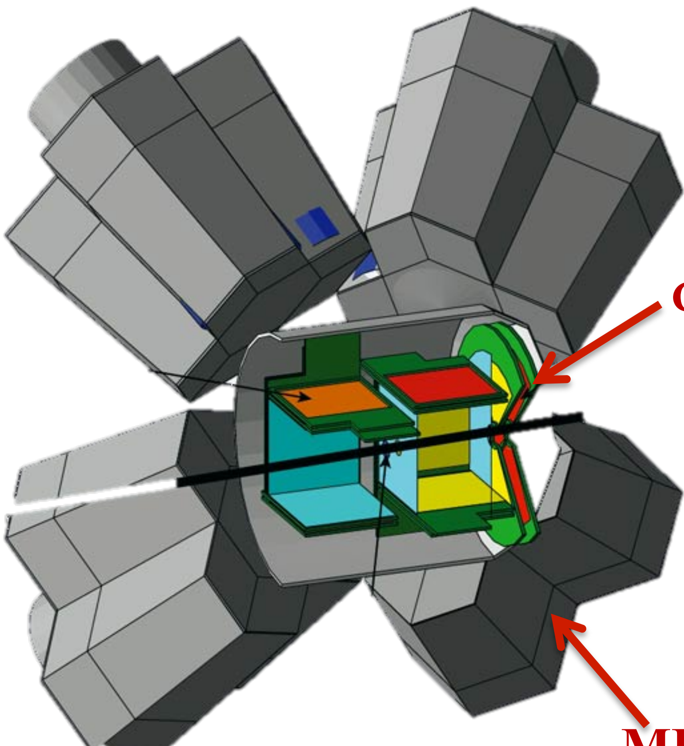
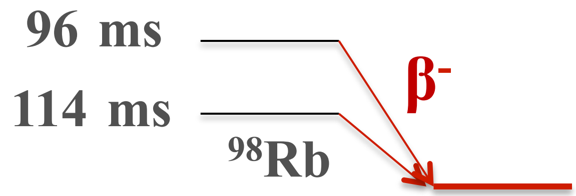
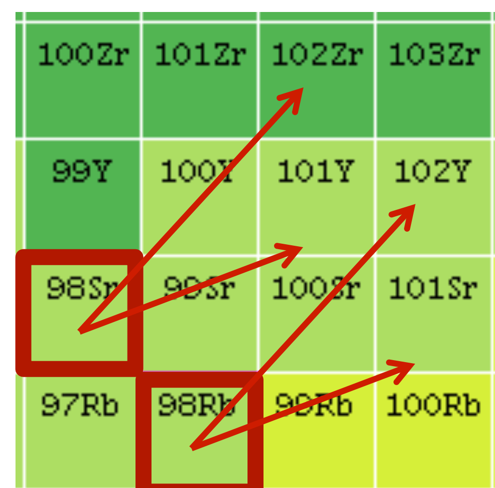


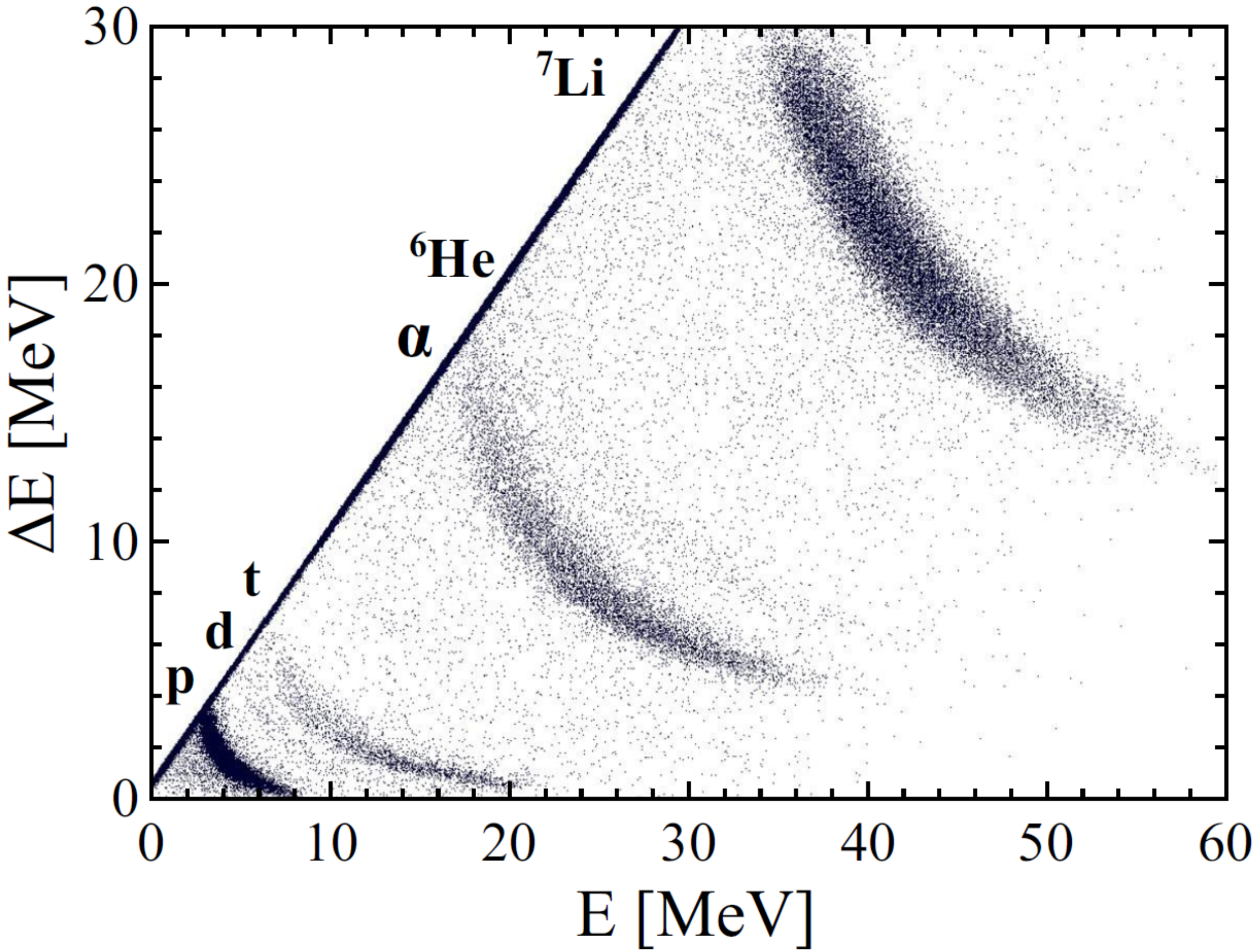
BEAM COMPOSITION



- $^{98}Rb/^{98}Sr \approx 2/3$
- beam intensity ≈ $2 \cdot 10^4$ pps
- beam time: 3 days

Reactions took place on both Rb and Sr





CHANNELS OBSERVED

- **Elastic scattering**
- **Inelastic scattering**
- **1p pick-up**
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- **α-transfer**
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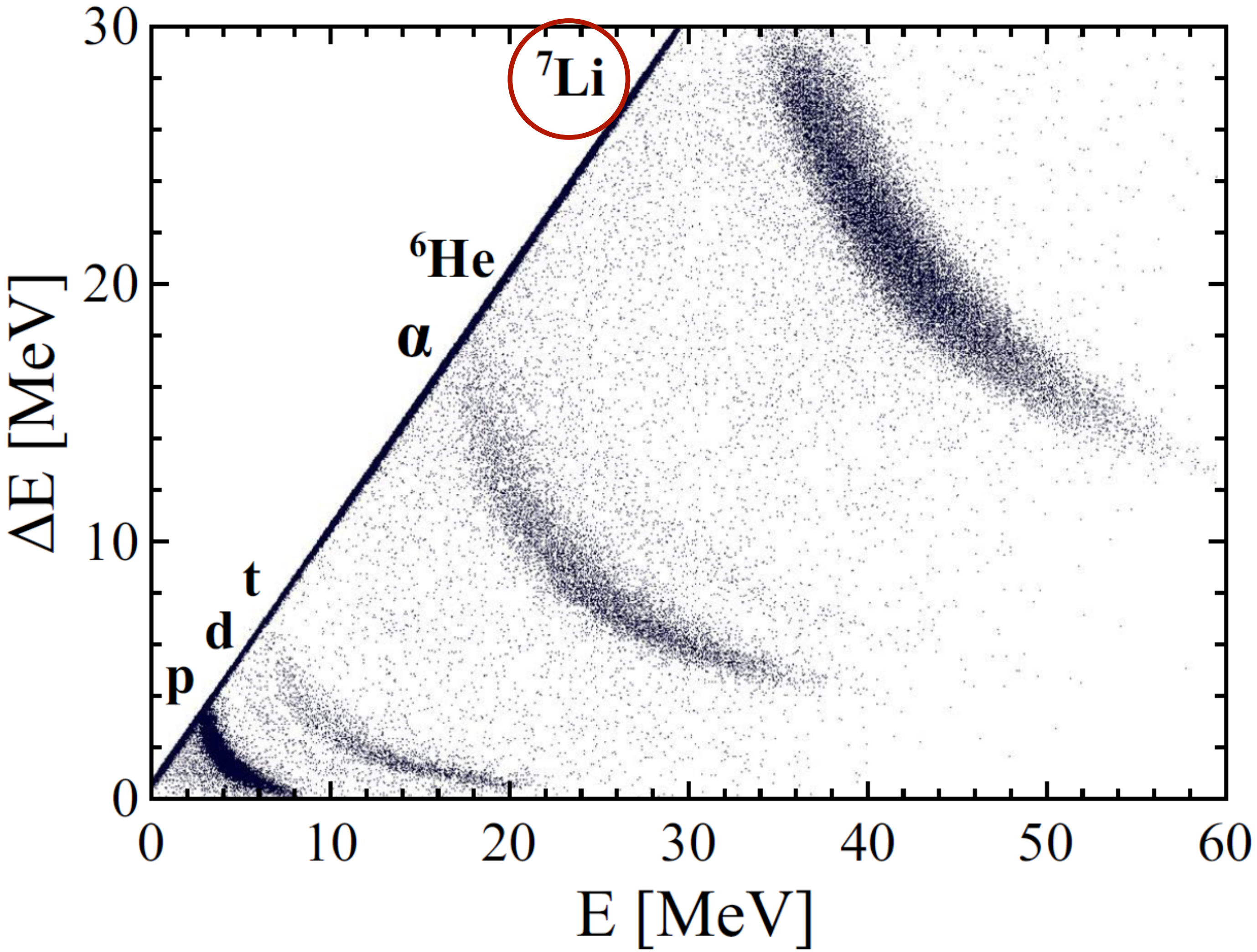
- **^{6}Li → α-d breakup**
- **Fusion - evaporation**



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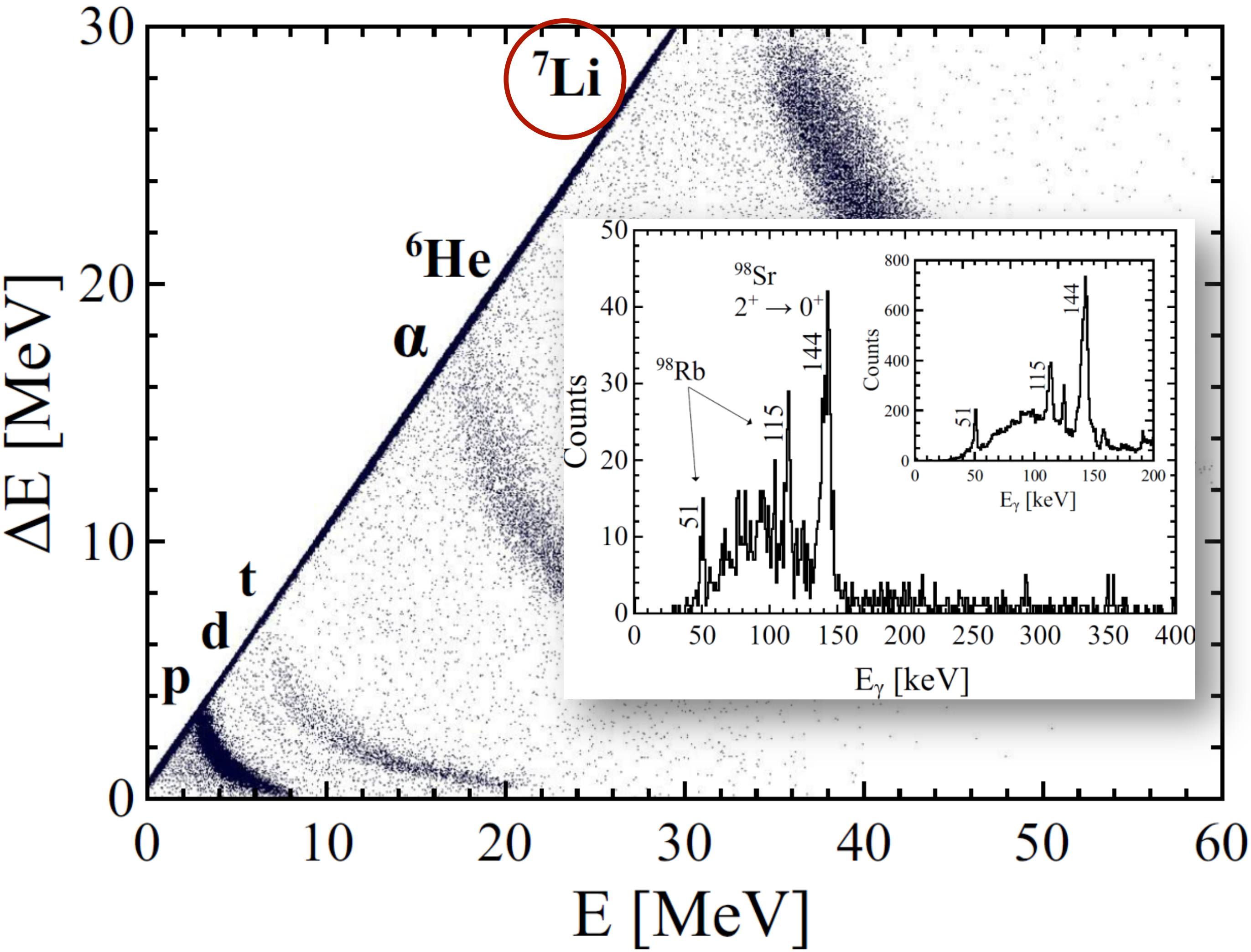

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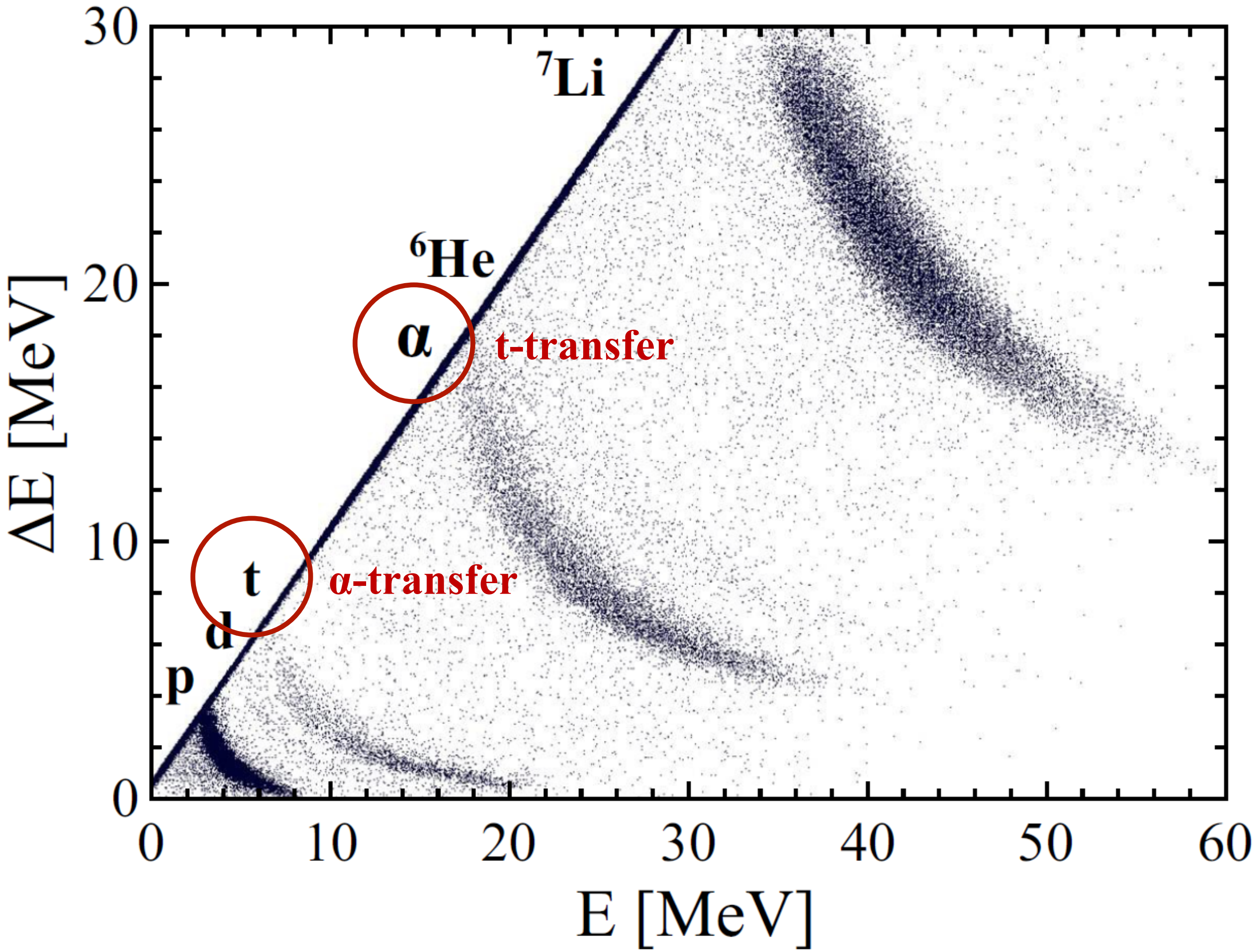

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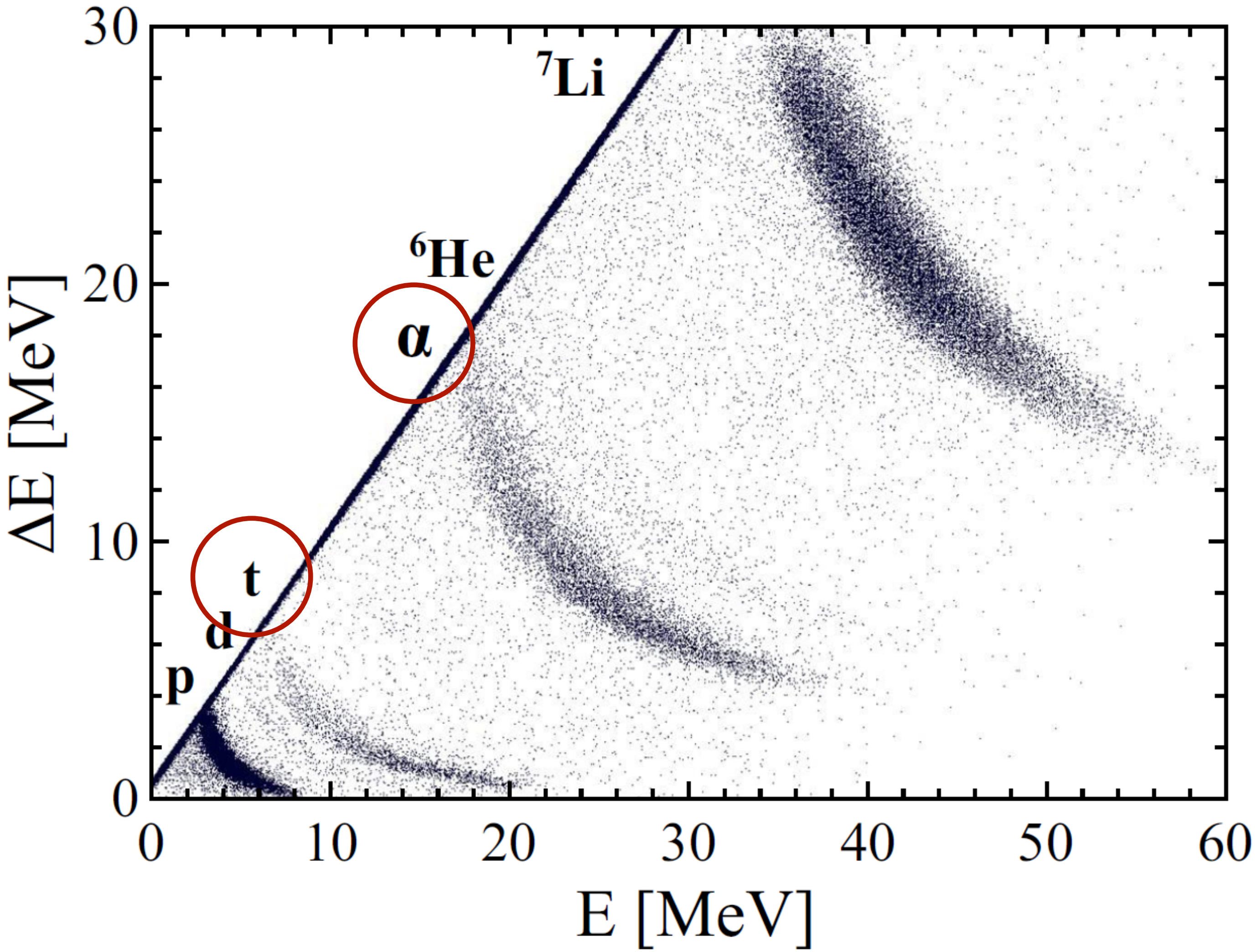

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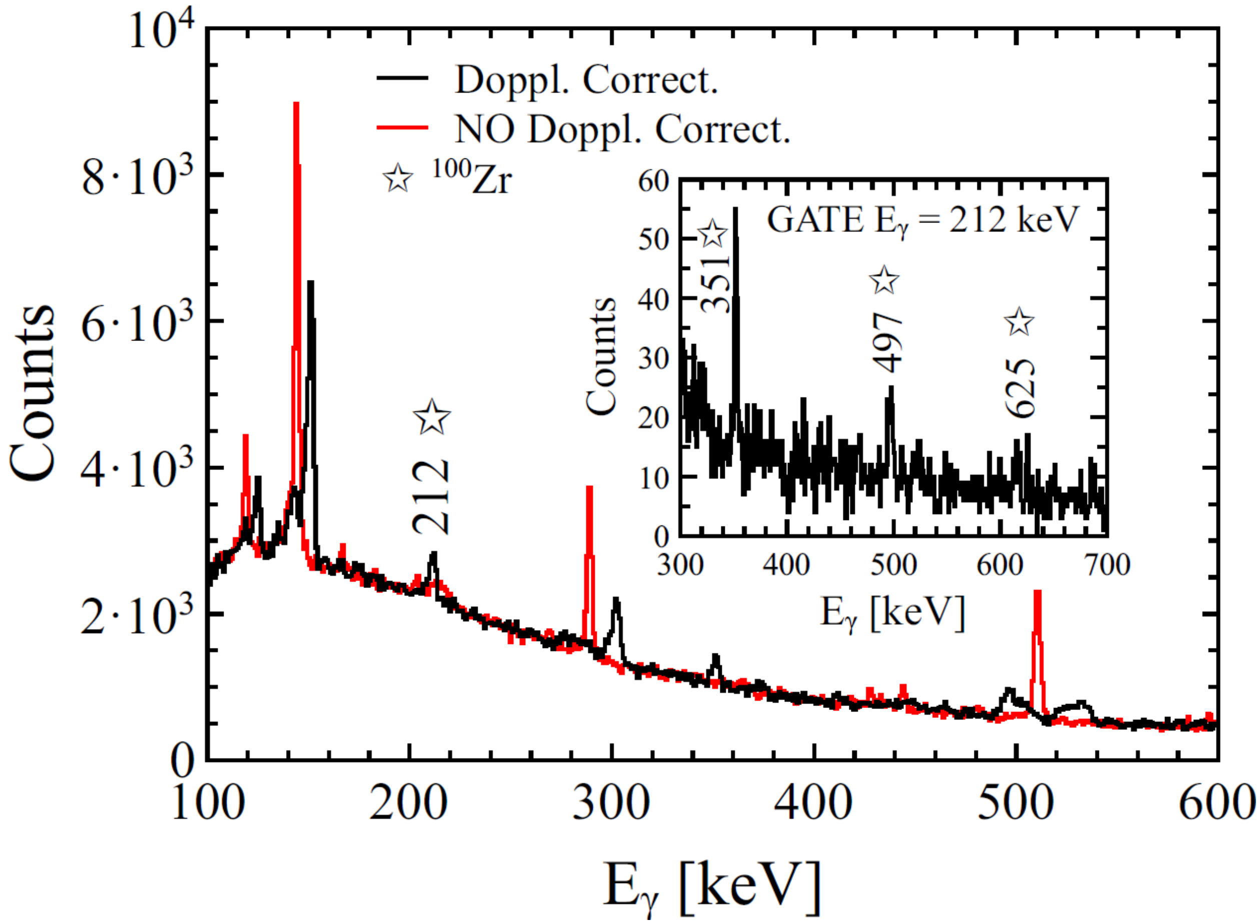

