1st one day workshop of HINP

8th of September 2012

optical potential and relevant reaction mechanisms at near barrier energies with nucleus-nucleus collisions

Athena Pakou, University of Ioannina

Outlook of the talk:

A survey will be given for the research performed by our group the last ten years related with the optical potential and reaction mechanisms at near barrier energies

Context :

- **The optical Potential**
- **Energy dependence of the optical potential**
- **Reaction mechanisms-fusion versus compound**
- **Coupling effects-Clustering effects**
- **Future perspectives**

The optical potential

A successful method to describe the nucleus-nucleus interaction is the optical potential method either in a macroscopic or a microscopic approach

$$U(r;E) = V(r;E) + iW(r;E)$$

Macroscopic approach- e.g. use a Woods-Saxon potential

depth

$$V(r,E) = \frac{V_0}{1+\exp\left(\frac{r-R}{\alpha}\right)}$$

radius

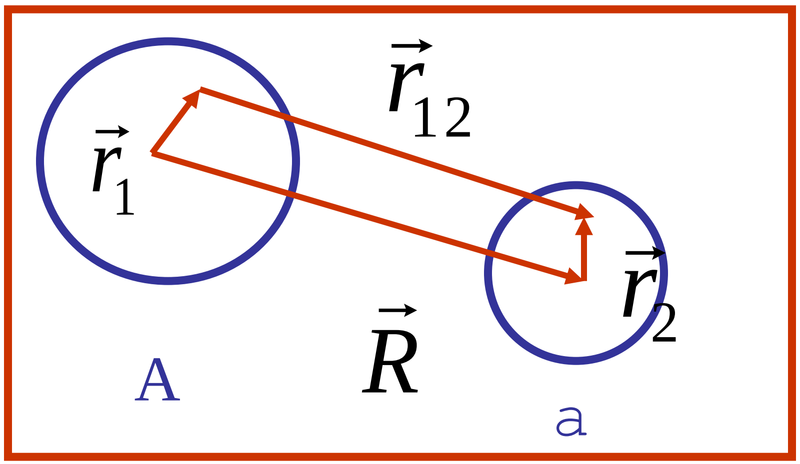
diffusivity

Adjustable parameters V_0, R, α

Igo ambiguities etc

Microscopic optical potentials

$$u_{12} = u_{00}(r_{12}) + u_{01}(r_{12})\vec{\tau}_1\vec{\tau}_2 + u_{10}(r_{12})\vec{\sigma}_1\vec{\sigma}_{21} + u_{11}(r_{12})\vec{\sigma}_1\vec{\sigma}_2\vec{\tau}_1\vec{\tau}_2$$



$$\vec{r}_{12} = \vec{R} - \vec{r}_1 + \vec{r}_2$$

$$U(\vec{R}) = \iint \rho_A(\vec{r}_1)\rho_a(\vec{r}_2)u(\vec{r}_{12})d\vec{r}_1 d\vec{r}_2$$

The M3Y-Reid interaction

$$u^{M3Y}(r) = \left[7999\frac{e^{-4r}}{4r} - 2134\frac{e^{-2.5r}}{2.5r}\right]$$

$$u_{00}(r) = u^{M3Y}(r) + \alpha_1(E)\delta(\vec{r})$$

$$\alpha_1(E) = -276(1 - 0.005E/A)MeVfm^3$$

The DDM3Y interaction

$$u(E,\rho,r) = u^{M3Y}(r)f(E,\rho)$$

$$f(E,\rho) = C(E)\left[1 + \alpha(E)e^{-\beta(E)\rho}\right]$$

$$\rho(r) = \rho_1(r_1) + \rho_2(r_2)$$

G. R. Satchler and W. G. Love Phys. Rep. 55 (1979) 183, and N. P. A438 (1985) 525.

N. Alamanos et P. Roussel-Chomaz Ann. Phys. Fr. 21 (1996) 601-668

Tools for probing the Optical potential

ELASTIC SCATTERING - our main tool

Other tools

- Total reaction cross sections - describe the flux absorption
- Fusion Cross sections- probe the potential at the inner side of the nucleus
- Direct reactions-peripheral interactions