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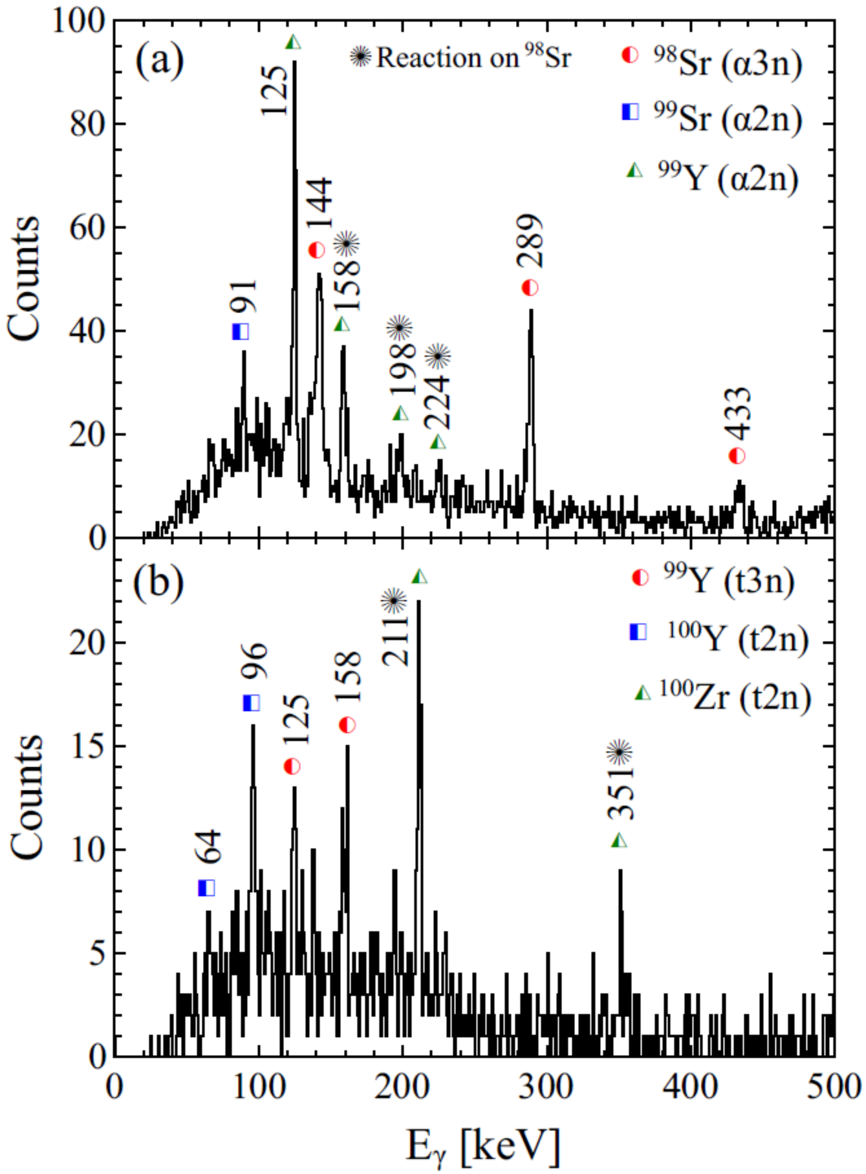
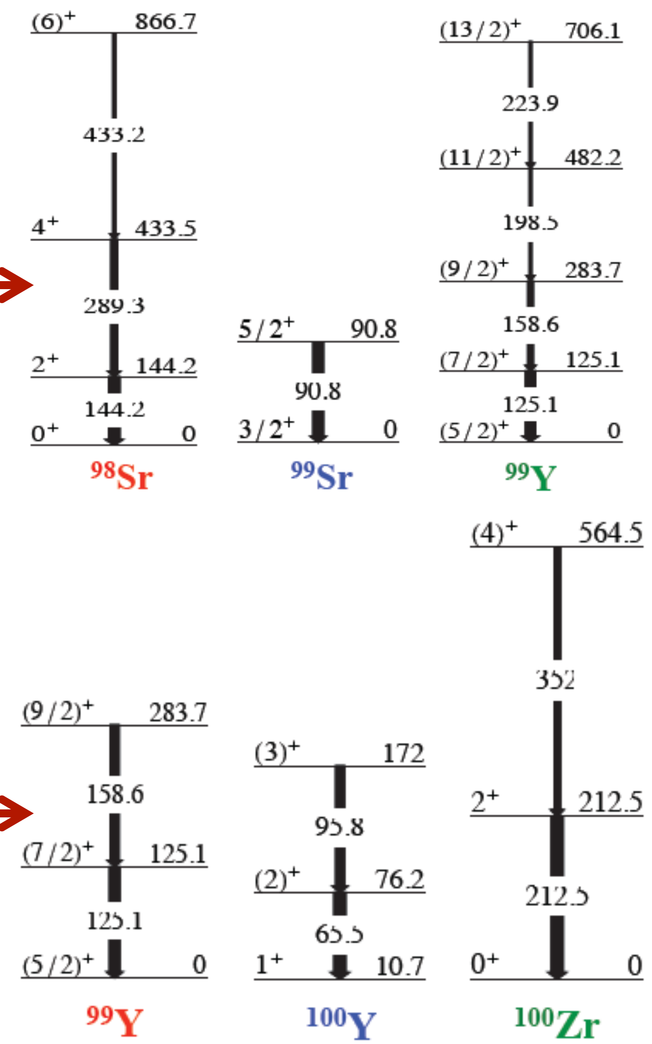
^{98}Rb + ^{7}Li = ^{105}Zr*

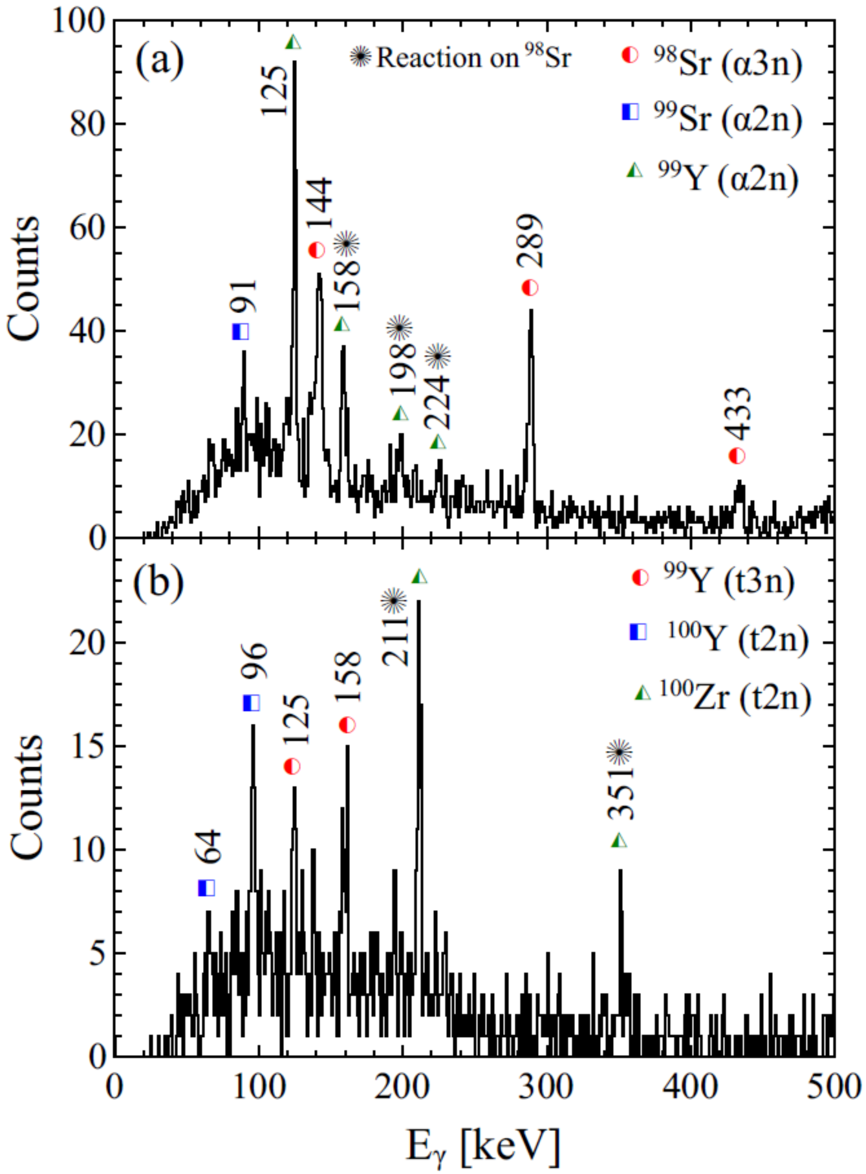
-5n = ^{100}Zr



t-transfer

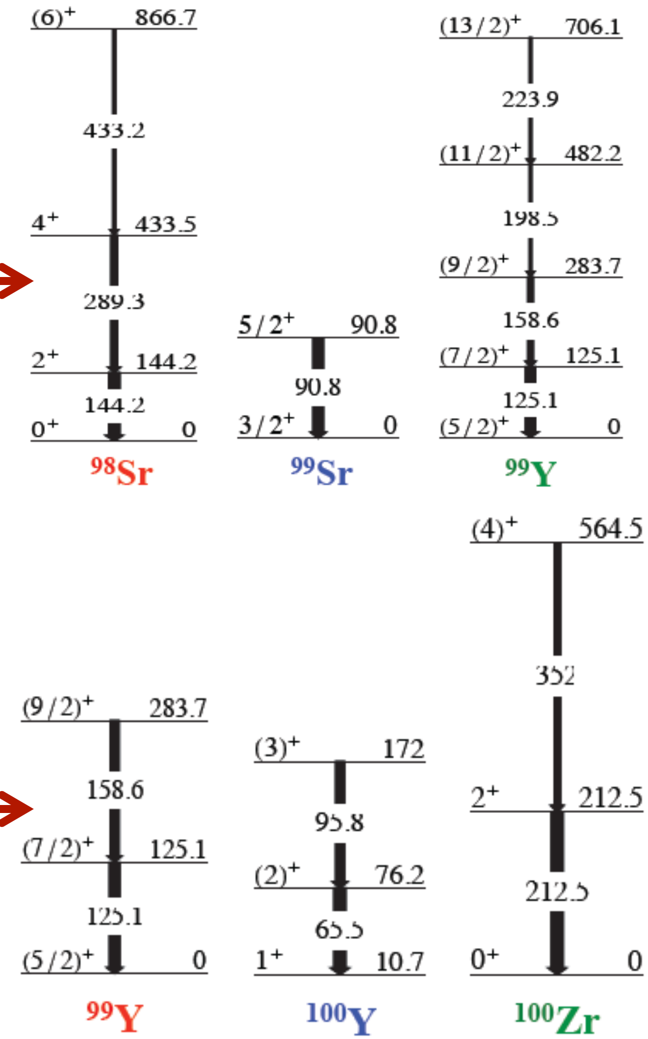
α-transfer



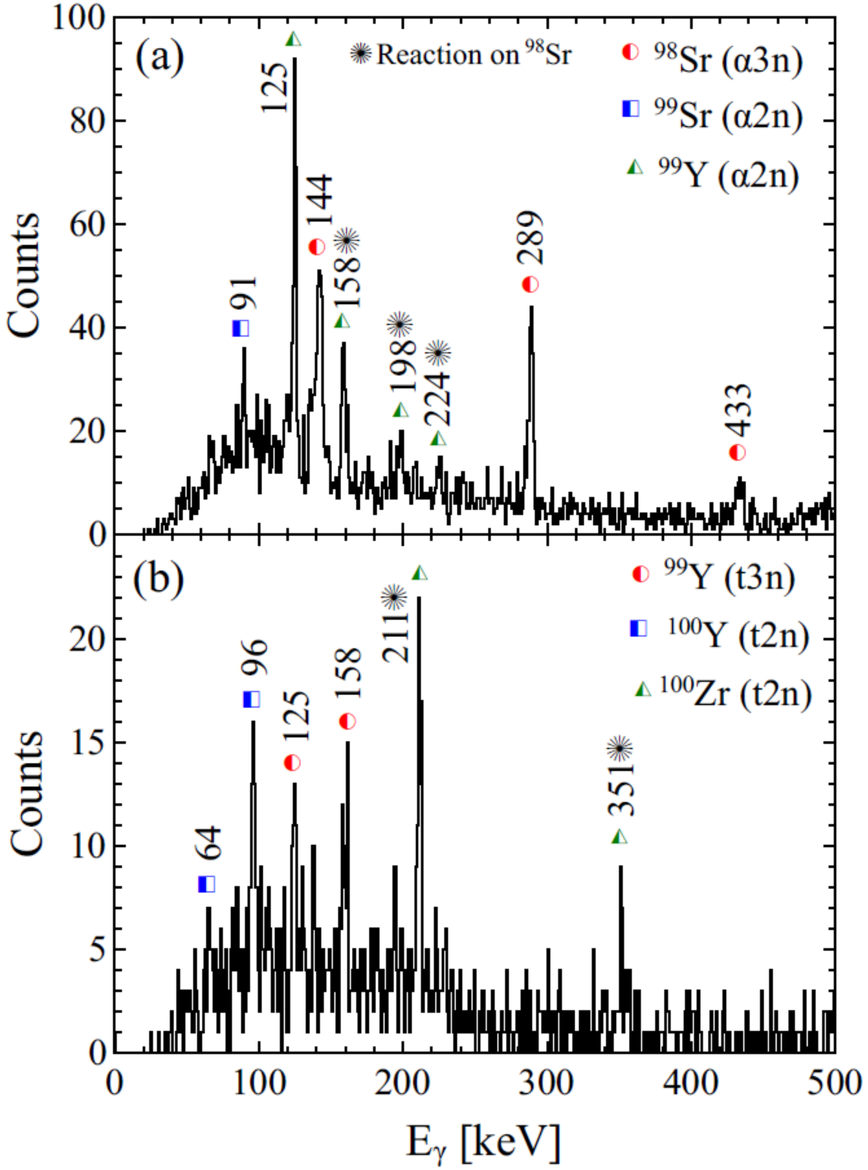


t-transfer

α-transfer



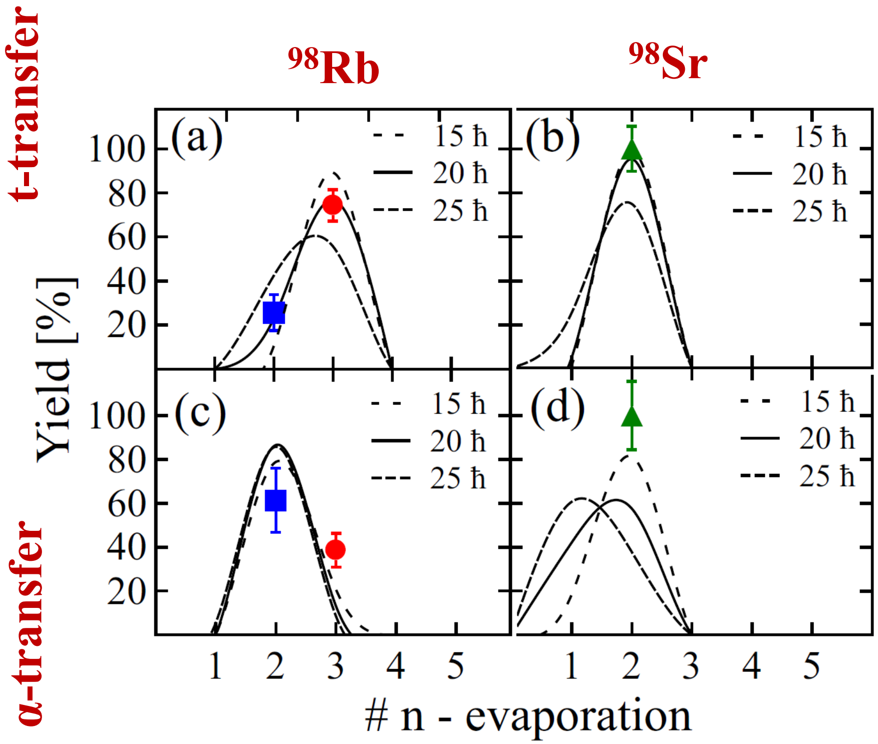
γ – spectroscopy limited by: low beam intensity and short beam time



NEUTRON EVAPORATION

S_n = 3 – 5 MeV

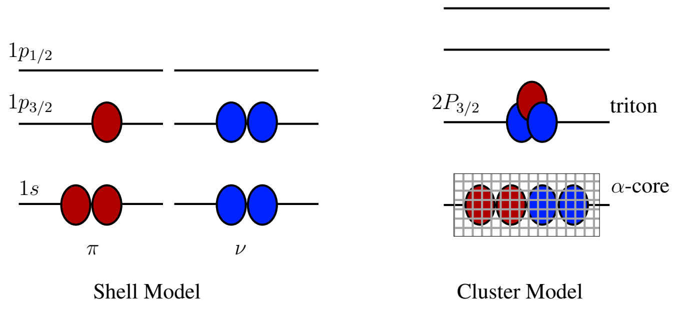
S_{2n} = 8-10 MeV



CASCADE

^{7}Li g.s. WAVE FUNCTION

- **α – t in a relative P-state**
- **Gaussian potential with a volume and s.o term**



$$2(N-1)+L=\sum_i (2(n_i-1)+l_i)$$

FINAL STATES WAVE FUNCTIONS

- **Excitation energy higher than ^{98}Rb – fragment separation energy**
- **weakly bound states close to the continuum**

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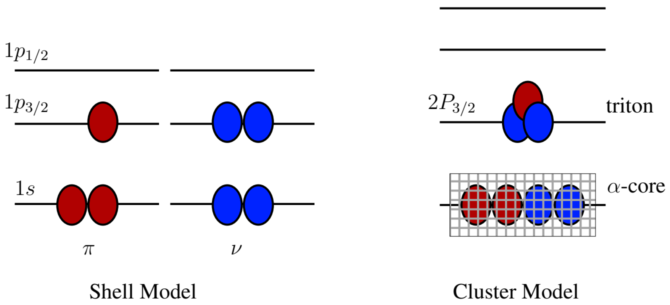

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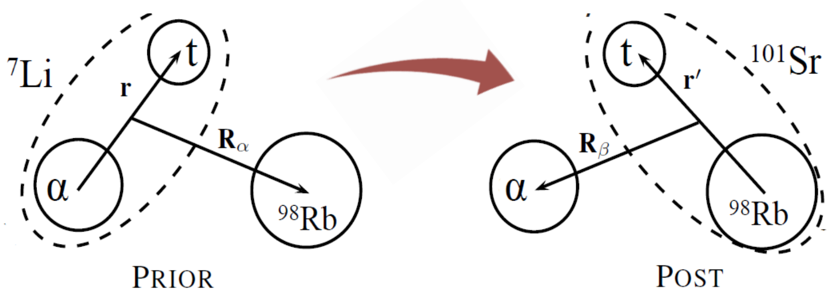
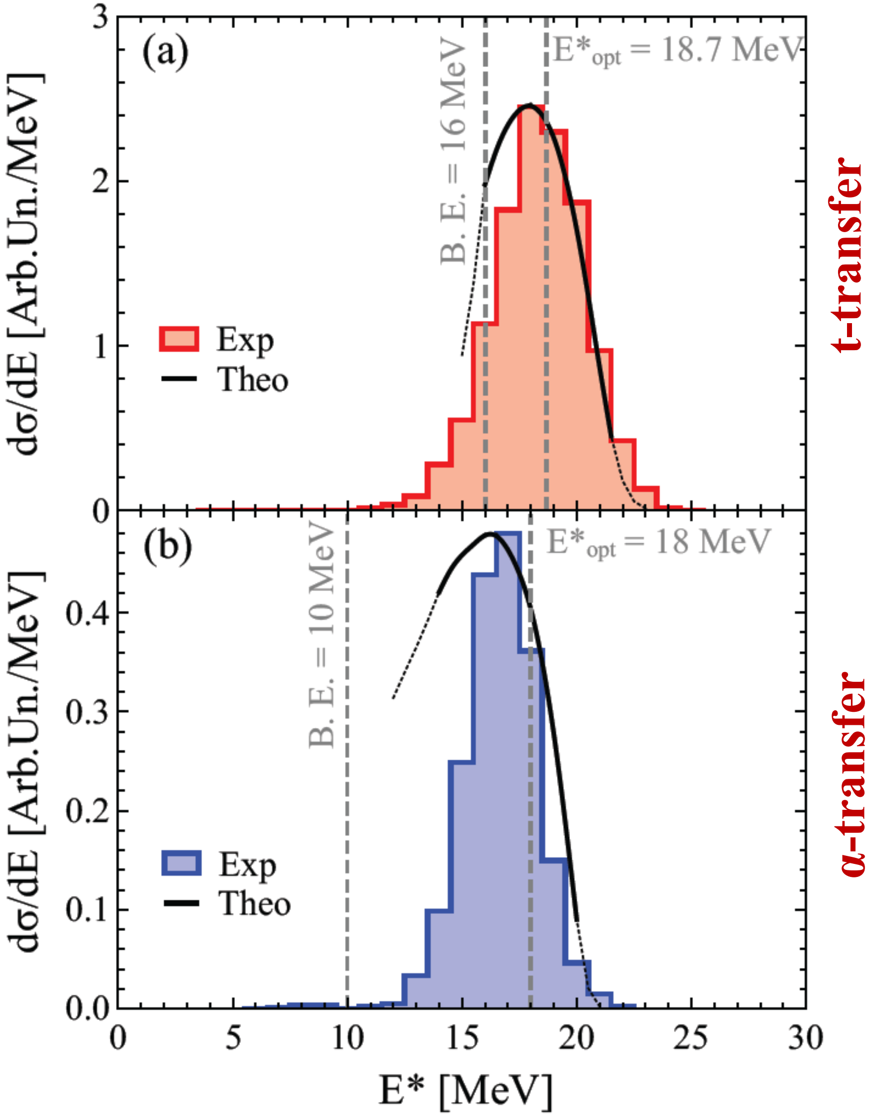
TRANFER CROSS SECTION