- **Backscattering technique-NEW Method**

PhD Study : Zerva et al., PRC 80, 017601(2009)

PRC 82, 044607(2010)

EPJA 48, 102 (2012)

Completed work on : $^{6,7}Li+^{28}Si$

REACTIONS with WEAKLY BOUND STABLE NUCLEI on LIGHT TARGETS near BARRIER

- **ELASTIC SCATTERING**
- **BREAKUP**
- **TOTAL REACTION CROSS SECTIONS**
- **TRANSFER at BARRIER**
- **FUSION MEASUREMENTS**

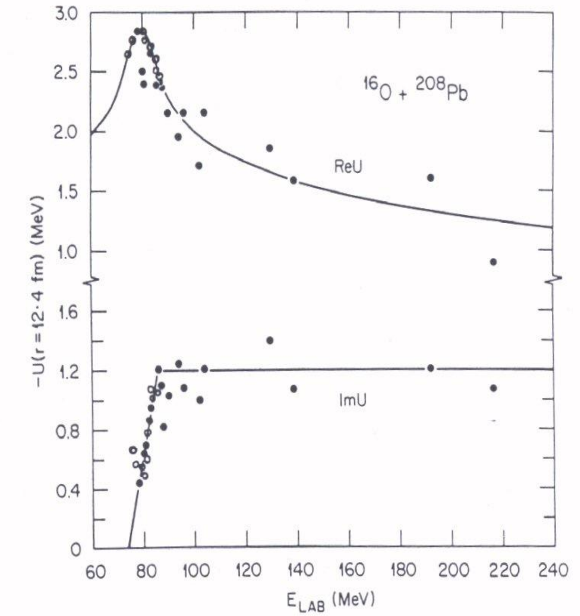
A. Pakou et al, **PRC78**,067601; **PRC76**,054601; **PRC73**,051603; **PRC71**,014603; **PRC69**,057602; **PRC69**,054602, **EPJA39**,187; **NPA784**,13; **PRL90**,202701,**PLB556**,21;**PLB633**,691

ENERGY DEPENDENCE at near barrier

- Potential THRESHOLD ANOMALY

$$U(r;E) = V(r;E) + iW(r;E)$$

Stable projectiles



dispersion relation

$$V(r;E) = V_0(r;E) + \Delta V(r;E)$$

$$\Delta V = \frac{P}{\pi}\int_0^{\infty} \frac{W(r;E')}{E' - E} dE'$$

The anomaly and the validity of dispersion was questioned for

weakly bound projectiles

by Satchler and reported in Phys. Rep. 199(1991) 147

The energy dependence of the optical potential at near and sub-barrier energies is strong, known as potential threshold anomaly. It is related through a dispersion relation to the behaviour of the imaginary part of the potential and thus to the variation of absorption

Absorption from the elastic channel implies the presence of couplings to other channels, which give rise to a correction to the real potential, which may be called «dynamical polarization potential»

anomaly a coupled channel effect

❖ The role of Reactions TODAY

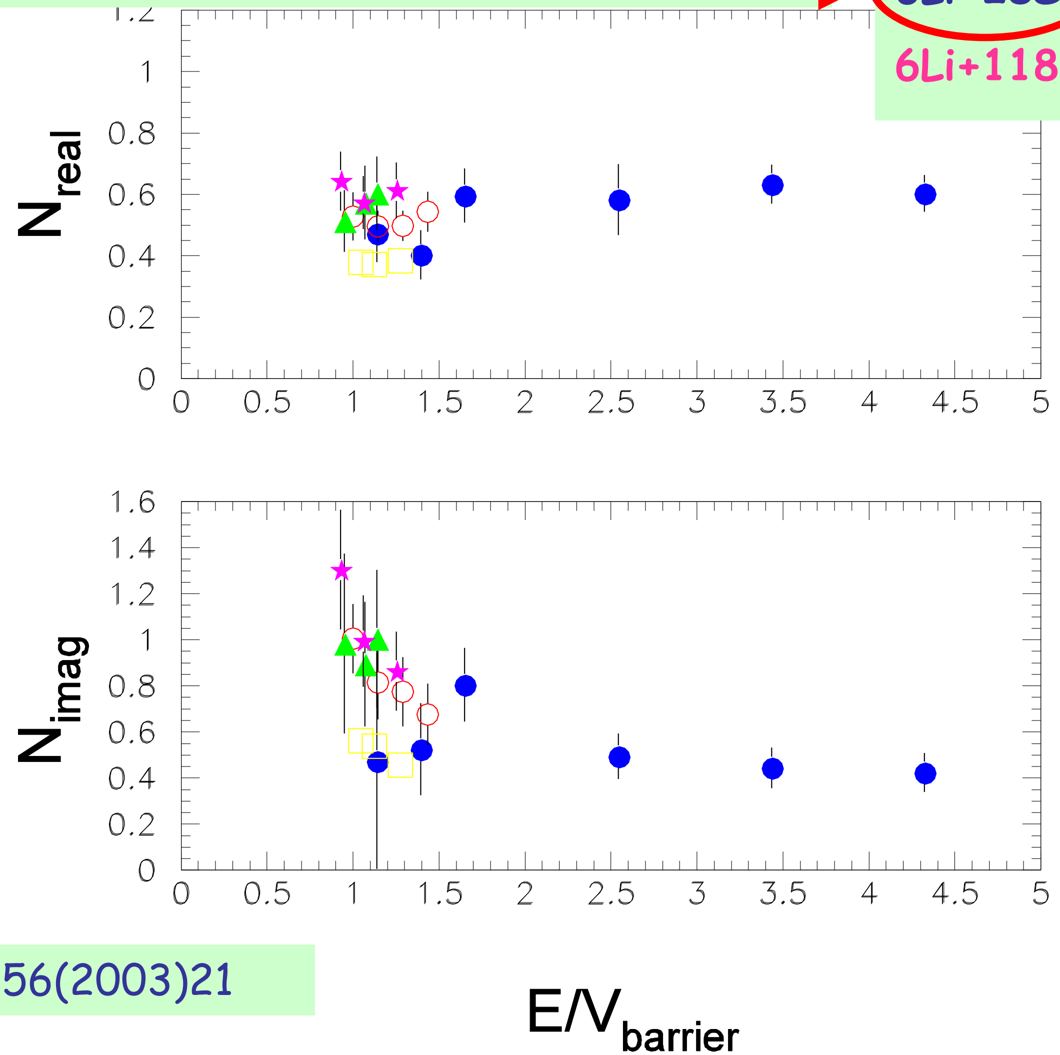
We believe that in order to understand the structure of nuclei and their interactions, it is vital to produce identify and study EXOTIC NUCLEI and the reactions mechanisms where are involved.

Instead in predecessor studies we can be involved in research with weakly bound but stable nuclei