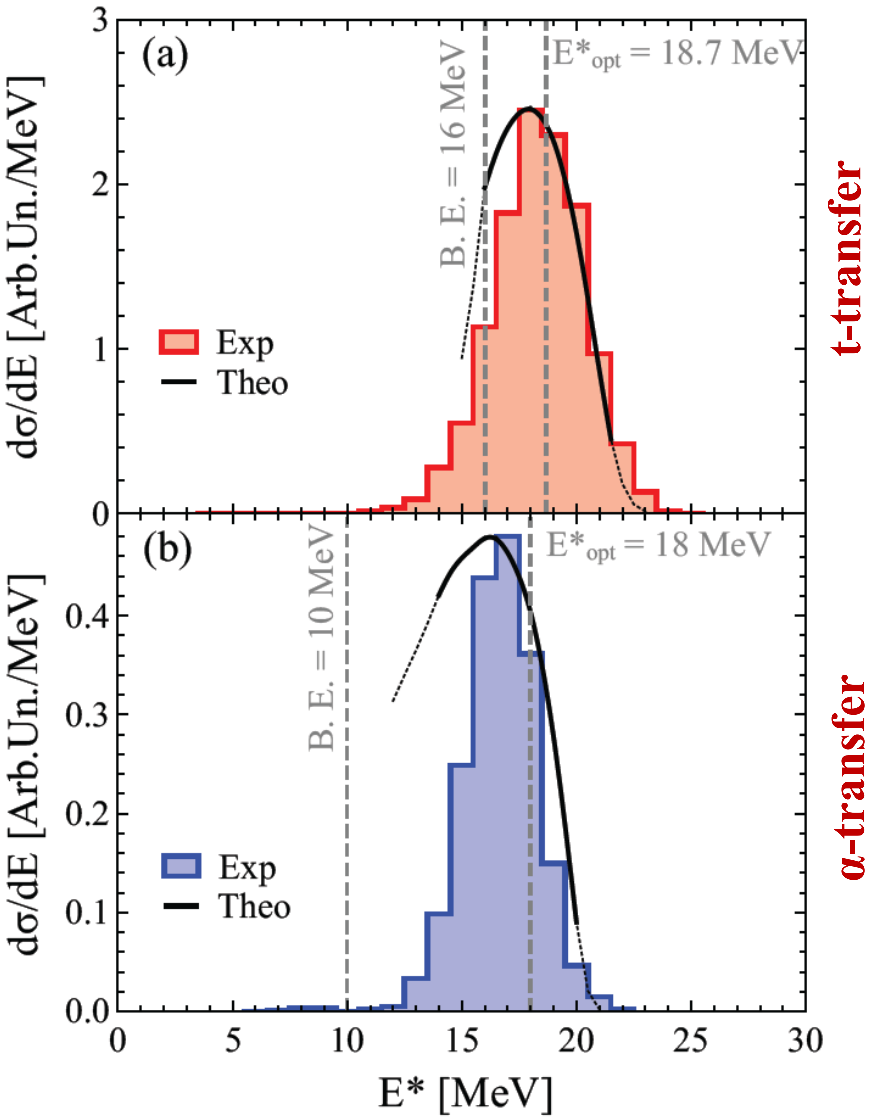


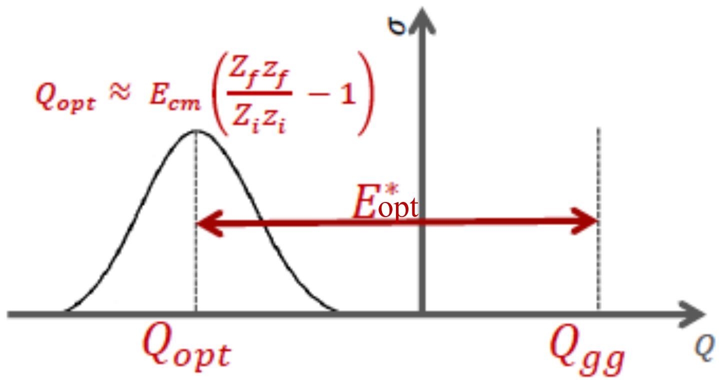
$$V_{int}^{POST}=V_{\alpha-t}+U_{Rb-\alpha}-U_{Sr-\alpha}\approx V_{\alpha-t}$$

- **1 – step DWBA**
- **Post rappresentation**
- **W.S. potentials for incoming and outgoing channels**
- **Several states with different angular momenta and excitation energies**

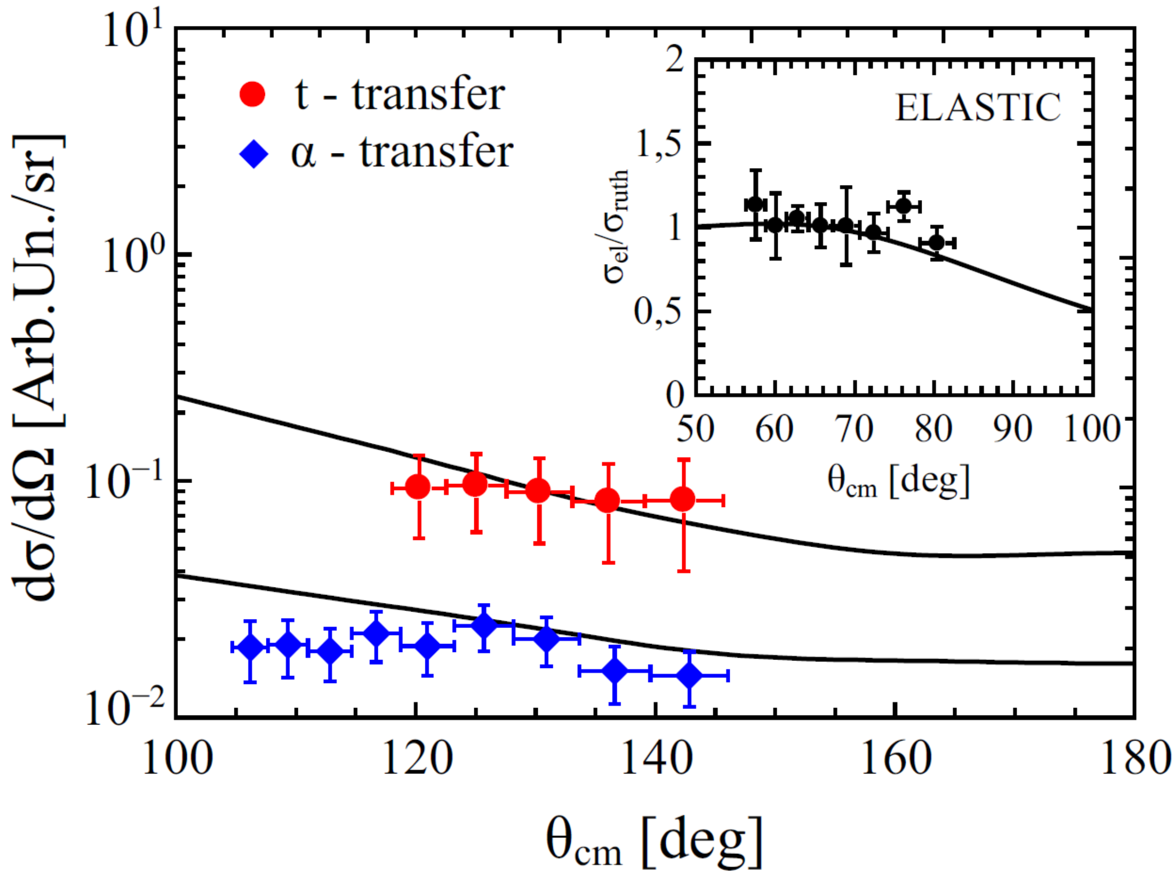
FRESCO

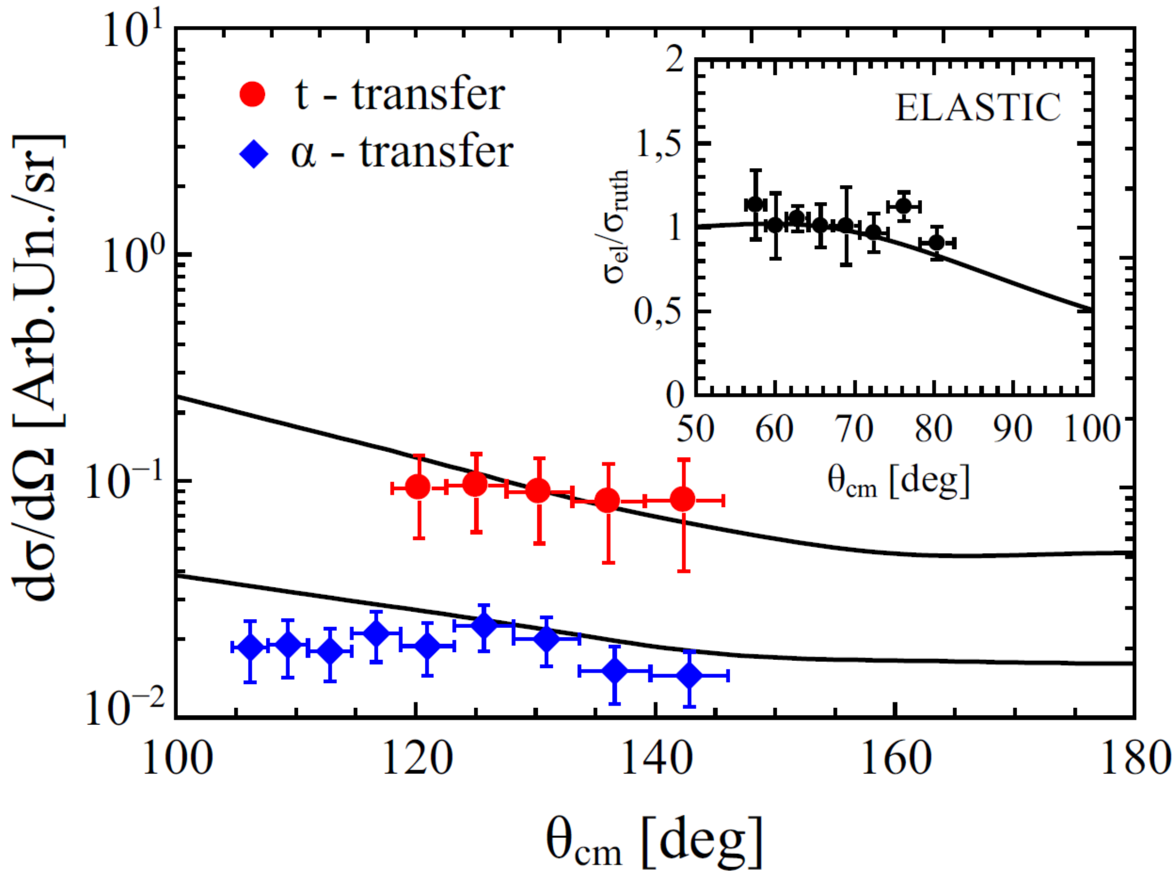

(a)
B. E. = 16 MeV
E*opt = 18.7 MeV
Exp
Theo
dσ/dE [Arb.Un./MeV]
(b)
B. E. = 10 MeV
E*opt = 18 MeV
Exp
Theo
dσ/dE [Arb.Un./MeV]
E* [MeV]
t-transfer
α-transfer





	t-transfer	α-transfer
Q_{gg} [MeV]	13.6	7.6
Q_{opt} [MeV]	-5.1	-10.4
E^*_{opt} [MeV]	18.7	18
B.E. [MeV]	16	10


t - transfer
α - transfer
ELASTIC
σel/σruth
θcm [deg]
dσ/dΩ [Arb.Un./sr]
θcm [deg]



FROM EXPERIMENTAL DATA within 20 °

$$\sigma_{t-transfer} = 26.6 \pm 0.7 \text{ mb}$$
$$\sigma_{\alpha-transfer} = 5.3 \pm 0.2 \text{ mb}$$

Cluster-transfer reactions with RIB's in inverse kinematics:

- **A possible mechanism to populate medium-high energy and spin states in neutron – rich nuclei**

The ISOLDE pilot experiment*

- **^{98}Rb/^{98}Sr+^{7}Li @ 2.5 MeV/A**
- **In beam γ – spectroscopy limited by the low beam intensity**
- **Reaction dynamics pointing out to the direct nature of the process**
- **Improvements by considering the coupling to other channels and a proper representation of the states in the continuum**

Future perspectives:

- **Same experimental technique to populate even more neutron – rich nuclei with the new generation of radioactive beams at CARIBU, HIE –ISOLDE, SPIRAL2, SPES etc.**

CARIBU: ^{104}Zr + ^{7}Li @ 3.5 MeV/A

HIE - ISOLDE: ^{132}Sn + ^{7}Li @ 4 MeV/A

*S. Bottoni et al., Acta Phys. Pol. B 45, 343 (2014)
*S. Bottoni et al., Phys. Rev. C to be submitted

Collaboration

S. Bottoni[1,2,4], S. Leoni[1,2], B. Fornal[3], R. Raabe[4], K. Rusek[5], G. Benzoni[2], A. Bracco[1,2], F. C. L. Crespi[1,2], A. I. Morales[2], B. Bednarczyk[3], N. Cieplika[3], W. Królas[3], A. Maj[3], B. Szpak[3], M. Callens[4], J. Bouma[4], J. Elseviers[4], F. Falvigny[4], R. Orlandi[4], P. Reiter[6], M. Seidlitz[6], S. Hellgartner[7], D. Mücher[7], G. Georgiev[8], D. Balabanski[9], M. Sferrazza[10], M. Kowalska[11], E. Rapisarda[11] and the MINIBALL-T-REX collaboration.

[1] *Università degli Studi di Milano, Milano, Italy*
[2] *INFN sezione di Milano, Milano, Italy*
[3] *The Niewodniczanski Institute of Nuclear Physics, Kraków, Poland*
[4] *Instituut voor Kern- en Stralingsfysisca, KU Leuven, Leuven, Belgium*
[5] *Heavy Ion Laboratory, University of Warsaw, Warsaw, Poland*
[6] *Institut für Kernphysik der Universität zu Köln, Köln, Germany*
[7] *Physik Department, Technische Universität München, München , Germany*
[8] *CSNSM, Orsay, France*
[9] *IRNE-BAS, Sofia, Bulgaria*
[10] *Université libre de Bruxelles, Bruxelles, Belgium*
[11] *ISOLDE, CERN, Geneve, Switzerland*

Thank you for your attention

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EXTRA SLIDES

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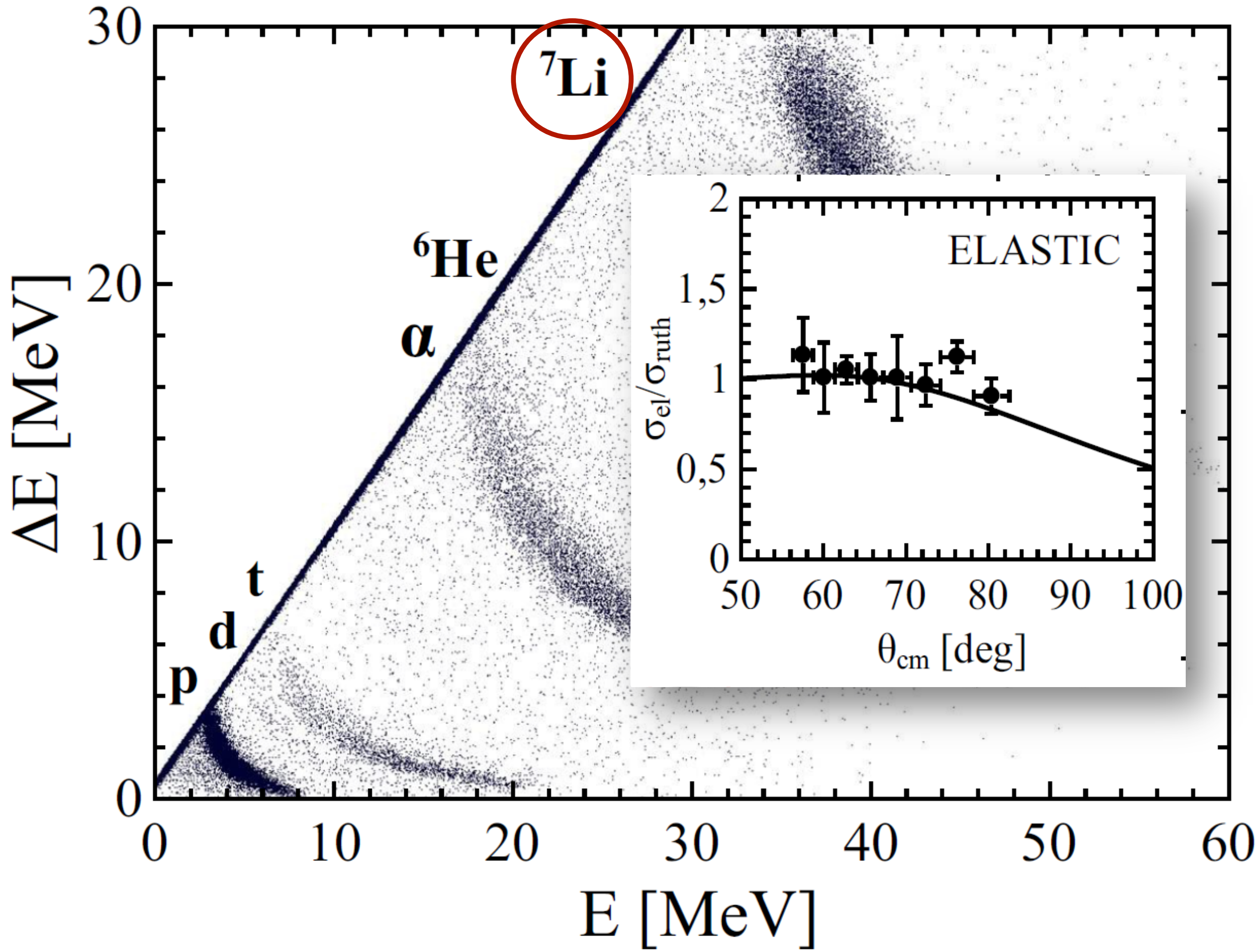

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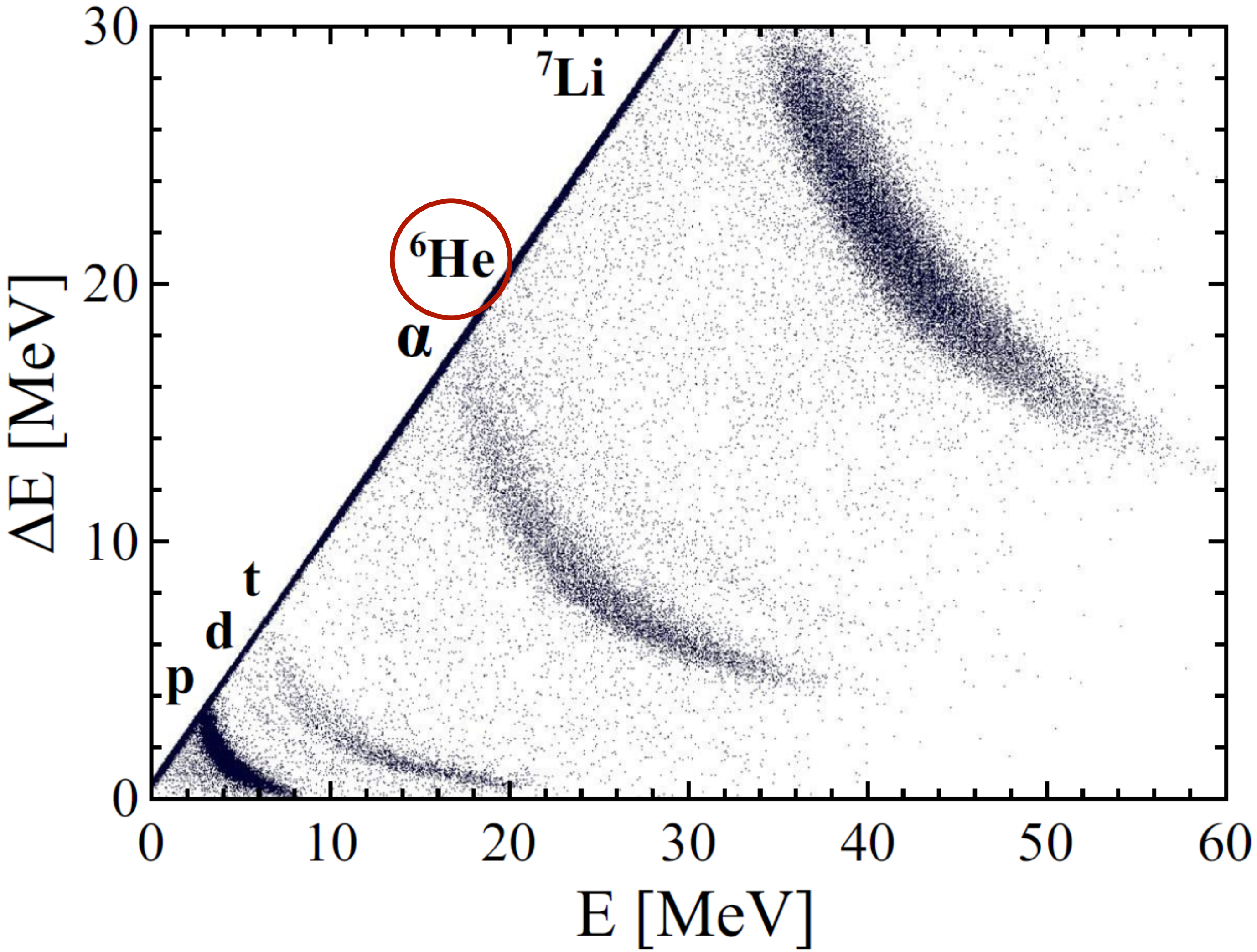

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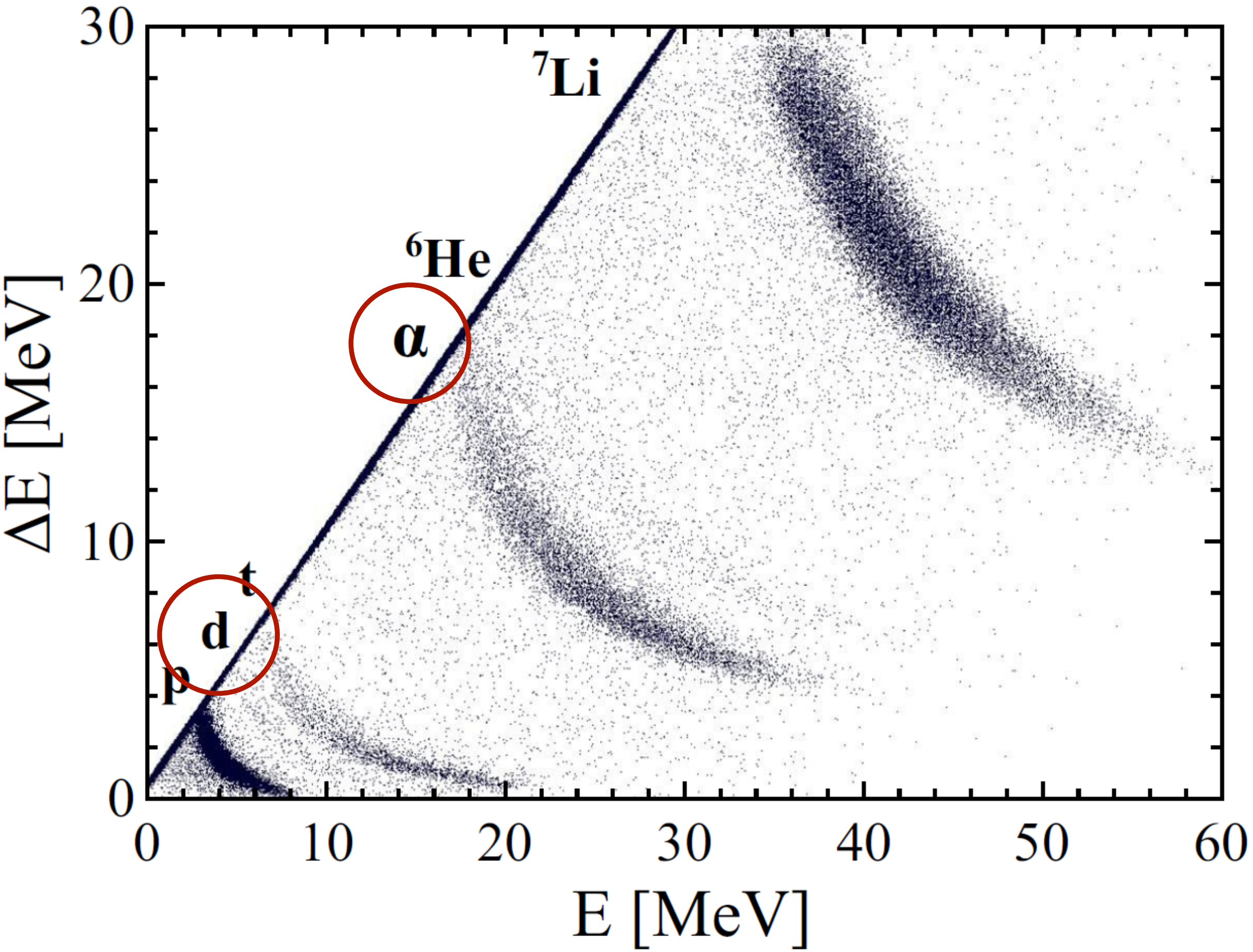