Most popular candidates worldwide ^{6}Li, ^{7}Li

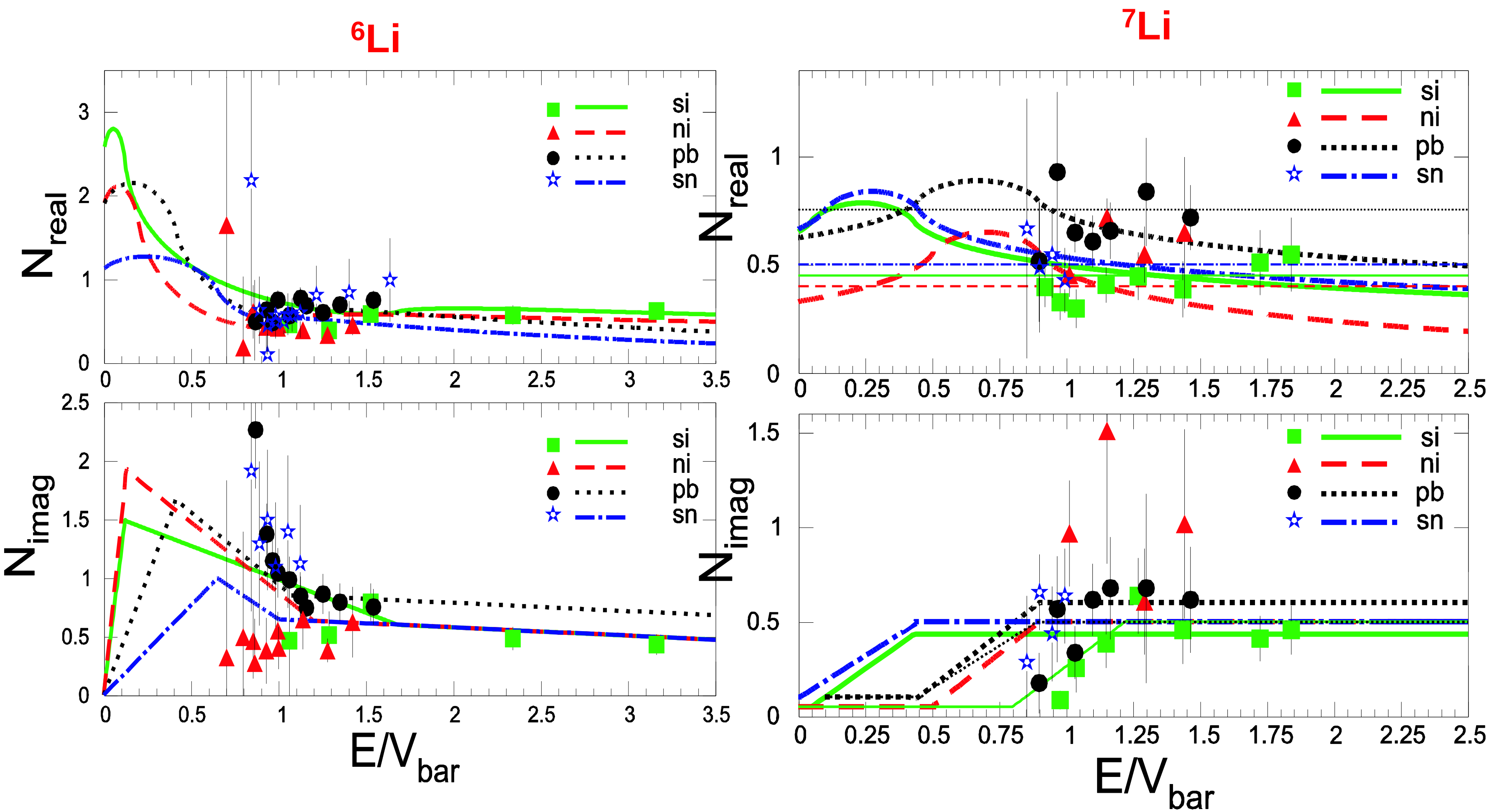
Normalization factors of the real and imaginary microscopic potential for

6Li+28Si, 6Li+58Ni
6Li+118Sn, 6Li+208Pb



A. Pakou et al. PLB 556(2003)21

Energy dependence of $^{6,7}Li+^{28}Si$



K. Zerva will report on the energy dependence of the optical potential by combining the elastic scattering and backscattering NEW technique

First observation:

The threshold anomaly is different for the weakly bound systems. It is different for ^{6}Li than ^{7}Li.

The dispersion relation may not be valid

Projectile breakup effects in elastic scattering

Y. Sakuragi, Phys. Rev. C35 (87) 2161

The coupling generates a repulsive real potential

It depends slightly on the energy and the target

it has a negligible imaginary part

questions

- **What other terms contribute to the polarization potential which can smooth out the anomaly for weakly bound nuclei**
- **Is that coupling sufficient to interpret the threshold anomaly for weakly bound nuclei and the variation between 6Li and 7Li**

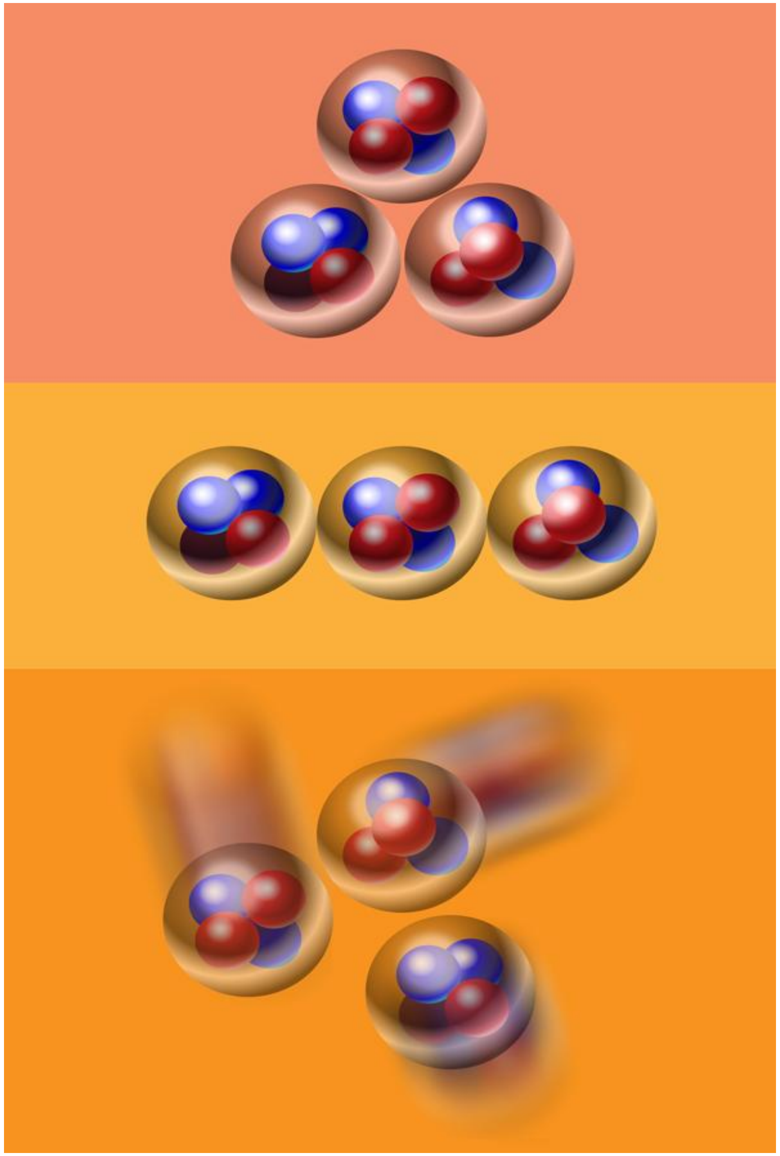
????

Other questions

- **What is the role of the structure of Nuclei??**
- **Contribution of Clustering??-**

(should be very important for exotic drip line nuclei

Very important for nucleosynthesis)



Viewpoint :

The astrophysical synthesis of carbon and heavier elements essential to the existence of planets and life, depends on a quirk of nuclear physics

Fusion of two alpha cores in the hot cores of stars easily create 8Be, BUT this decays back to two alpha’s in a short time

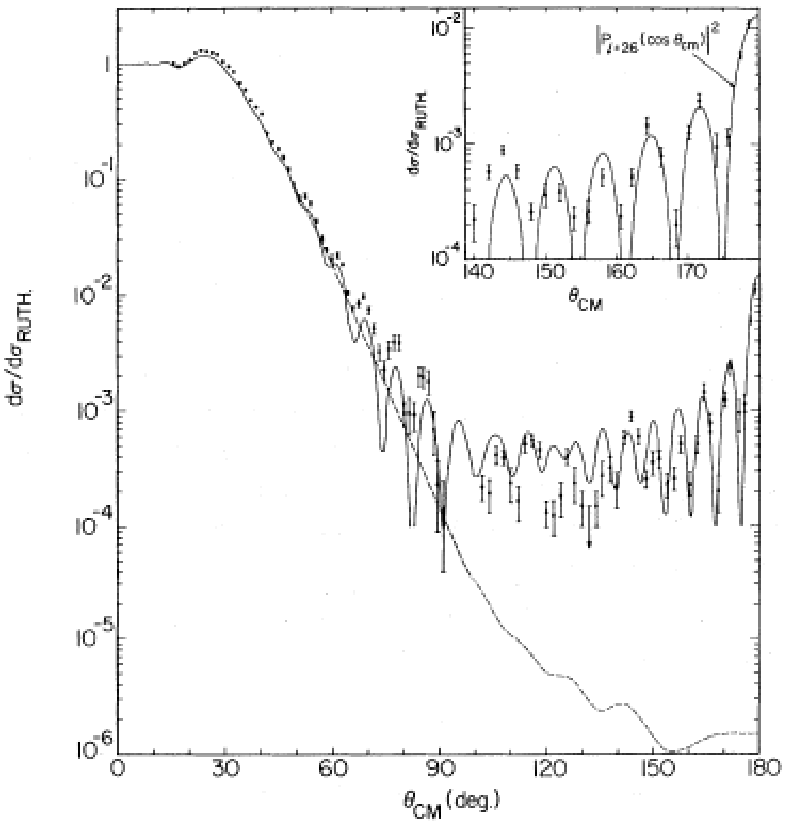
How then ^{8}Be can be the seed of 12C??