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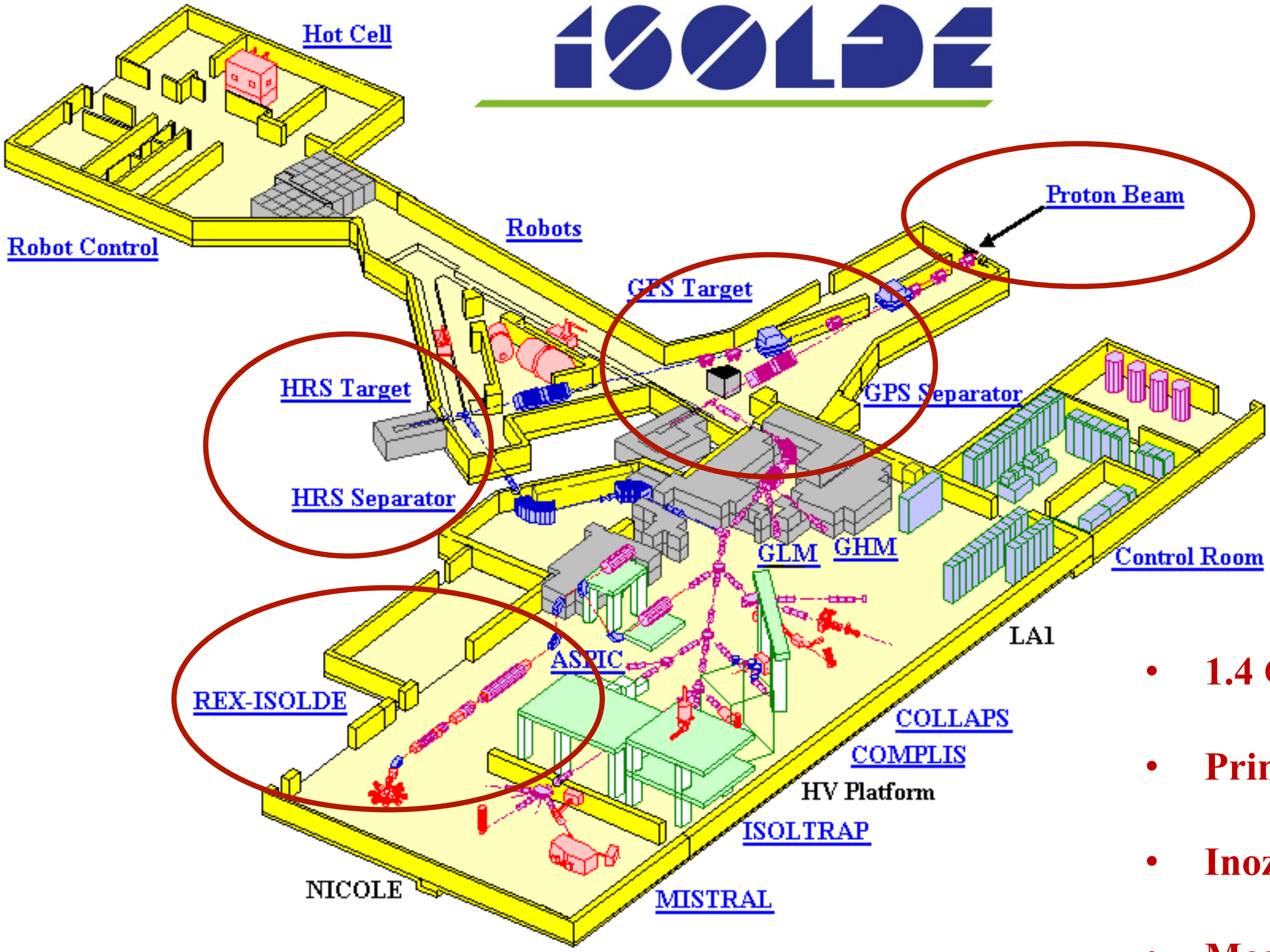
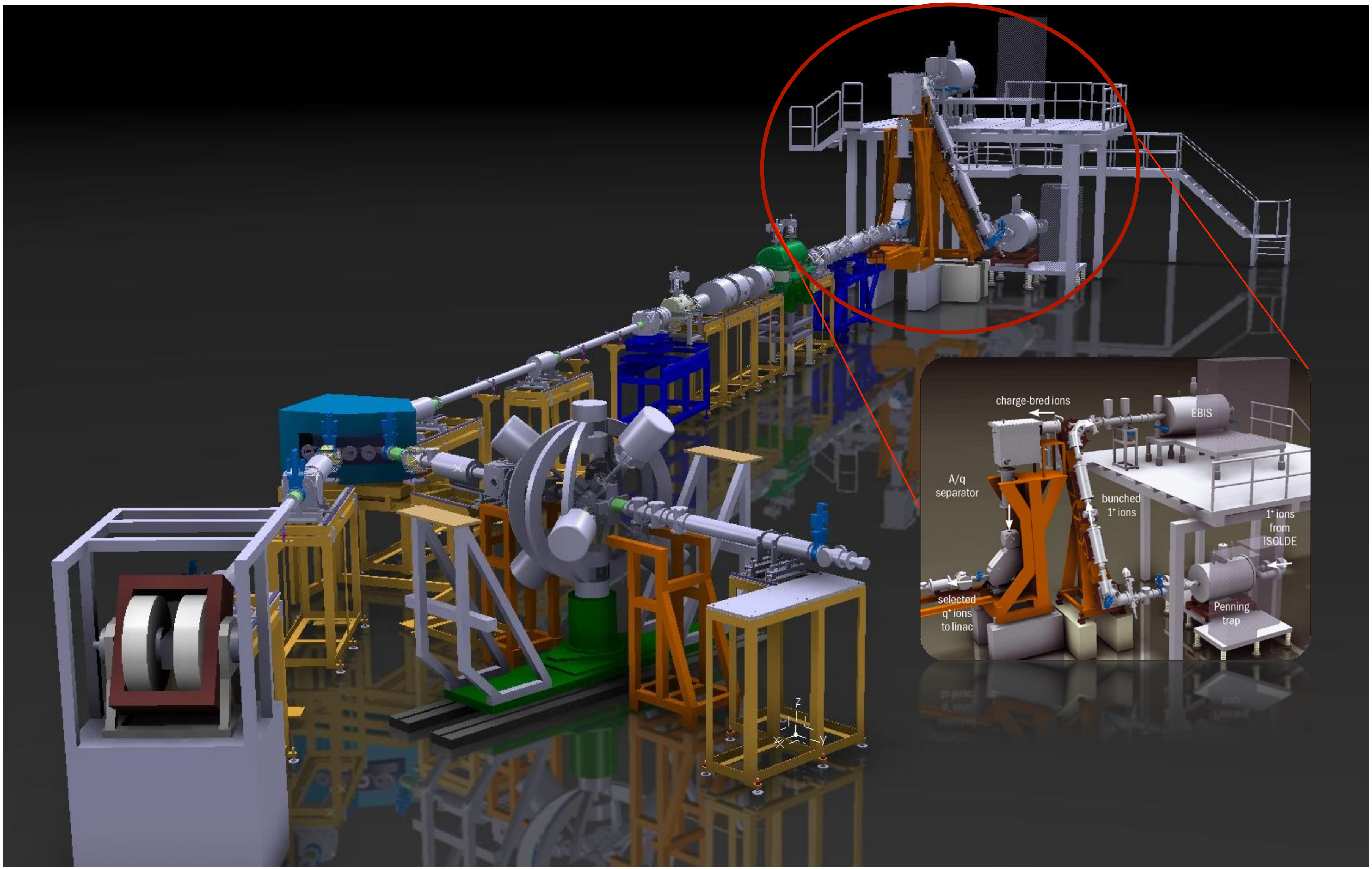
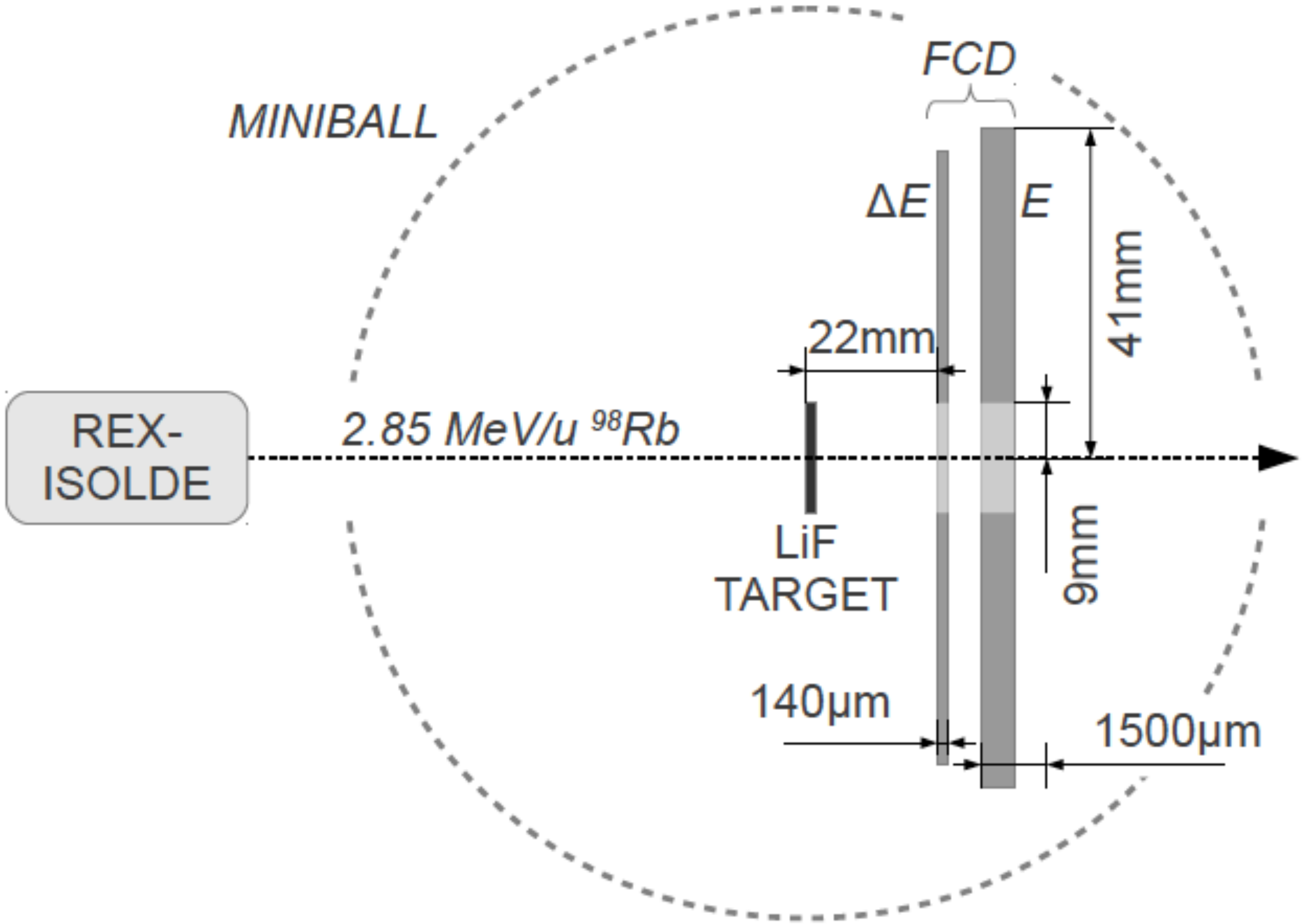
The ISOLDE pilot experiment: ISOLDE

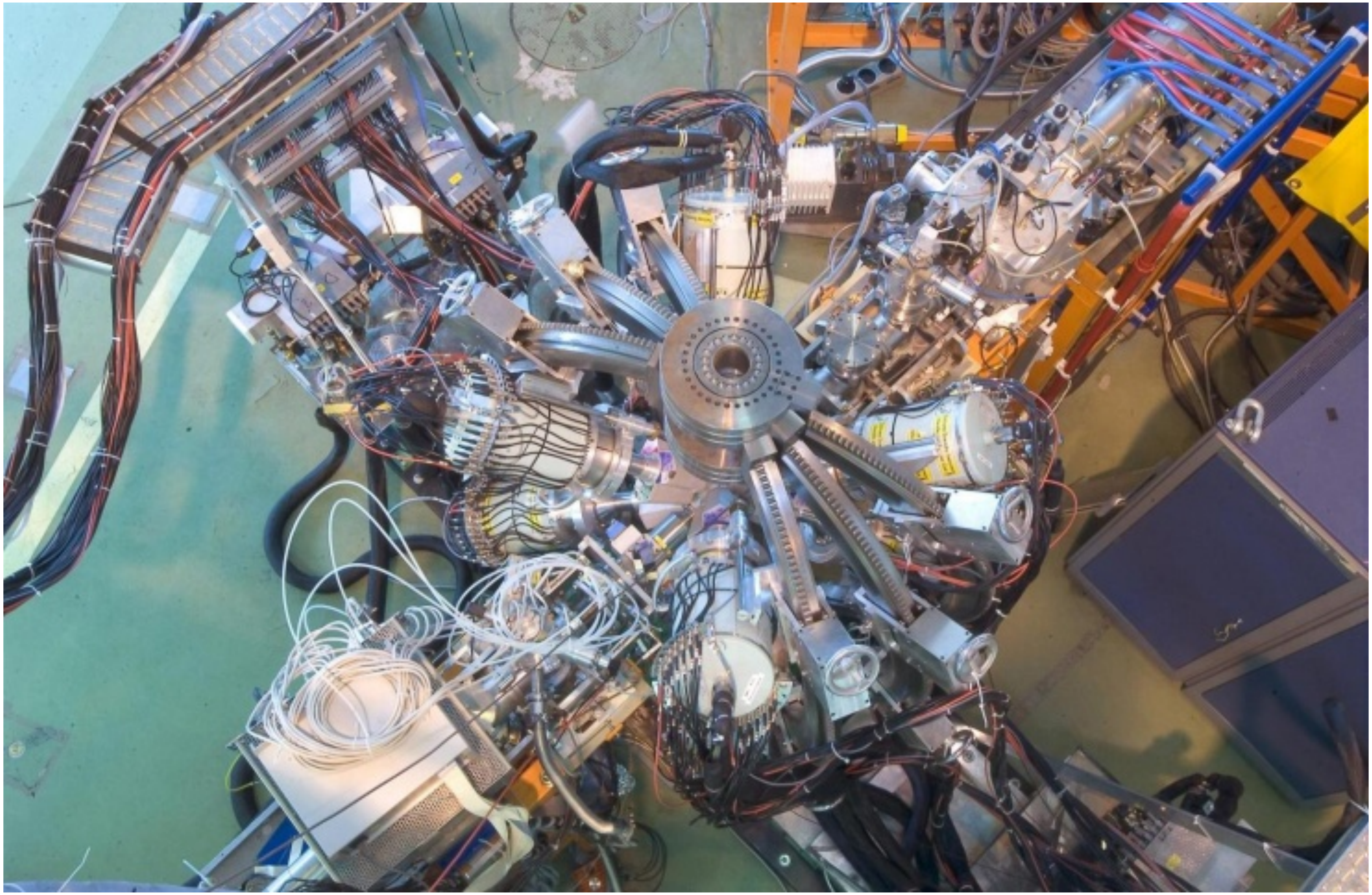


- **1.4 GeV protons from PS BOOSTER**
- **Primary target: UCx**
- **Inoziation**
- **Mass separation: GPS and HRS**
- **Post acceleration: REX - ISOLDE**

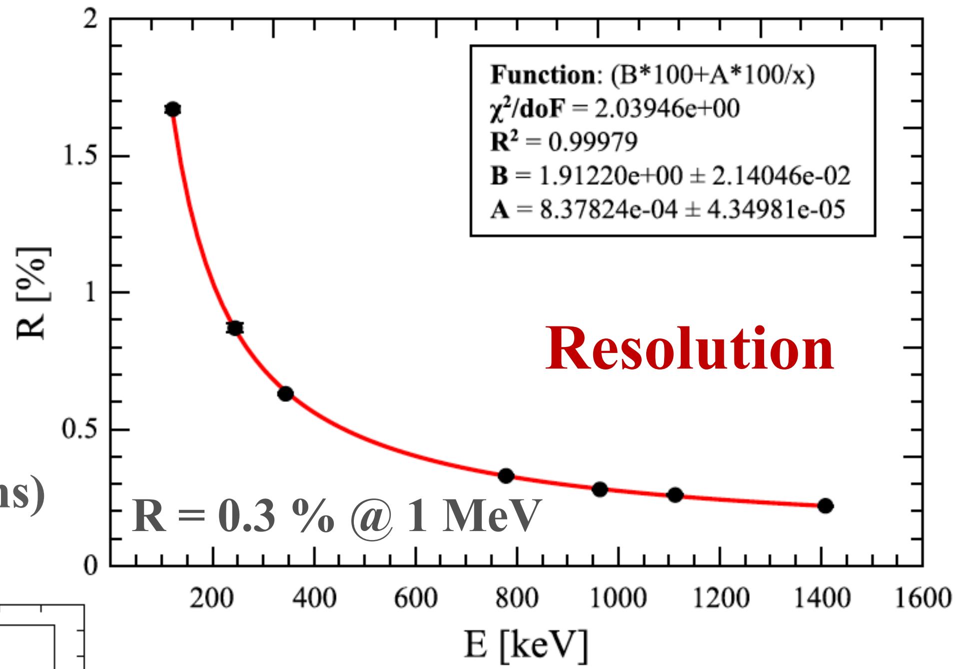

charge-bred ions
EBIS
A/q
separator
bunched
1+ ions
1+ ions
from
ISOLDE
selected
q+ ions
to linac
Penning
trap

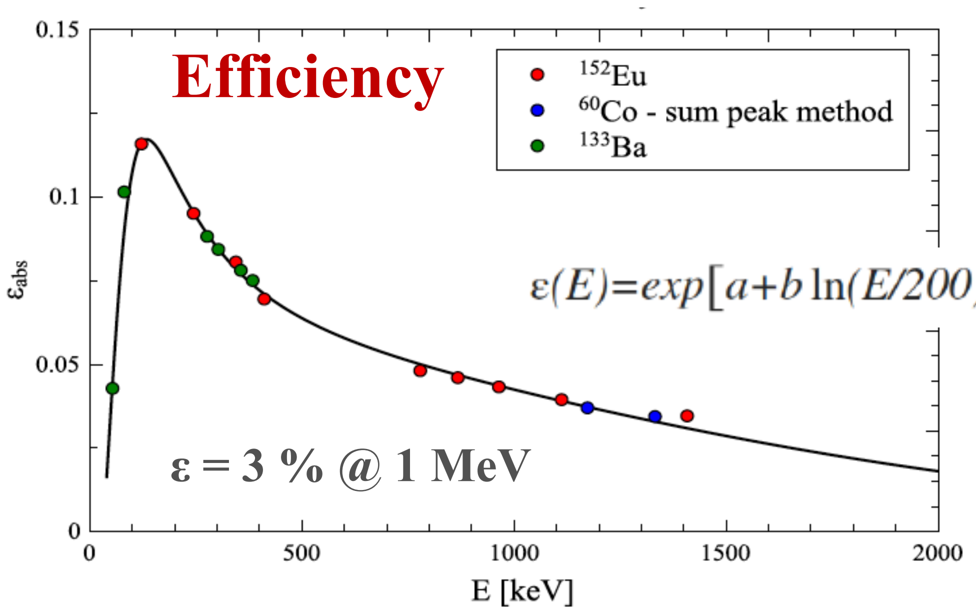

MINIBALL
FCD
ΔE
E
41mm
22mm
REX-
ISOLDE
2.85 MeV/u 98Rb
LiF
TARGET
9mm
140μm
1500μm

MINIBALL array



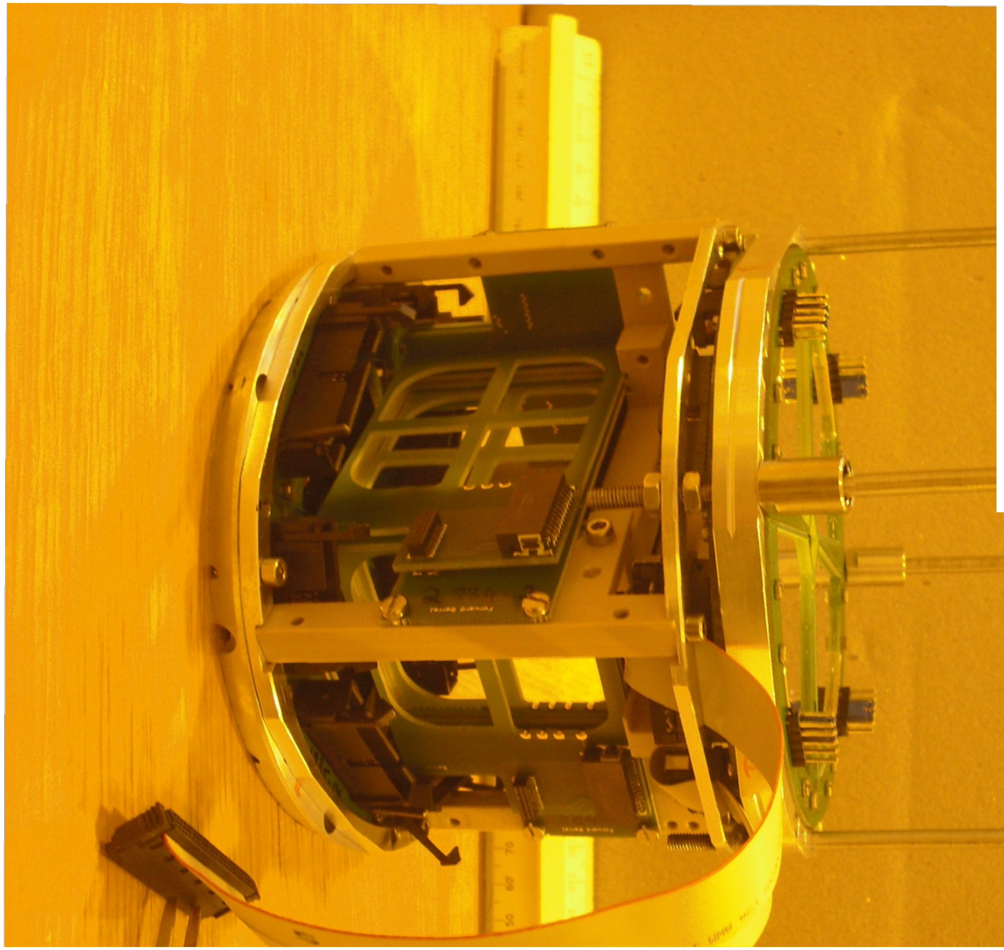
- 24 HpGe crystals (70mm X 78mm)
- 8 triple clusters (no Compton Suppr.)
- Six-fold electronic segmentation
- Digital electronics
- Energy and time (40 MHz) signals (25 ns)