Fred Hoyle suggested in 1953 that ^{12}C must have an excited state at approximately the sum of en. for 8Be+α

Candidate state at ~10MeV

PRC84,054308(2011)

Clustering in elastic scattering



$^{16}O+^{28}Si$ at 40MeV

At intermediate energies in a semi classical approach such patterns can be interpreted as an interference phenomenon between nearside (positive angle scattering) and farside (negative angle scattering)

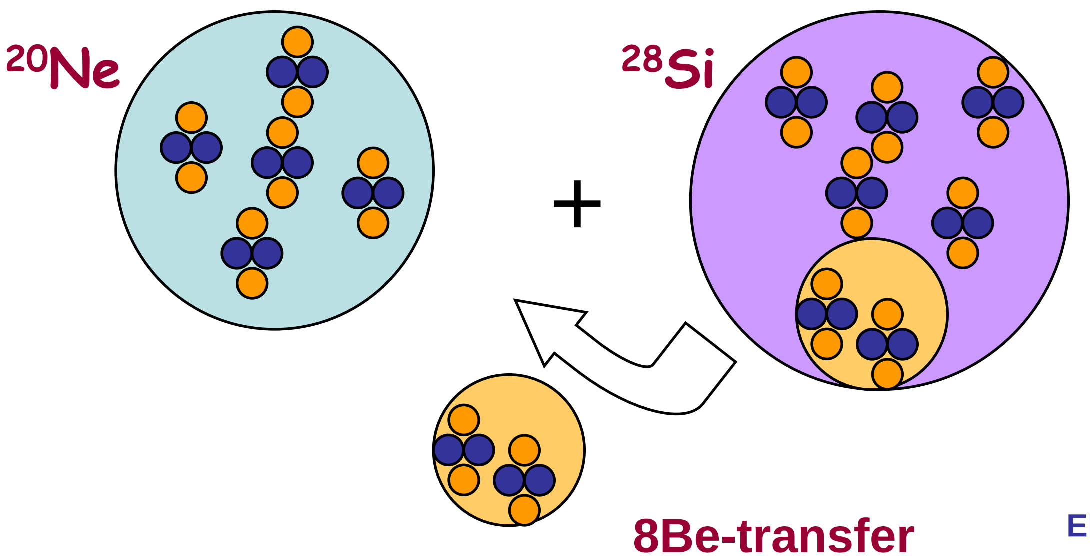
At low energies other mechanisms based on reaction couplings are more appropriate

Elastic transfer a prominent answer to this problem

PRL 82,3972 (1999)

NEW MEASUREMENT : **$^{20}Ne+^{28}Si$ elastic scattering** at near barrier energies

Our collaboration with the University of Warsaw and Soltan Institute; Department of Nuclear Reactions - WARSAW

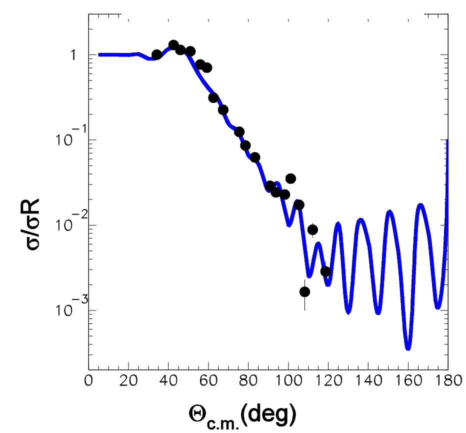


ELASTIC TRANSFER

N. Keeley-Soltan Institute:

8Be transfer more probable than a sequential transfer of two alpha's

ELASTIC SCATTERING of $^{20}Ne+^{28}Si$ at 52MeV



The measurements will be reported by **O. Sgouros** and **V. Soukeras** as a part of their MSc degree