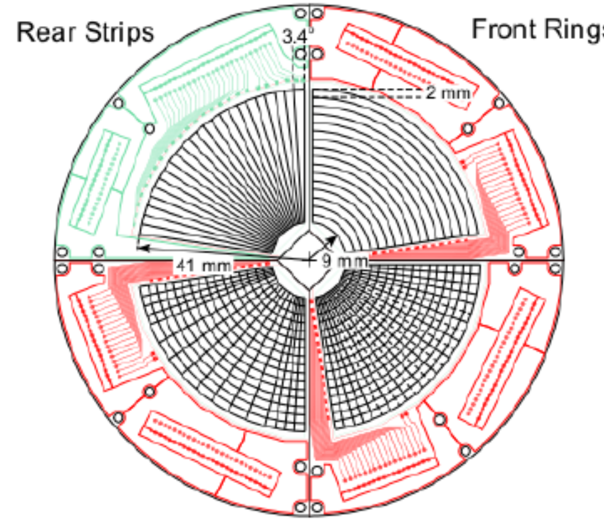




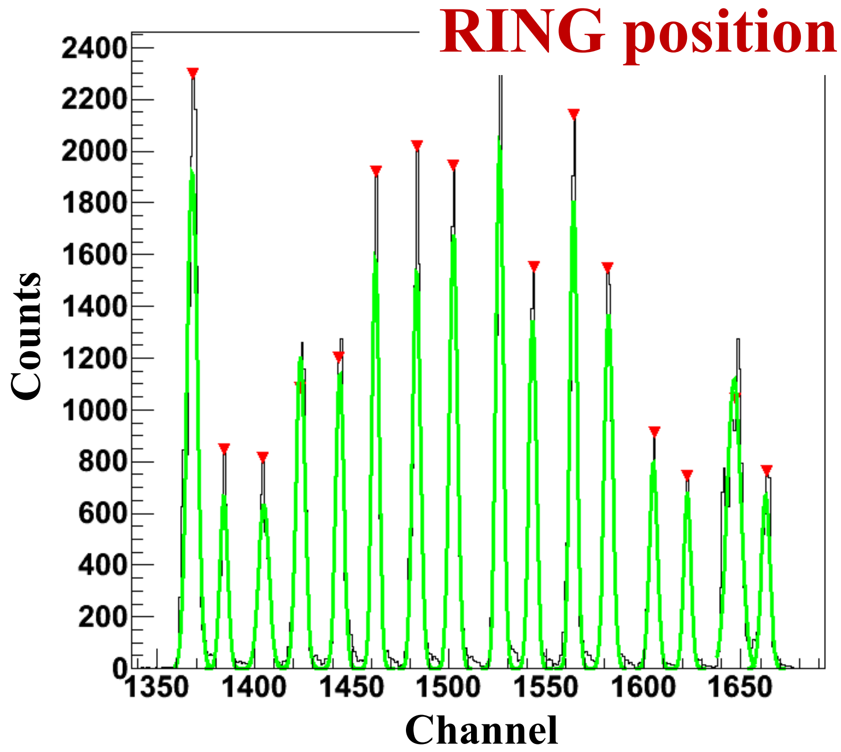
$$\varepsilon(E)=exp\left[a+b\ln(E/200)+c\ln(E/200)^2+d\ln(E/200)^3+e\ln(E/200)^4\right]$$

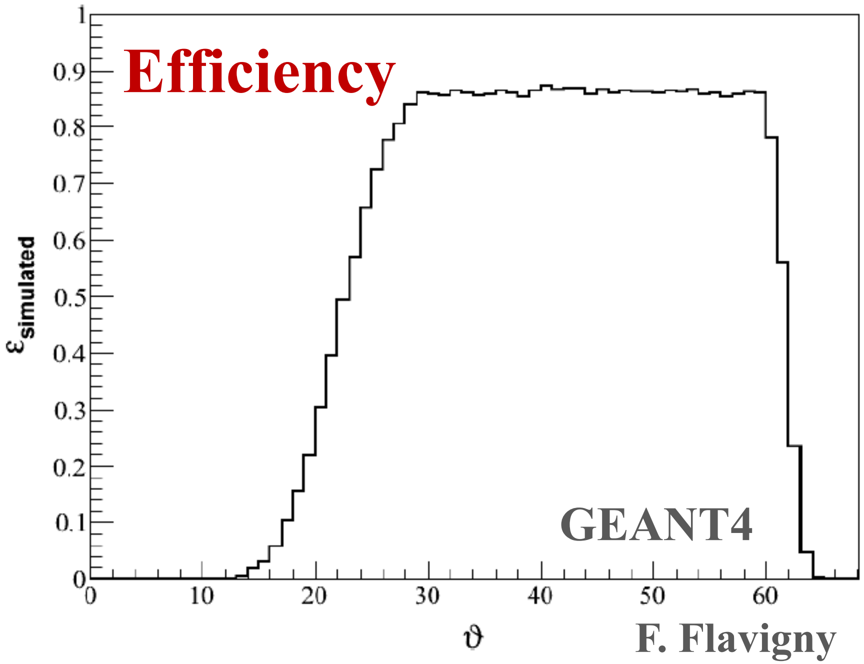
CD Silicon detector



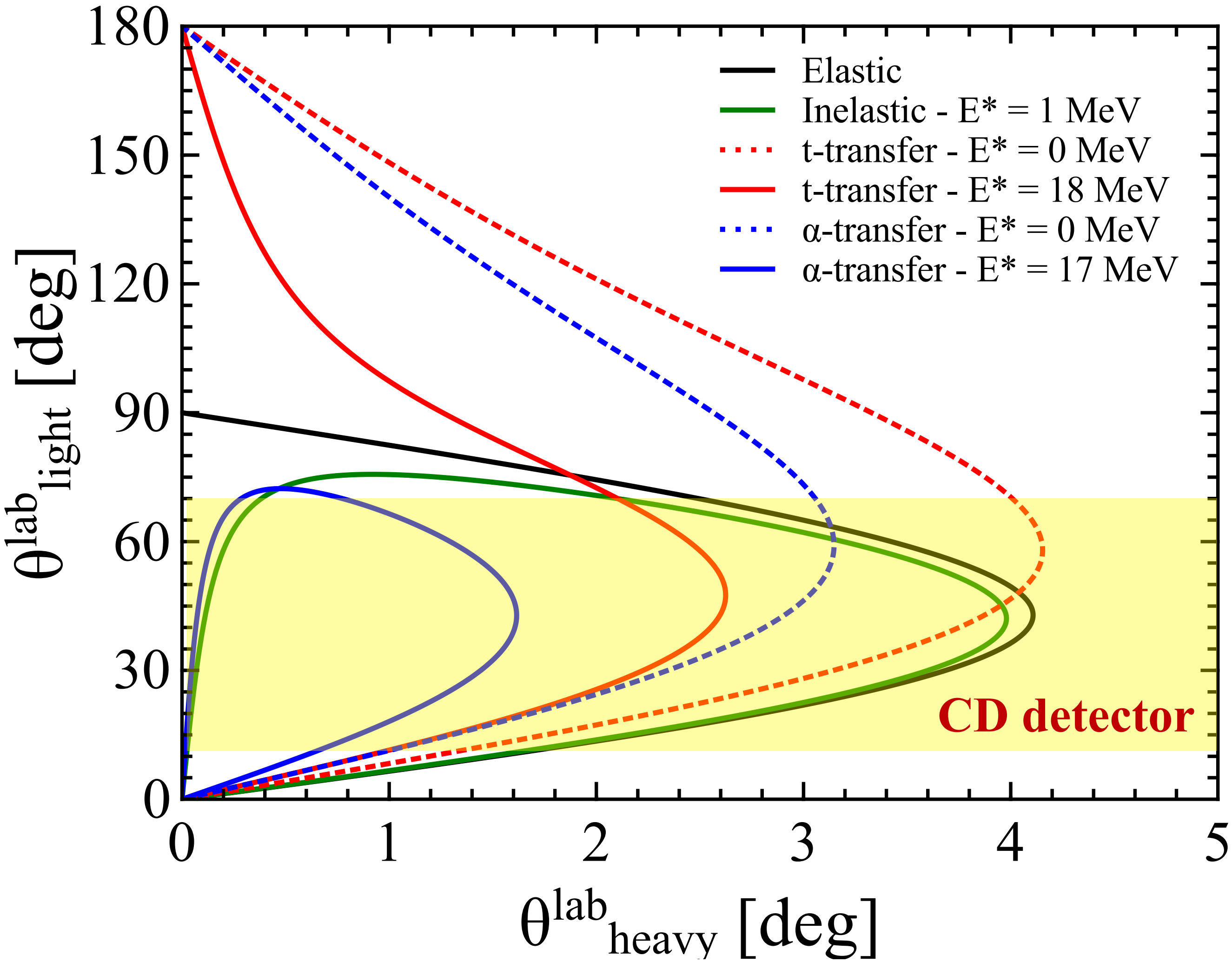


- **DSSSD detector**
- **ΔE – E configuration**
- **16 position sensitive anular strips (rings)**
- **24 position sensitive sector strips**
- **Energy, position and time signals**

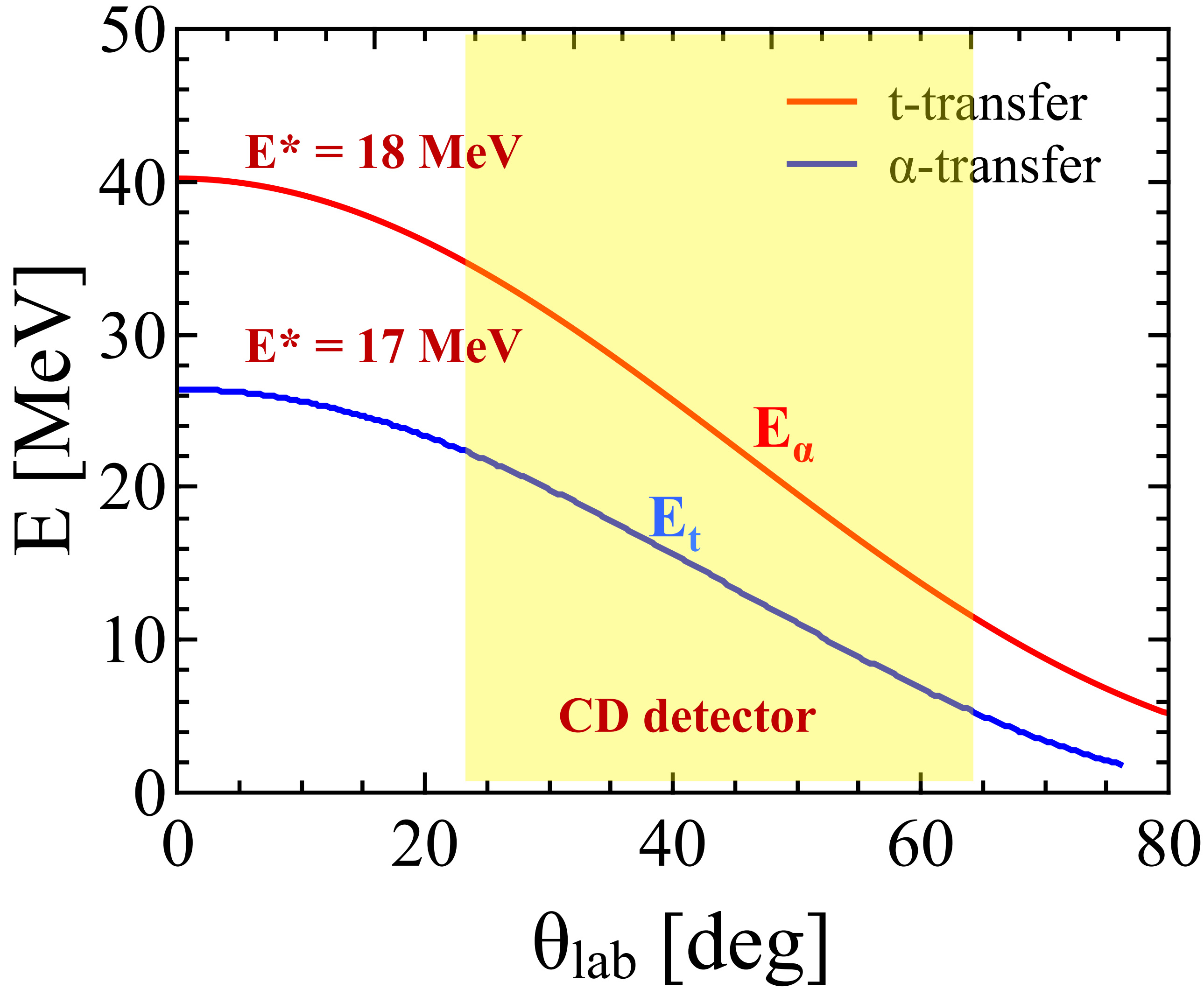




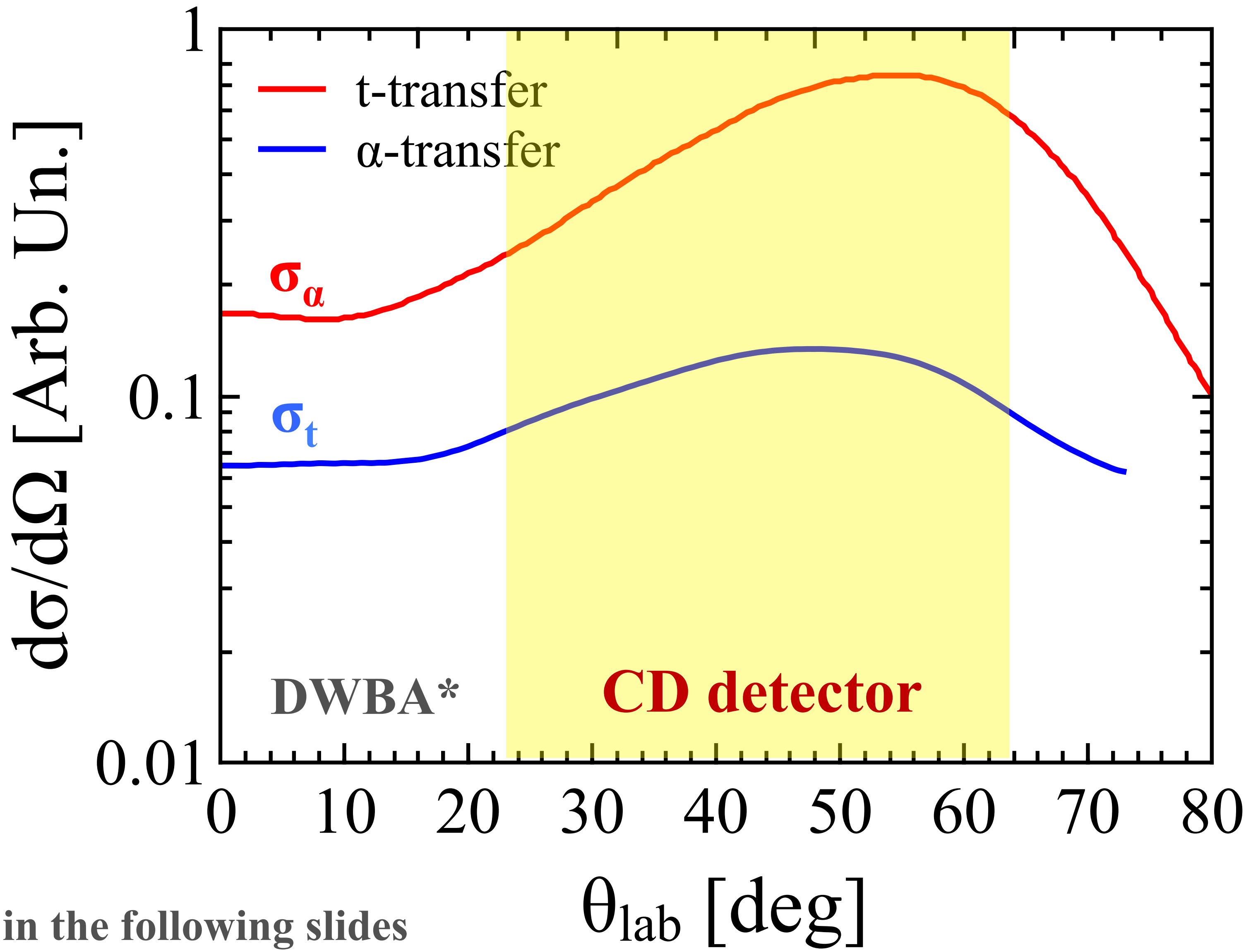
$22° < \theta_{lab} < 62°$



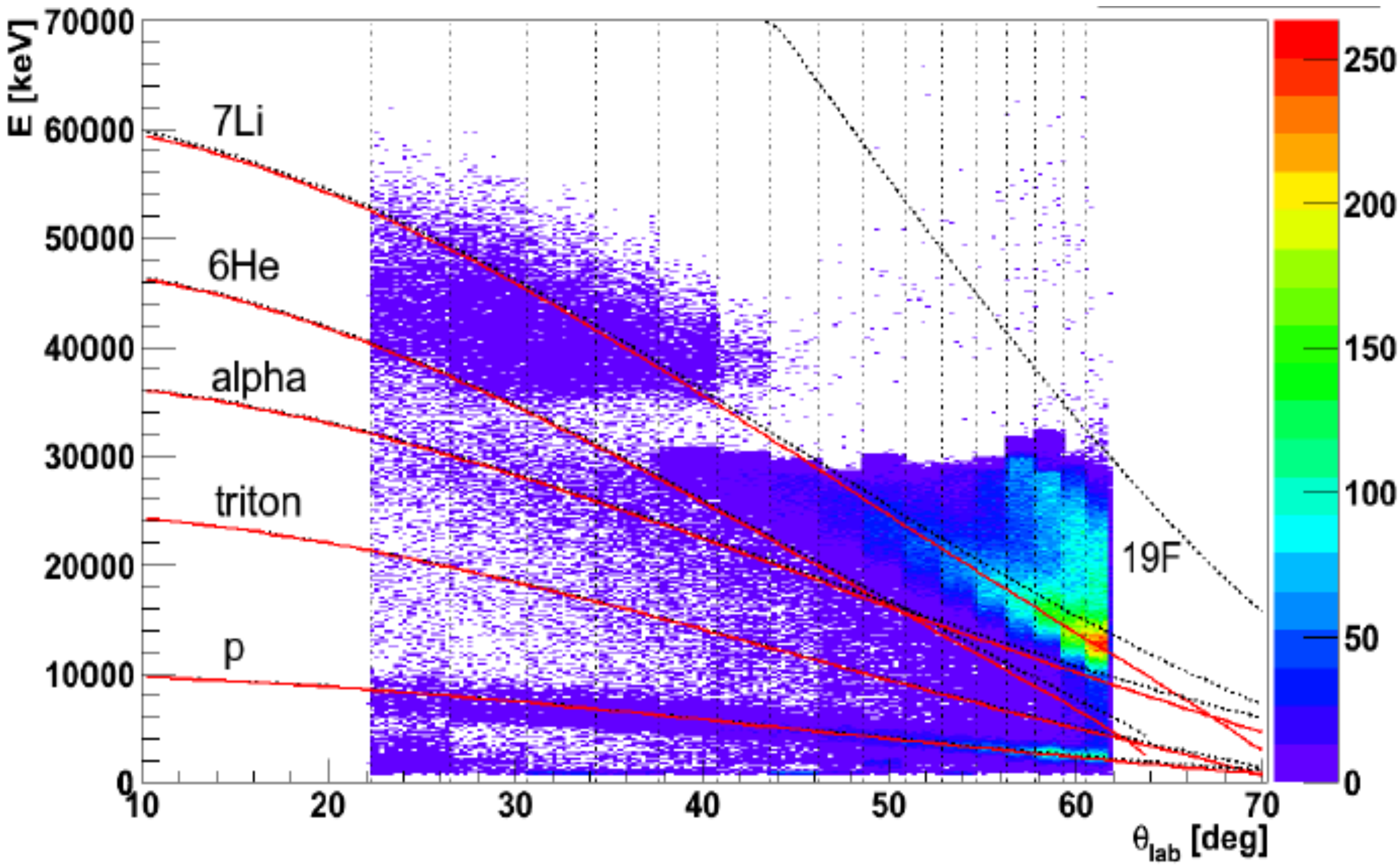
Two – body kinematics $^{98}Rb+^{7}Li$ @ 2.5 MeV/A



Two – body kinematics $^{98}Rb+^{7}Li$ @ 2.5 MeV/A

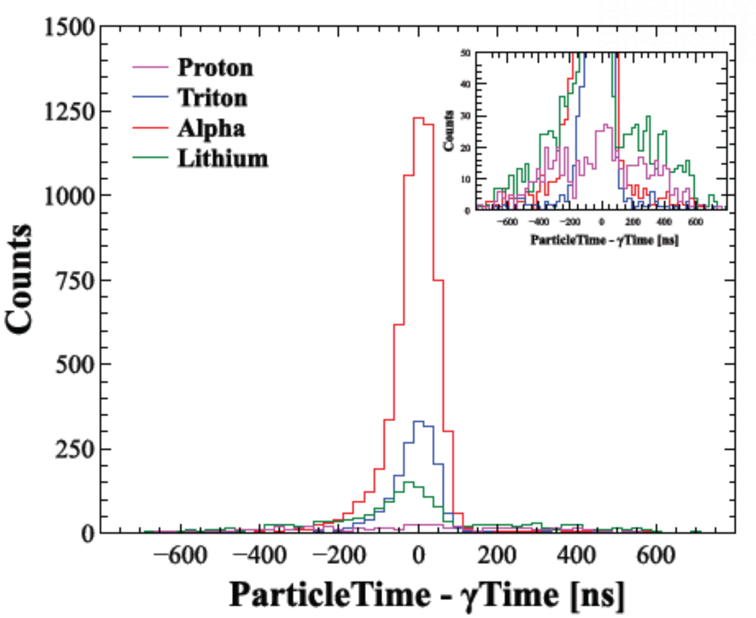


*details in the following slides

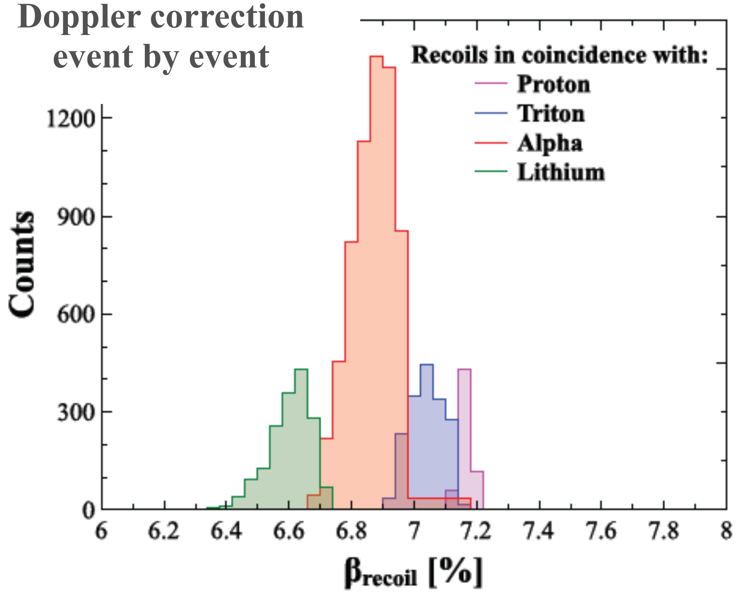


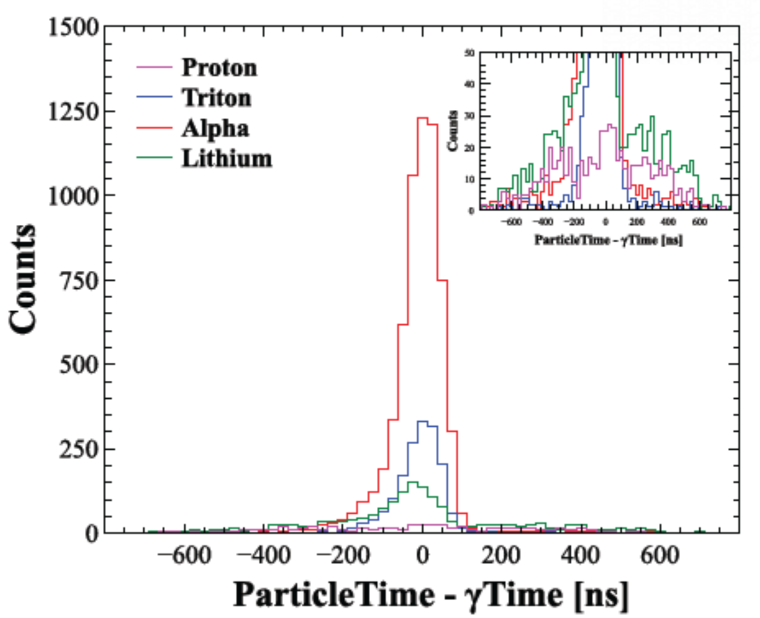
Elastic scattering used to cross check target-CD distance

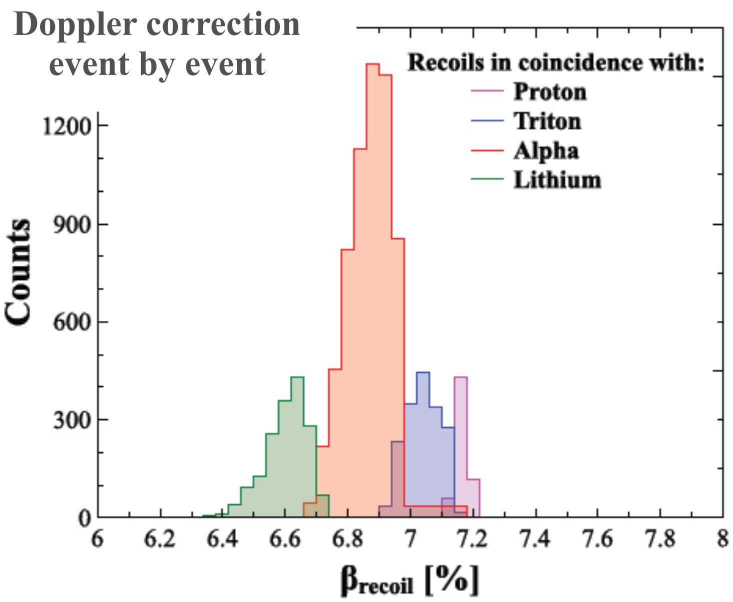
Final distance = 22mm

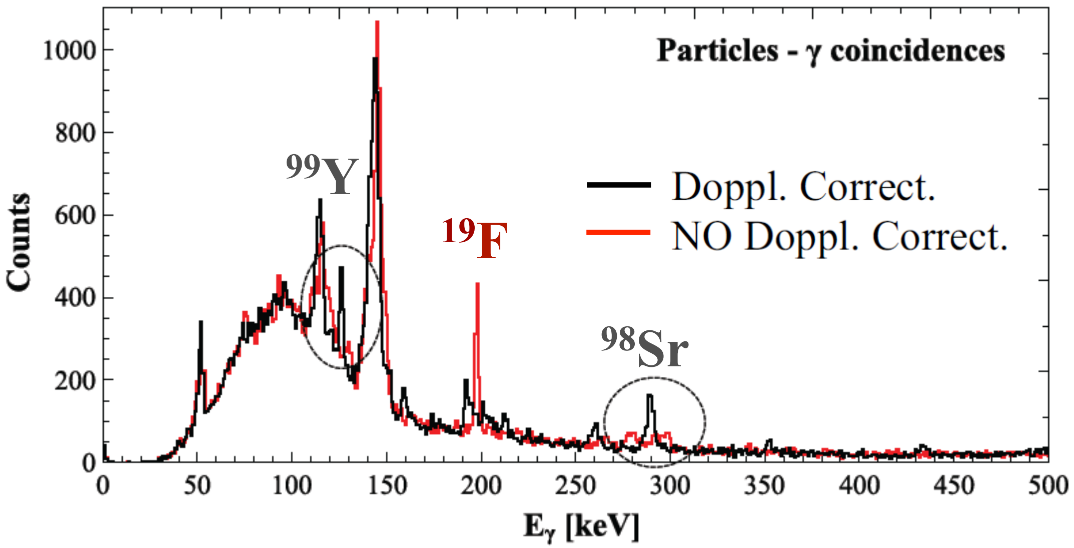


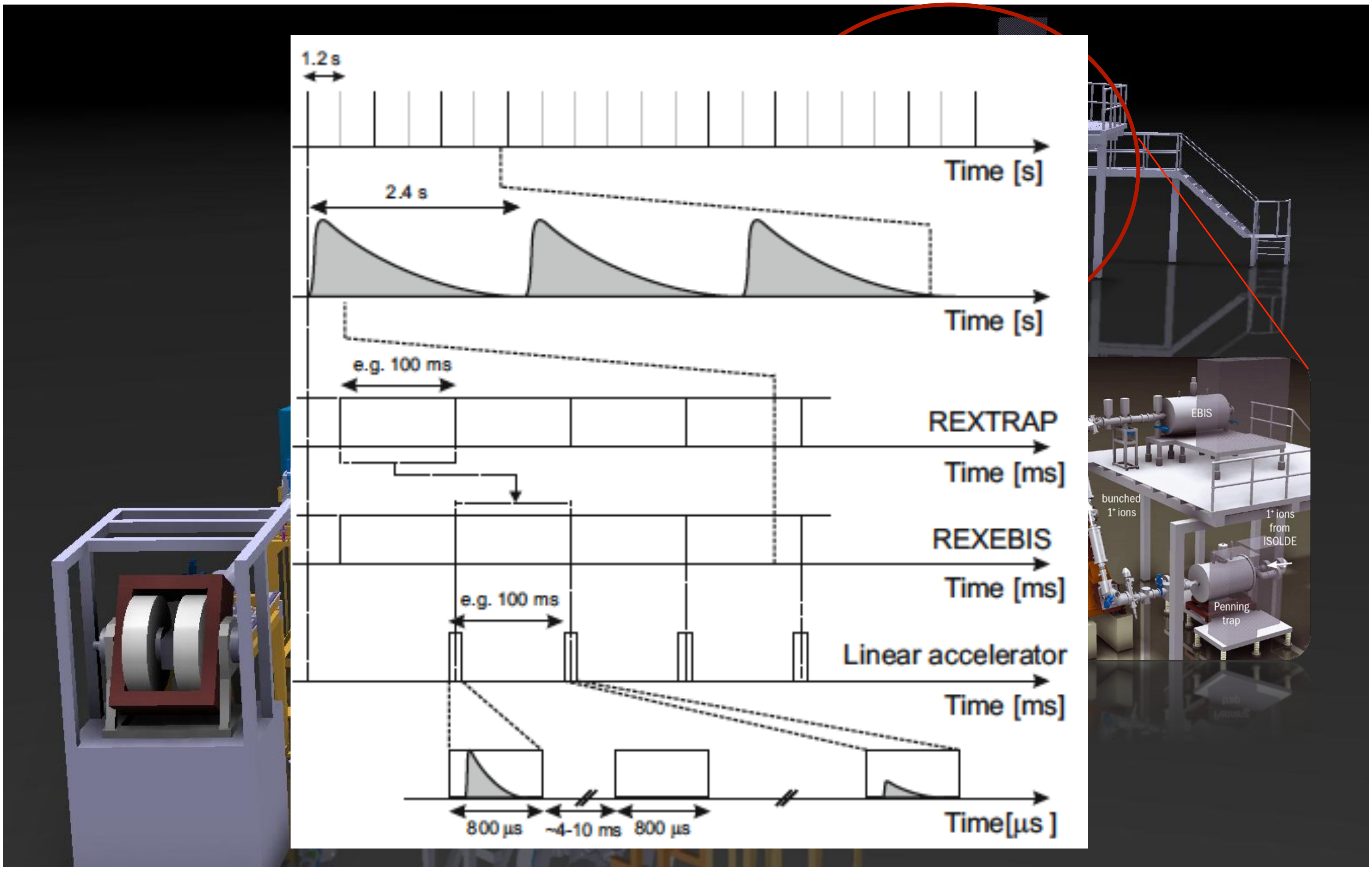
Doppler correction event by event




Proton
Triton
Alpha
Lithium
Counts
ParticleTime - γTime [ns]
1500
1250
1000
750
500
250
0
−600 −400 −200 0 200 400 600


Doppler correction event by event
Recoils in coincidence with:
Proton
Triton
Alpha
Lithium
Counts
βrecoil [%]
1200
900
600
300
0
6 6.2 6.4 6.6 6.8 7 7.2 7.4 7.6 7.8 8

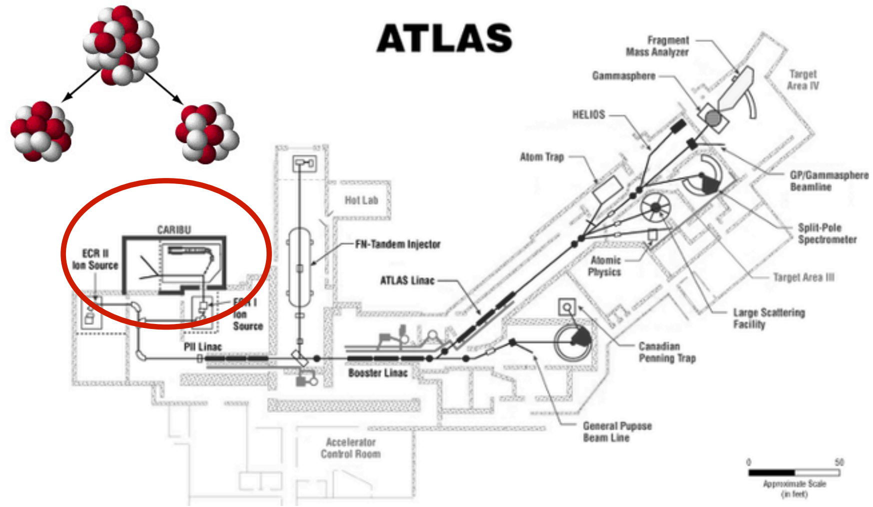

Particles - γ coincidences
99Y
19F
98Sr
Doppl. Correct.
NO Doppl. Correct.
Counts
Eγ [keV]
1000
800
600
400
200
0
0 50 100 150 200 250 300 350 400 450 500


1.2 s
Time [s]
2.4 s
Time [s]
e.g. 100 ms
REXTRAP
Time [ms]
REXEBIS
Time [ms]
e.g. 100 ms
Linear accelerator
Time [ms]
800 µs
~4-10 ms
800 µs
Time[µs]
EBIS
bunched
1+ ions
1+ ions
from
ISOLDE
Penning
trap

$^{104}Zr+^{7}Li$ @ 3.5 MeV/A
ANL - CARIBU

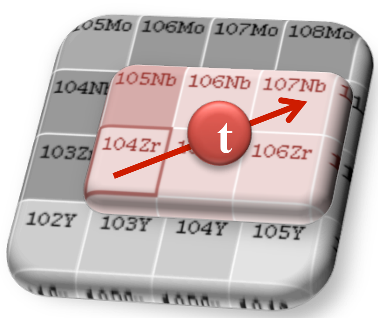
GRETINA **PHOSWICH**

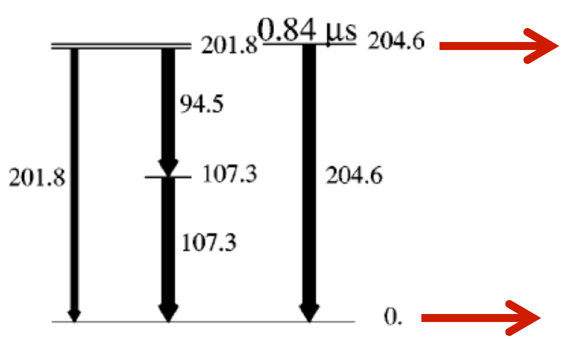
1 Ci ^{252}Cf



^{104}Zr is a unique beam produced at CARIBU that can not be produced by ISOL technique

Cluster - transfer

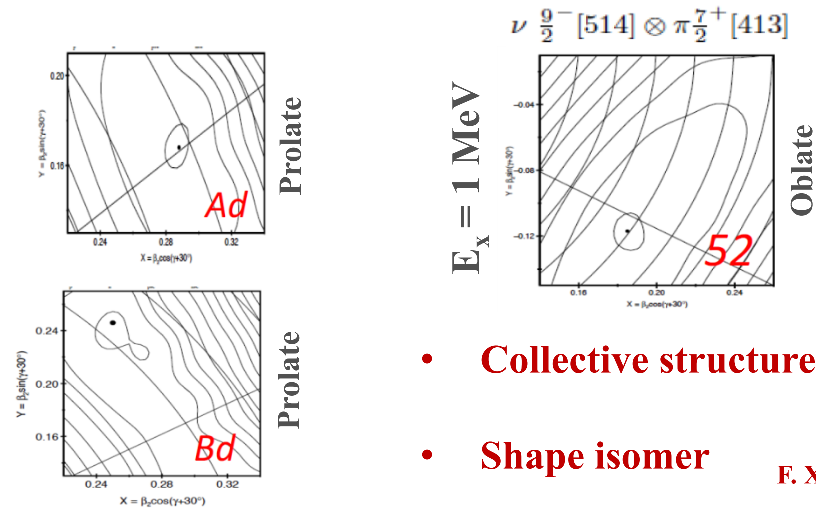




^{106}Nb

Prolate – Oblate shape transitions

$\nu\ \frac{9}{2}^{-}[514] \otimes \pi \frac{7}{2}^{+}[413]$

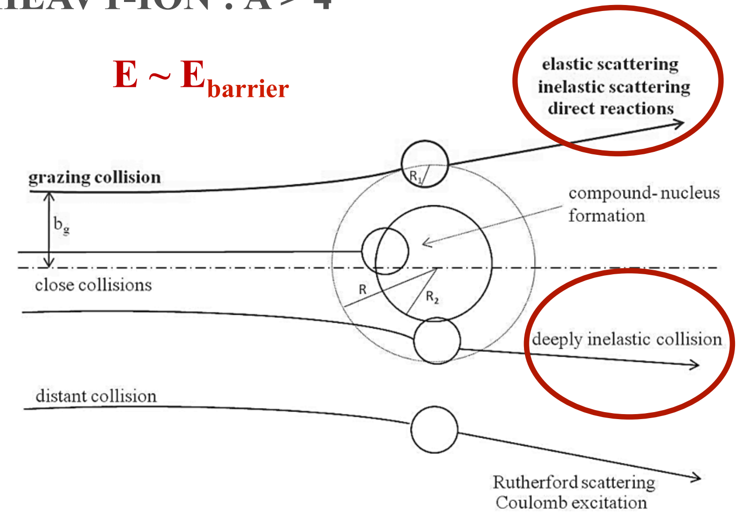


- **Collective structures**
- **Shape isomer**

F. Xu

HEAVY-ION : A > 4

$E \sim E_{barrier}$



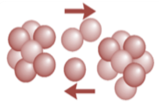
CLUSTER - TRANSFER REACTIONS

- **Weakly-bound nucleus with a cluster structure**
- **^{7}Li → B.E.(α-t) = 2.5 MeV**
- **Transfer of either fragments**

QUASI – ELASTIC REGIME

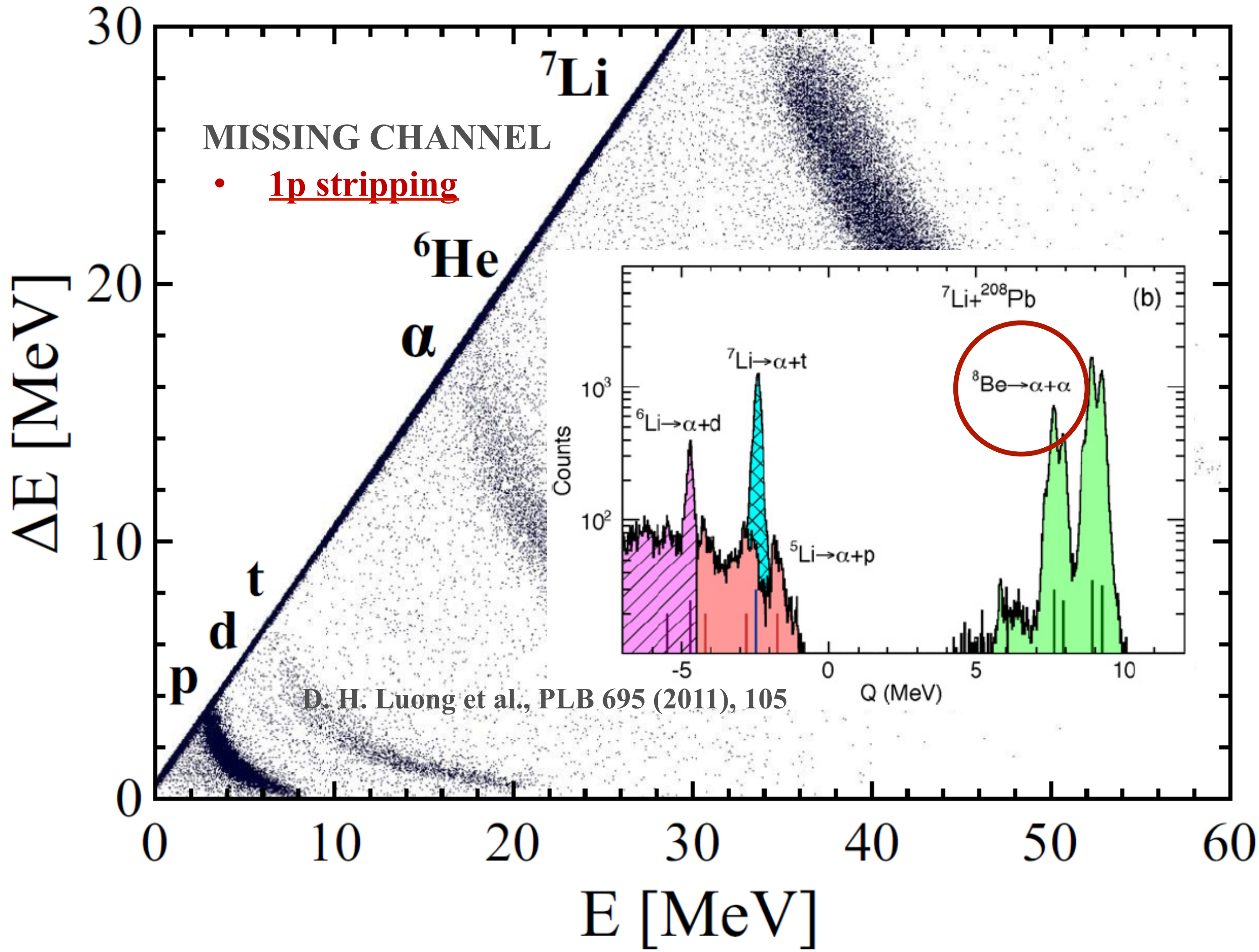
- **Few degrees of freedom - binary process**
- **Spin selection in low-lying states**
- **Cross section governed by Optimum Q-value**

Multi-nucleon transfer



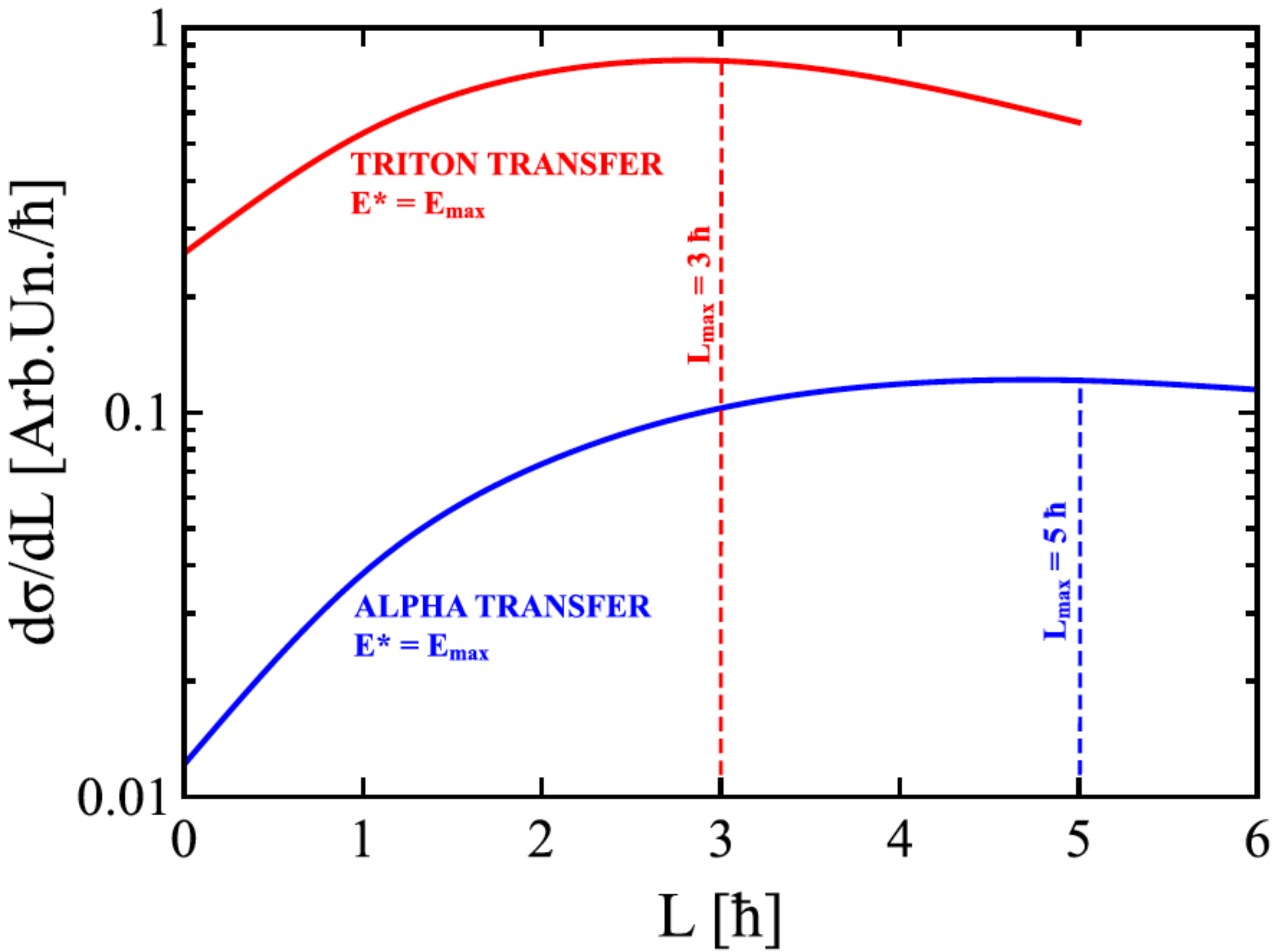
DEEP – INELASTIC COLLISIONS

- **Many degrees of freedom**
- **High-spin and energy states**
- **Particles evaporation**

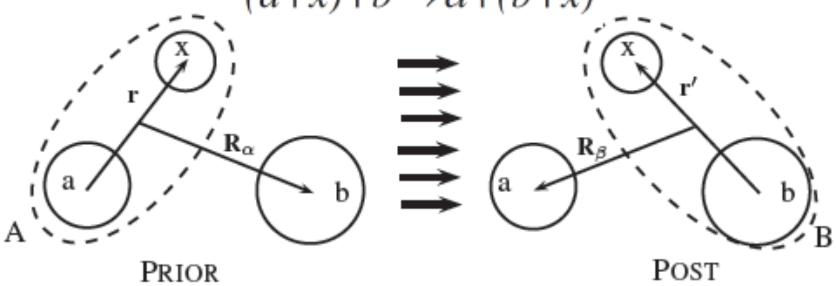


CHANNELS OBSERVED

- **Elastic scattering**
- **Inelastic scattering**
- **1p pick-up**
- **t-transfer**
- **α-transfer**
- **α-t breakup (< 20 %)**
- **^{6}Li → α-d elastic breakup**
- **Fusion - evaporation**


TRITON TRANSFER
E* = Emax
Lmax = 3 ħ
ALPHA TRANSFER
E* = Emax
Lmax = 5 ħ
dσ/dL [Arb.Un./ħ]
L [ħ]
1
0.1
0.01
0
1
2
3
4
5
6

$$(a+x)+b \rightarrow a+(b+x)$$



- **Total wave function:**

$$\psi_{tot} = \varphi_A(r)\chi_\alpha(R_\alpha) + \varphi_B(r')\chi_\beta(R_\beta)$$

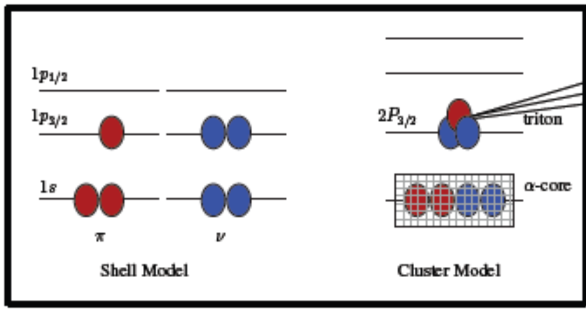
- **Cross section:**

$$\sigma \sim \langle \varphi_B \chi_\beta | V_{int} | \varphi_A \chi_\alpha \rangle$$

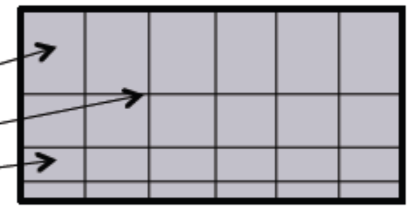
- **Internal states:**

$$\varphi_{J_{tot}M_{tot}} = \frac{u(r)}{r} \left[\left[Y_{l_x} \otimes \xi_{s_x} \right]_{j_x} \otimes \xi_{s_{core}} \right]_{J_{tot}M_{tot}}$$

1-step DWBA transfer from cluster states to continuum



$$V_{int}^{POST}$$

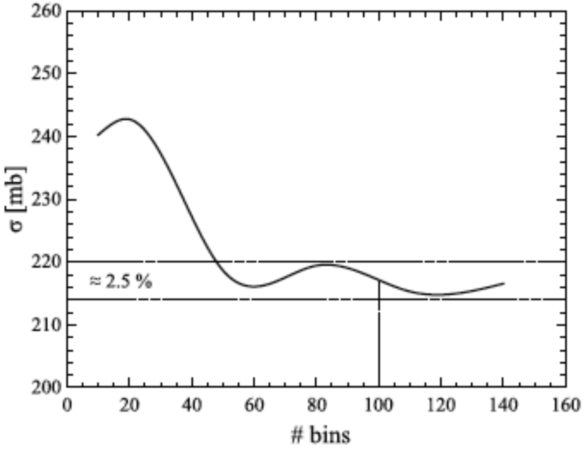


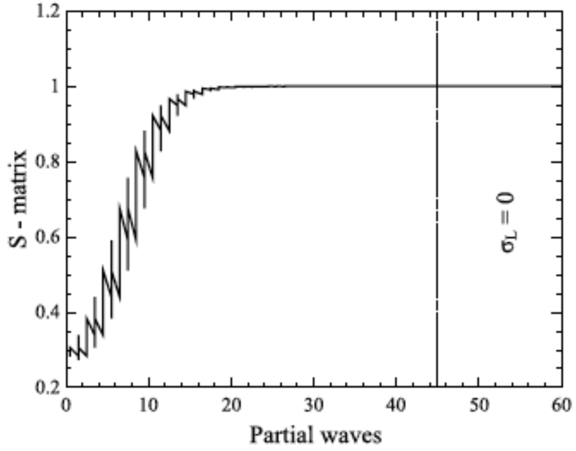
Continuum

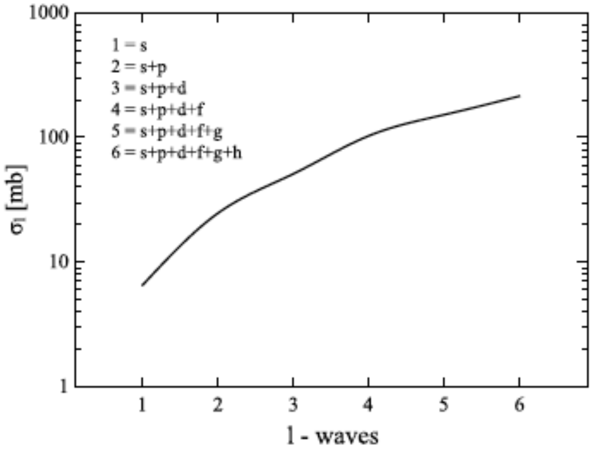
Optical parameters from elastic scattering

Cluster model (e.g. ^{7}Li=α_core+t):

t – transfer (^{98}Rb)



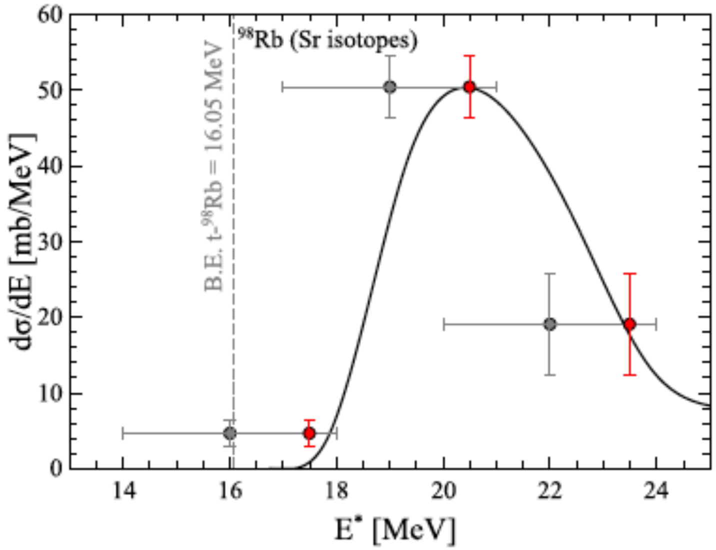


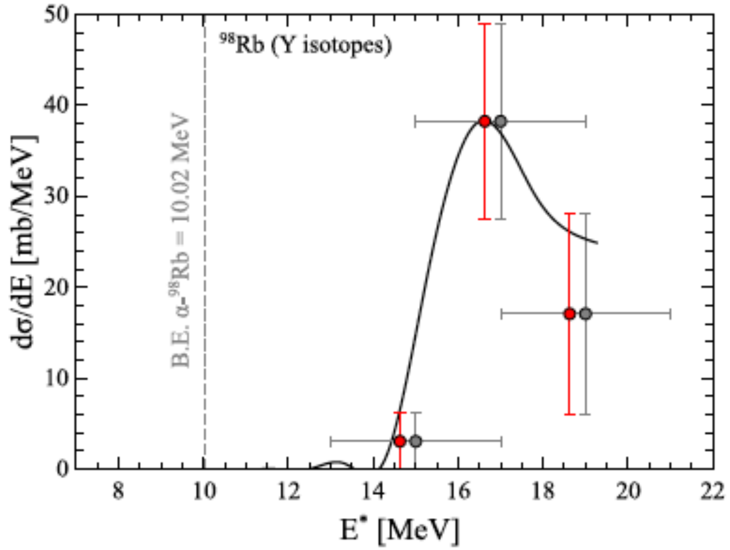


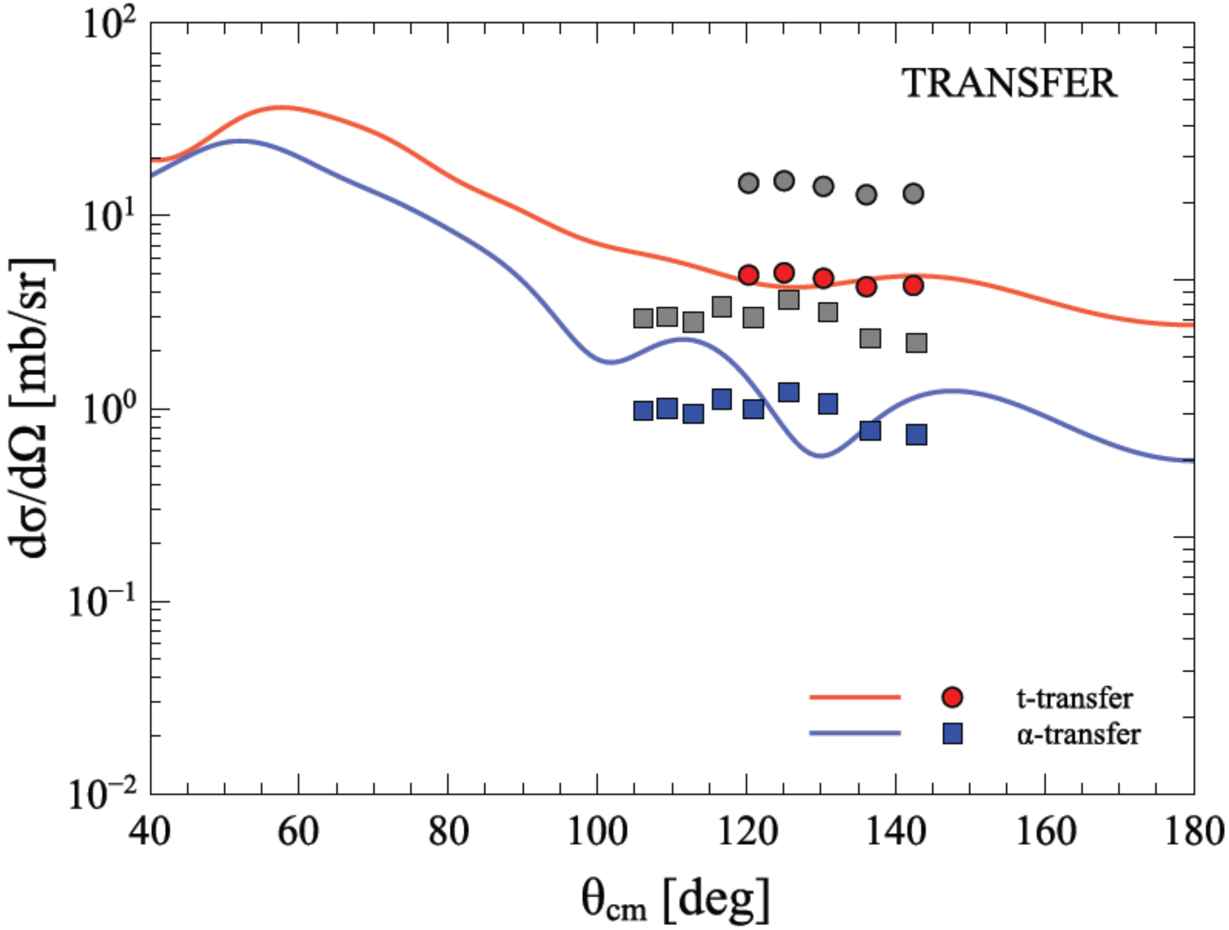
t - transfer

α- transfer

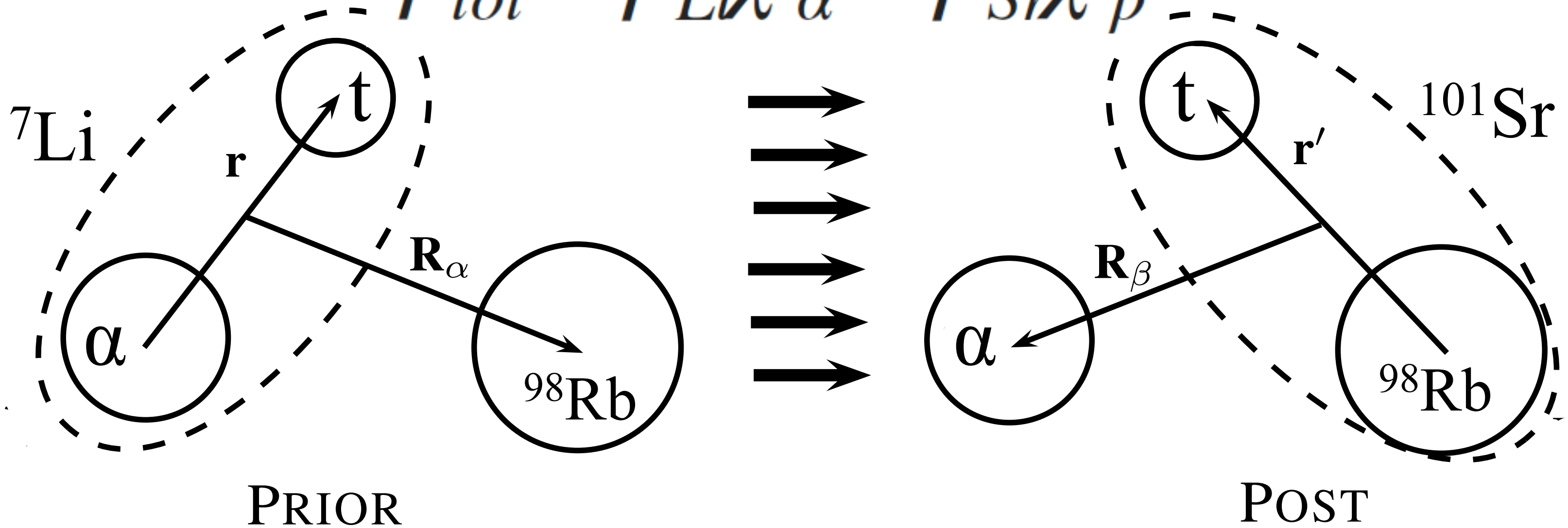
^{98}Rb






TRANSFER
t-transfer
α-transfer
dσ/dΩ [mb/sr]
θcm [deg]
10^2
10^1
10^0
10^−1
10^−2
40
60
80
100
120
140
160
180

$$\Psi_{tot} = \varphi_{Li}\chi_{\alpha} + \varphi_{Sr}\chi_{\beta}$$



$$V_{int}^{PRIOR} = V_{Rb\text{-}t} + U_{Rb\text{-}\alpha} - U_{Rb\text{-}Li}$$

$$V_{int}^{POST} = V_{\alpha\text{-}t} + U_{Rb\text{-}\alpha} - U_{Sr\text{-}\alpha} \approx V_{\alpha\text{-}t}$$

Main | Remnant

t – transfer (^{98}Rb)

$$\frac{d\sigma}{d\Omega} = \frac{\mu_\alpha \mu_\beta}{2\pi\hbar^2}\left(\frac{k_\beta}{k_\alpha}\right)|T|^2 \qquad T_{POST} = \langle \chi_\beta \varphi_{Sr} | V_{\alpha-t} | \chi_\alpha \varphi_{Li} \rangle$$

$$H_{Li}\varphi_{Li} = \varepsilon_{Li}\varphi_{Li}$$

$$H_{Sr}\varphi_{Sr} = \varepsilon_{Sr}\varphi_{Sr}$$

DWBA

$$\begin{cases} [E - T_\alpha - \varepsilon_{\mathrm{Li}} - U_{Rb-Li}]\chi'_\alpha \approx 0 \\ [E - T_\beta - \varepsilon_{\mathrm{Sr}} - U_{Sr-\alpha}]\chi'_\beta = V_{\alpha-t}\chi'_\alpha \end{cases}$$

$U_{Rb\text{-}Li}$ and $U_{Sr\text{-}\alpha}$

$$U(R) = U_{\mathrm{nuc}}(R) + U_{\mathrm{coul}}(R)$$

$$U_c(R) = \begin{cases} \frac{Z_1 Z_2 e^2}{2R_c}\left(3 - \frac{R^2}{R_c^2}\right) & \text{if } R \leq R_c \\ \frac{Z_1 Z_2 e^2}{R} & \text{if } R \geq R_c \end{cases}$$

$$U_{\mathrm{nuc}}(R) = V(r) + iW(r) = -\frac{V_0}{1+\exp\left(\frac{R-R_0}{a_0}\right)} - i\,\frac{W_0}{1+\exp\left(\frac{R-R_i}{a_i}\right)}$$

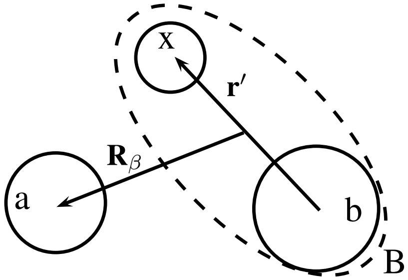
$V_{\alpha\text{-}t}$

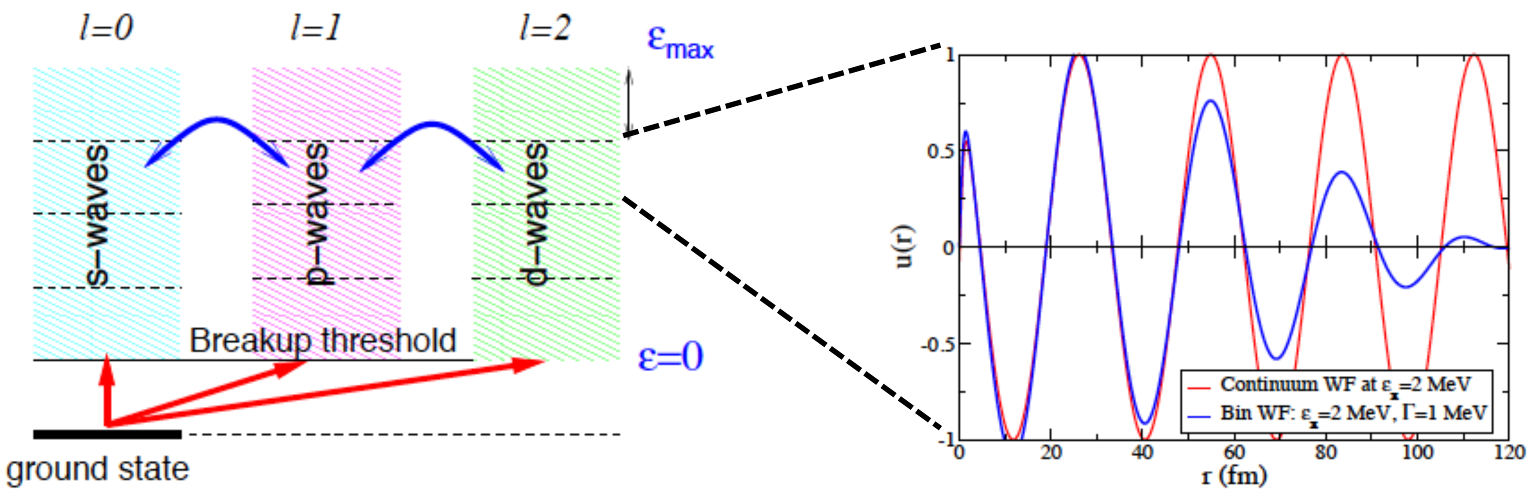
$$U(R) = U_{\rm nuc}(R) + U_{\rm coul}(R)$$

$$U_{nuc}(R) = \underbrace{-V_0 e^{-\left(\frac{R-R_0}{a_0}\right)^2}}_{\text{Volume (Gaussian)}} \underbrace{-2V_{so} e^{-\left(\frac{R-R_{so}}{a_{so}}\right)^2}\left(\frac{R-R_{so}}{a_{so}}\right)}_{\text{Spin Orbit (Gaussian)}}$$

Continuum

$$\varphi_{J_{tot}M_{tot}} = \frac{u(r)}{r}\left[\left[Y_{l_x}\otimes\xi_{s_x}\right]_{j_x}\otimes\xi_{s_{core}}\right]_{J_{tot}M_{tot}}$$



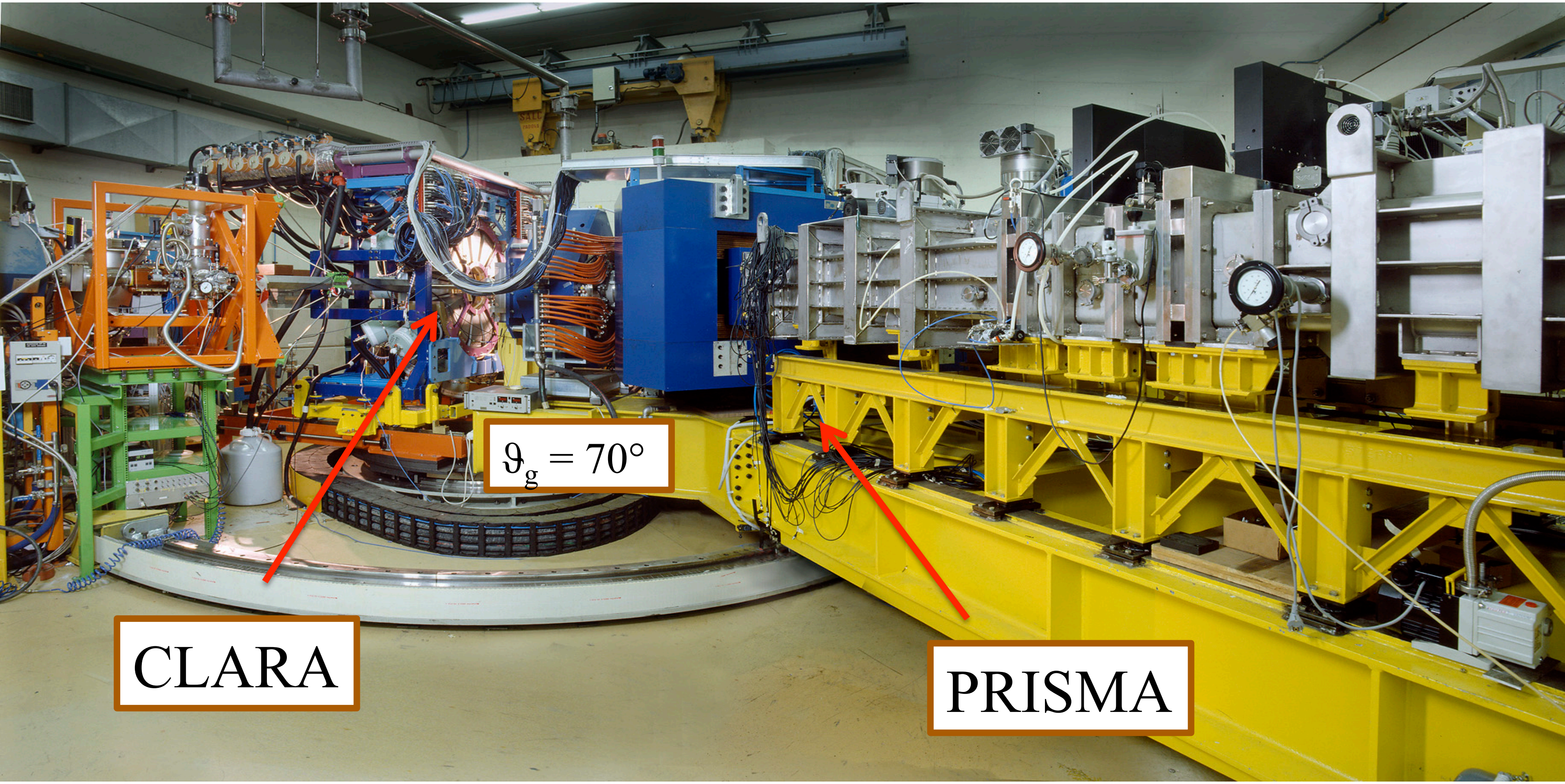


A. Moro (lectures at TRIUMF)

$$u_{\ell s j,n}(r) = \sqrt{\frac{2}{\pi N}}\int_{k_1}^{k_2} w(k)u_{\ell s j,k}(r)dk$$

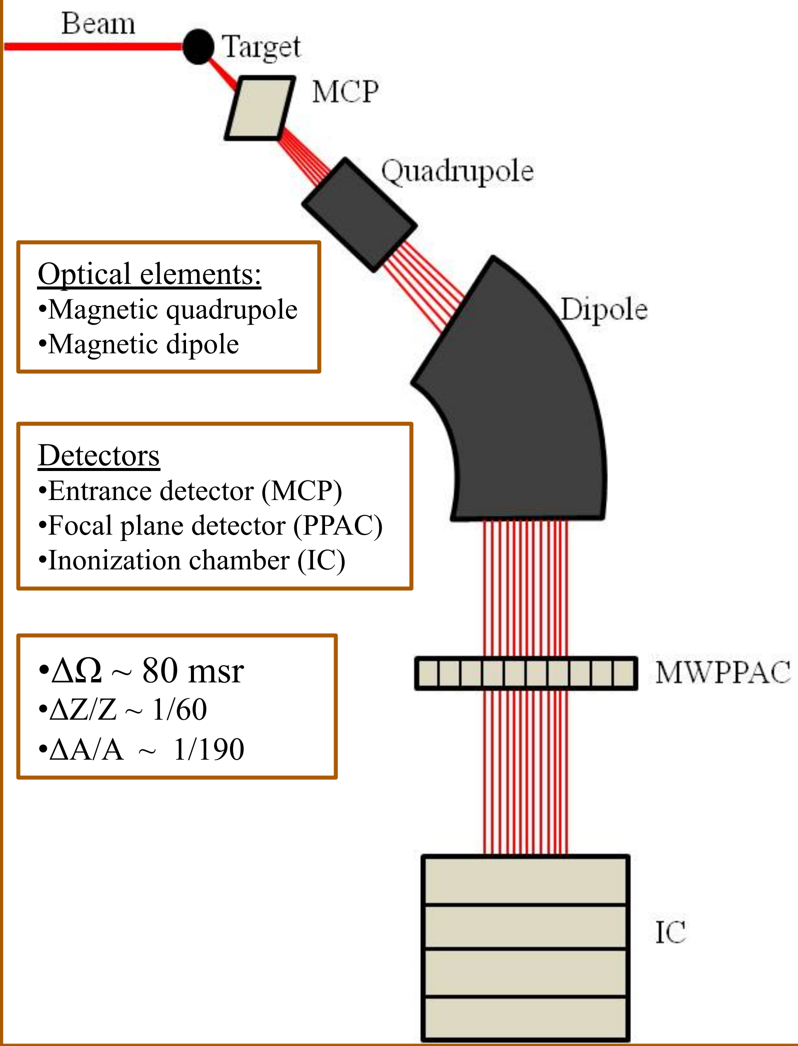
Resonant states: $sin\delta_l e^{-i\delta_l}$

Channel	V(MeV)	r_V(fm)	a_V(fm)	W(MeV)	r_W(fm)	a_W(fm)	R_C(fm)
^{7}Li + ^{98}Rb	114.2	1.286	0.853	15.643	1.739	0.809	5.994
α + ^{101}Sr	140.0	1.200	1.200	10.0	1.200	1.200	6.054
t + ^{102}Y	80.0	1.250	1.500	10.0	1.250	1.500	6.074



Particle - γ coincidence measurements

PRISMA



Optical elements:
- Magnetic quadrupole
- Magnetic dipole

Detectors
- Entrance detector (MCP)
- Focal plane detector (PPAC)
- Inonization chamber (IC)

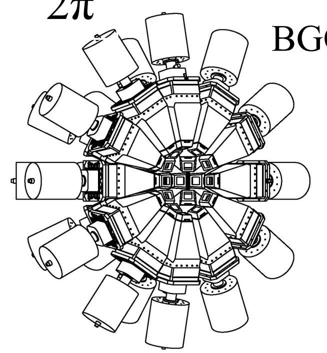
- $\Delta\Omega \sim 80$ msr
- $\Delta Z/Z \sim 1/60$
- $\Delta A/A \sim 1/190$

CLARA

25 HpGe Clover

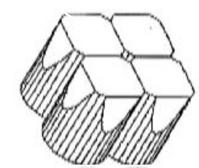
$\varepsilon \sim 3$ % @ $E_\gamma = 1.3$ MeV

2π



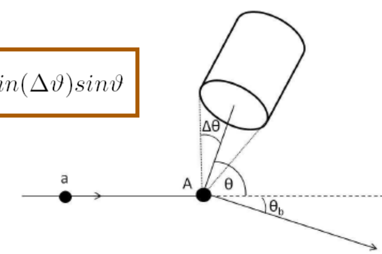
BGO

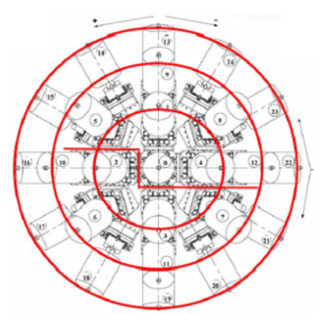
Composite Ge
50mm x 70mm



Compton polarimeter

$$\Delta FWHM = 2E_{\gamma 0}\frac{v}{c} sin(\Delta\vartheta) sin\vartheta$$

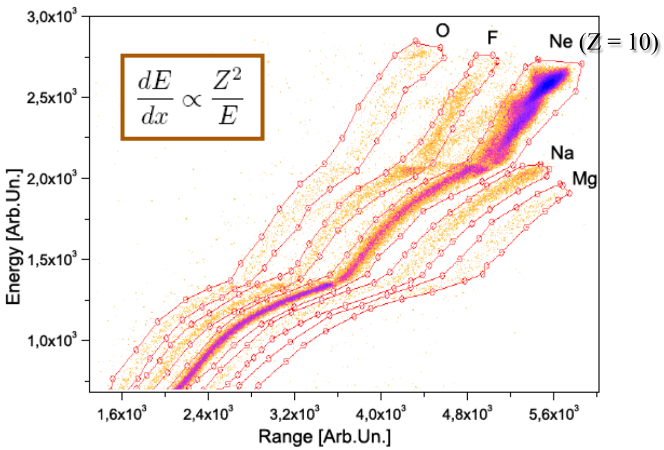




3 RINGS
$\theta \sim 100°\text{-}130°\text{-}150°$

γ angular distributions

Z selection

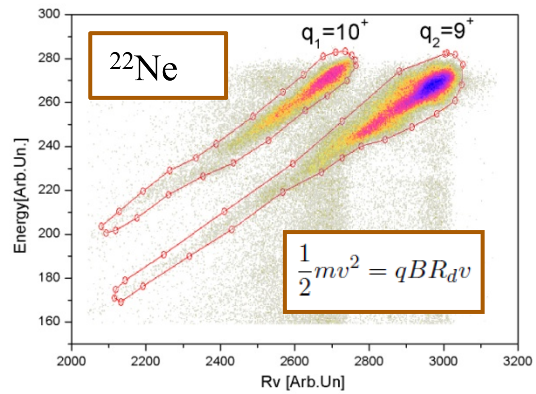


$$\frac{dE}{dx} \propto \frac{Z^2}{E}$$

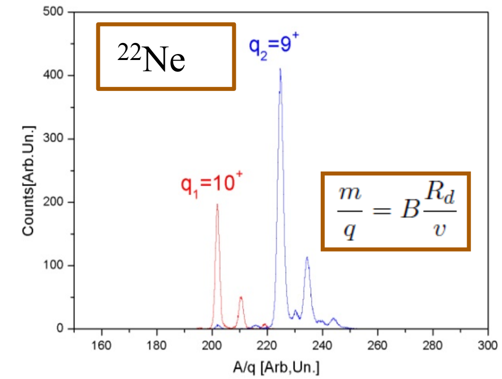
$$R(E) = \int_0^E dE' \left[\frac{dE'}{dx}\right]^{-1} \propto \frac{E^2}{z^2}$$

Charge states selection

$$|\vec{F}| = qvB_d = ma = \frac{mv^2}{R_d}$$

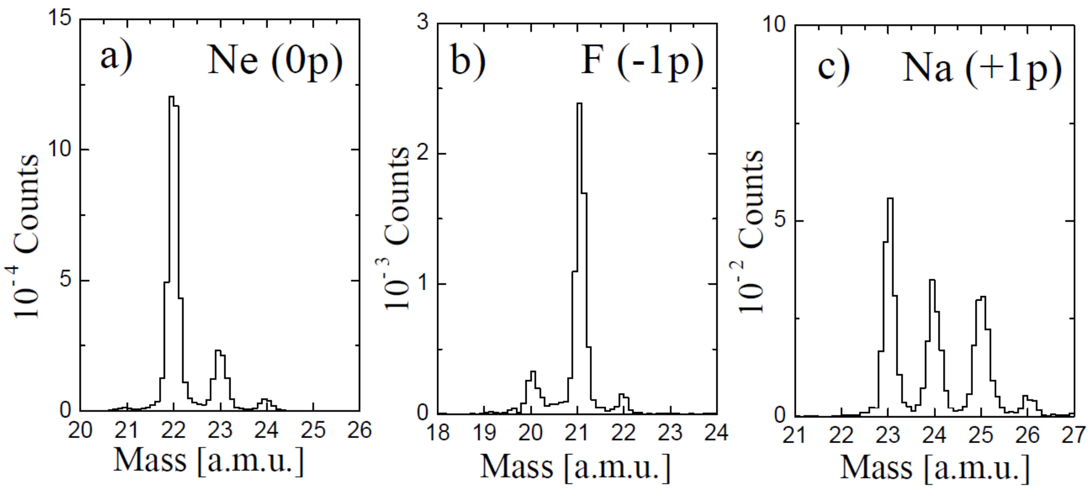


$$\frac{1}{2}mv^2 = qBR_dv$$



$$\frac{m}{q} = B\frac{R_d}{v}$$

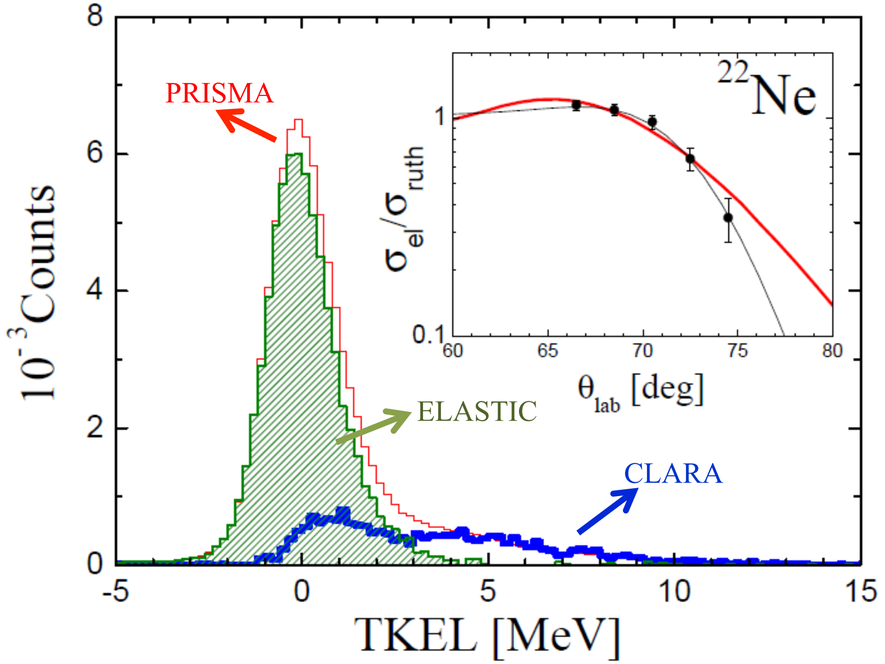
Mass spectra



Elastic cross section

$$Q = K_f - K_i = (m_a + m_A - m_b - m_B)c^2 - (E_b^* + E_B^*)$$

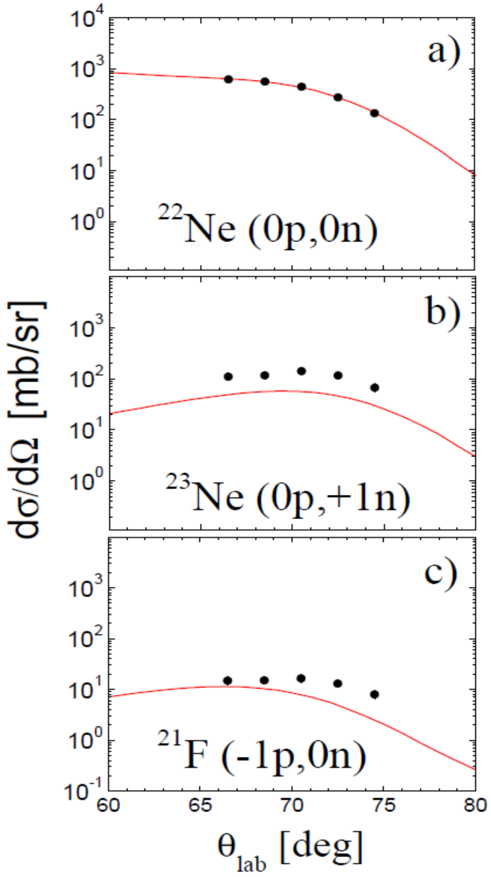
$$TKEL = -Q$$



$\sigma(\theta)/\sigma_{Ruth}$ → Normalization → $1\ \mathrm{mb/sr} = 215\ \mathrm{counts}$

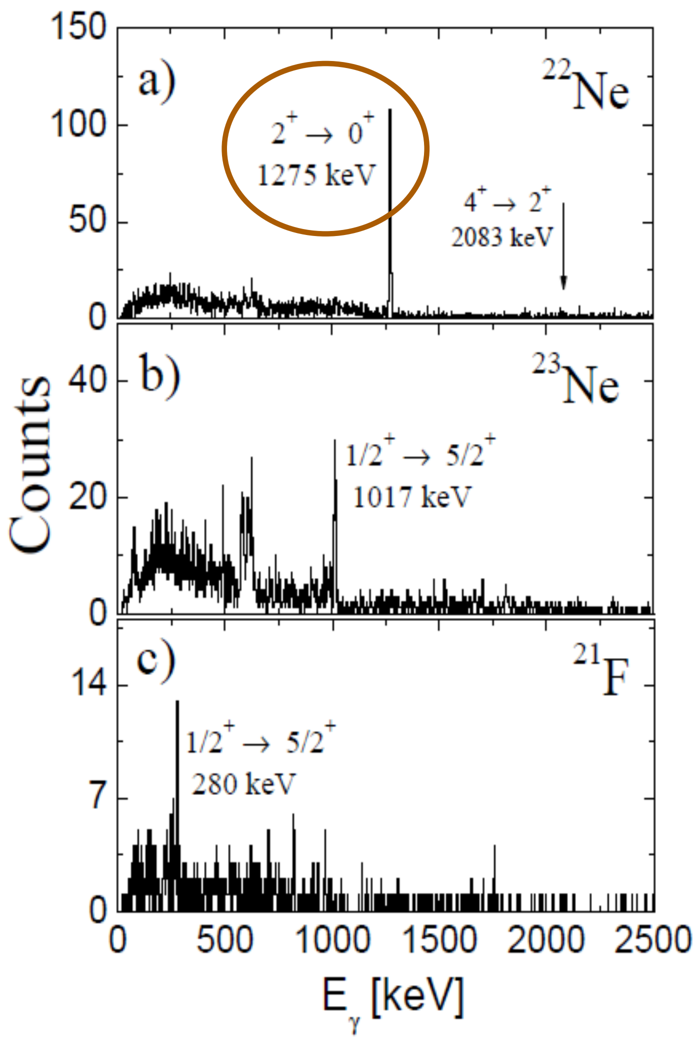
DWBA fit → Optical parameters

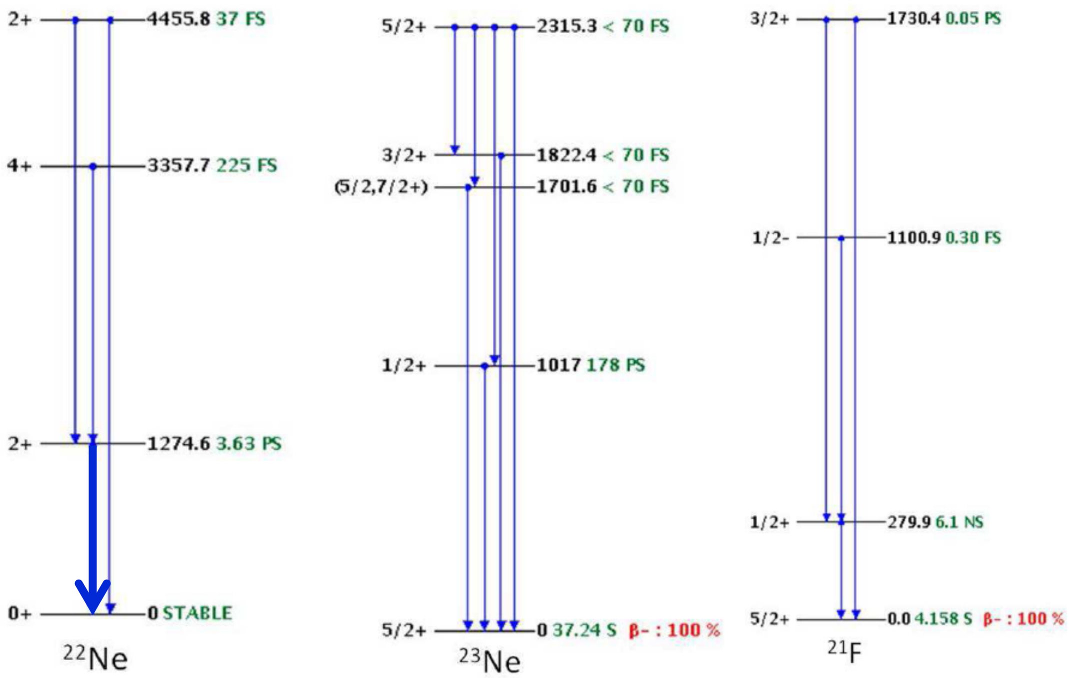
Inclusive cross sections



GRAZING

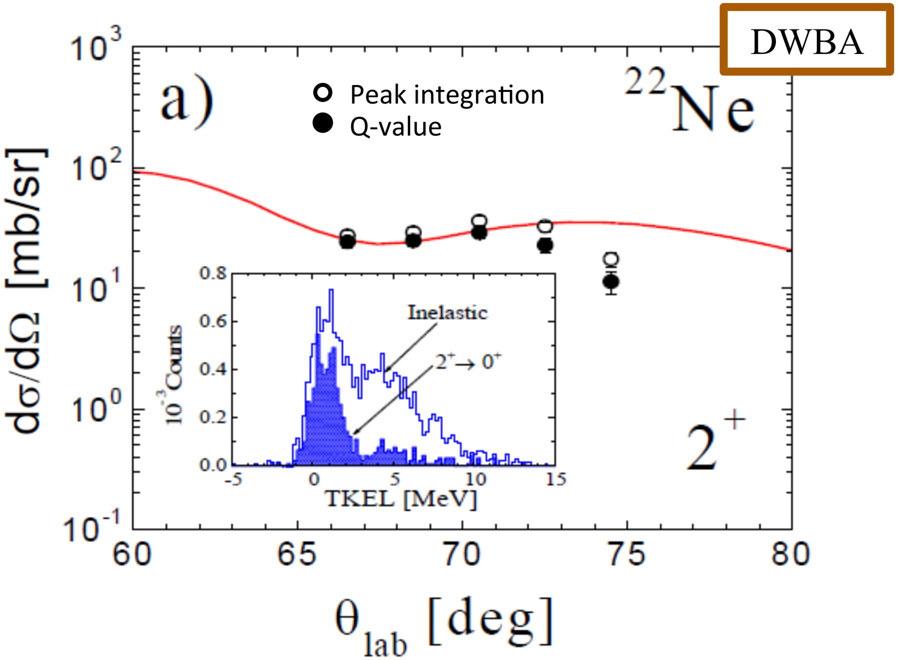
γ spectra

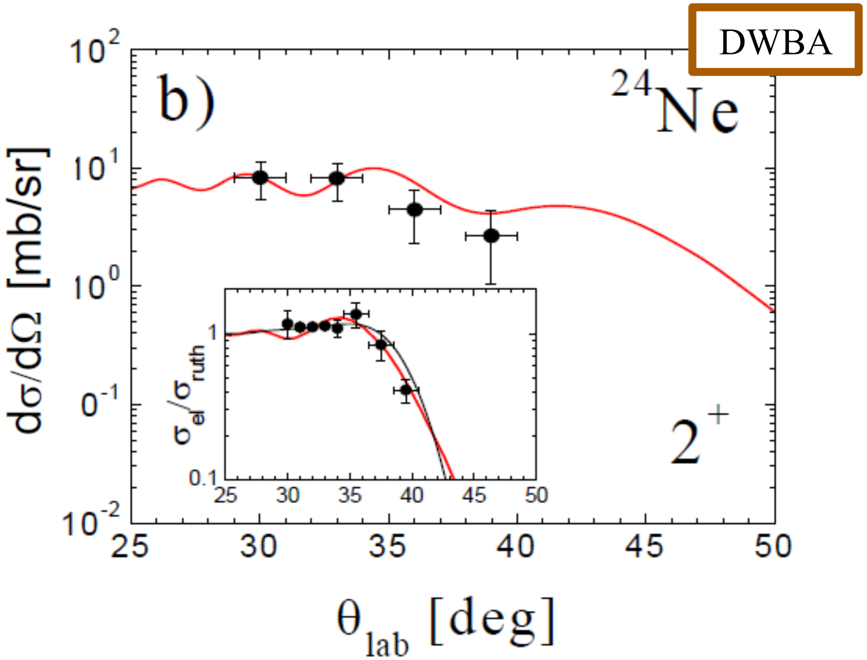




Doppler corrected event by event for v/c ≈ 10 %

Inelastic cross sections





^{22}Ne + ^{208}Pb @ 128 MeV

PRISMA+CLARA @ LNL

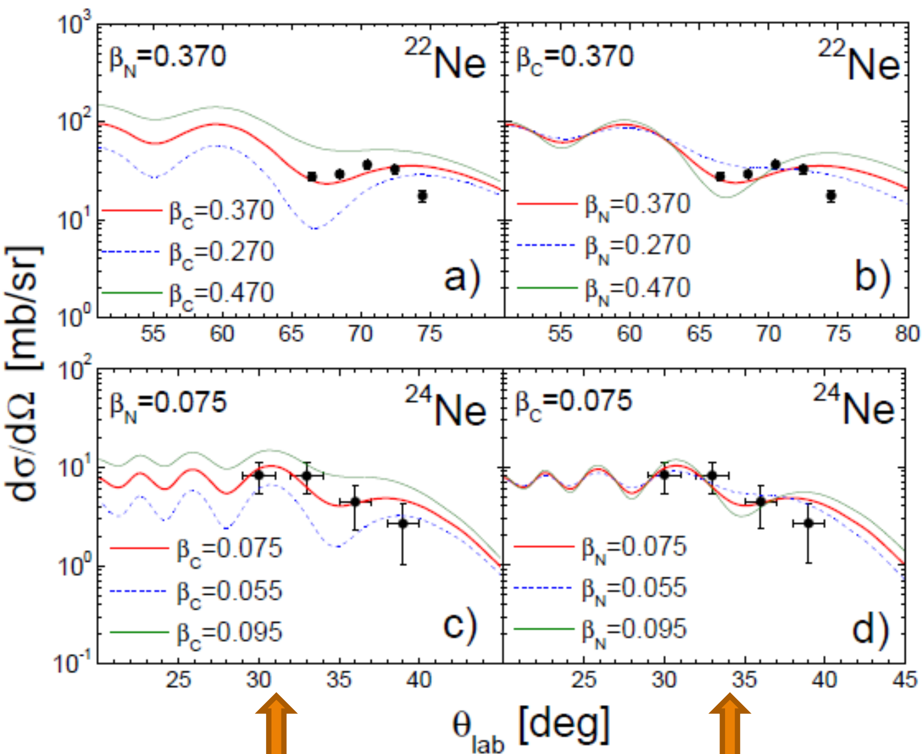
^{24}Ne + ^{208}Pb @ 182 MeV

VAMOS+EXOGAM @ GANIL

G. Benzoni et al., Eur. Phys. J. A 45, 287-292 (2010)

Deformation parameters

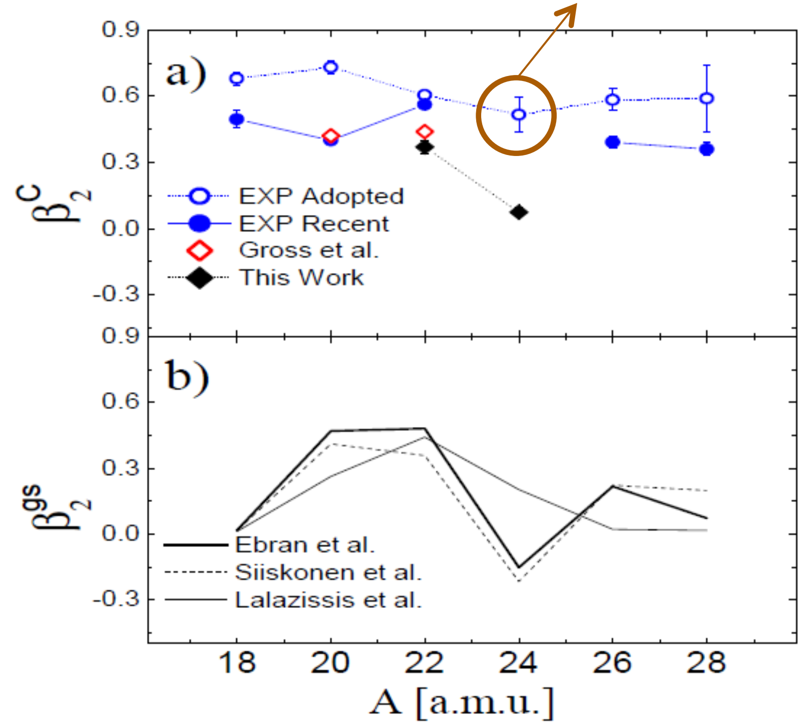
$$\beta_2^C = (4\pi/3ZR_0^2)[B(E2;0^+ \rightarrow 2^+)/e^2)]^{1/2}$$



Sensitivity to β_C

Sensitivity to β_N

Very old measurement!



Closure of $\nu 1d_{5/2}$ in ^{24}Ne

^{24}Ne is a nucleus of key importance in the study of shell evolution towards the “island of invertion”