FUSION
as a test ground for

Probing the nuclear potential at the inner side of the interaction barrier

Providing insight into a number of static and dynamic aspects-coupling channel effects

Coulomb distortion

Rotations

Excitation of vibrational states

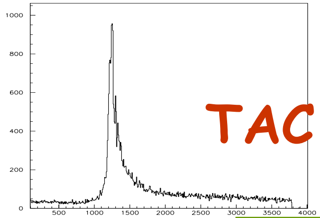
Quantal oscillations

Influence of nuclear stiffness

Static deformations

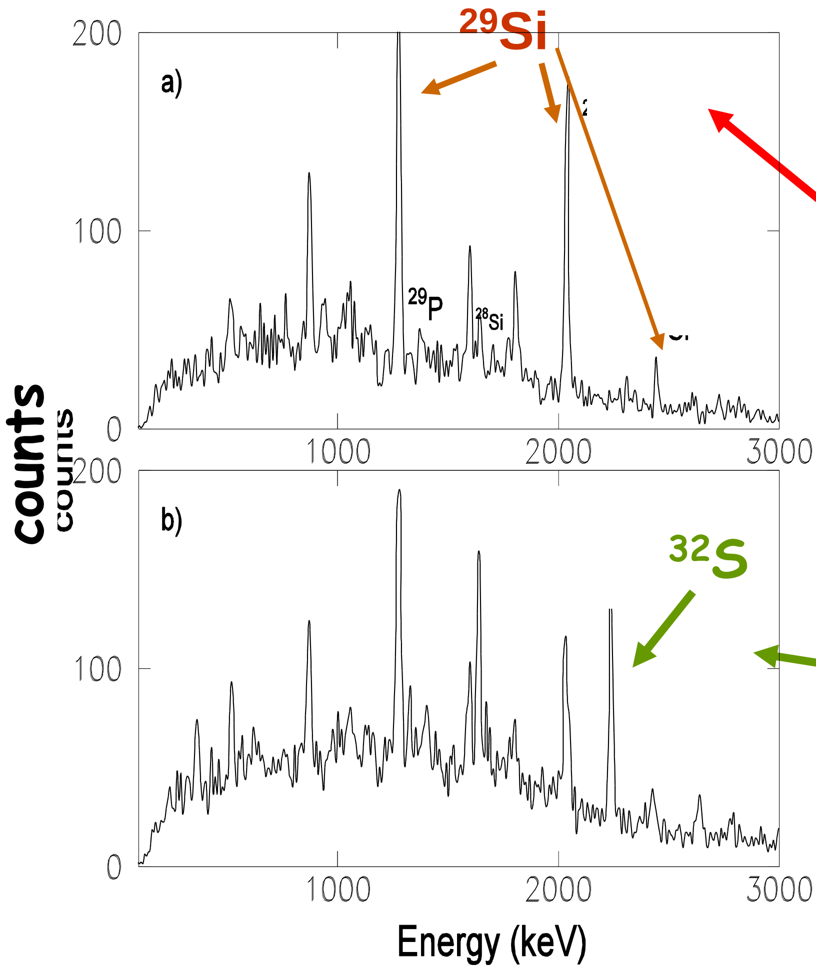
Reaction mechanisms : transfer-breakup

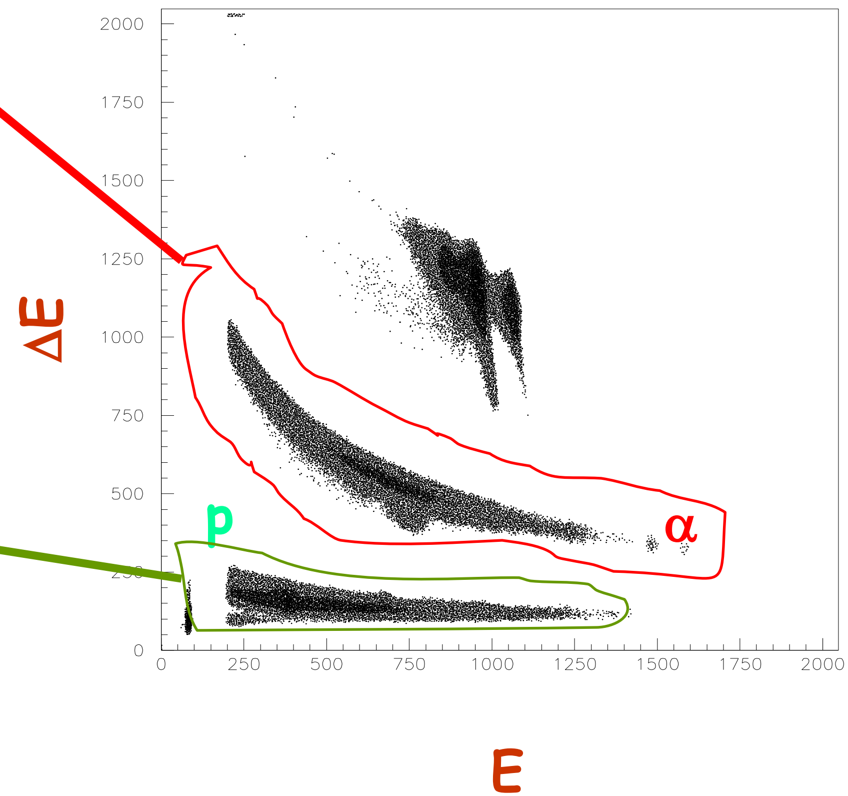
Gammas in coincidence with particles



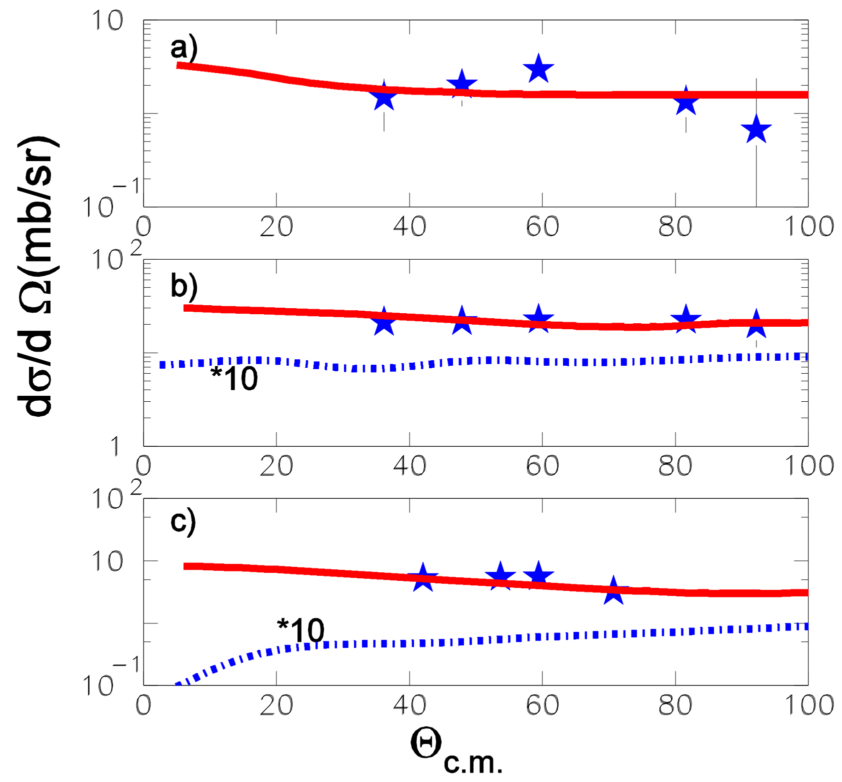
Old meausrement-
6,7Li+28Si

Particle identification with a Si telescope





Validation of compound calculations



$^{28}Si+\alpha+p+n$

E_{Li}=13MeV

$^{32}S+p+n$

E_{Li}=13MeV

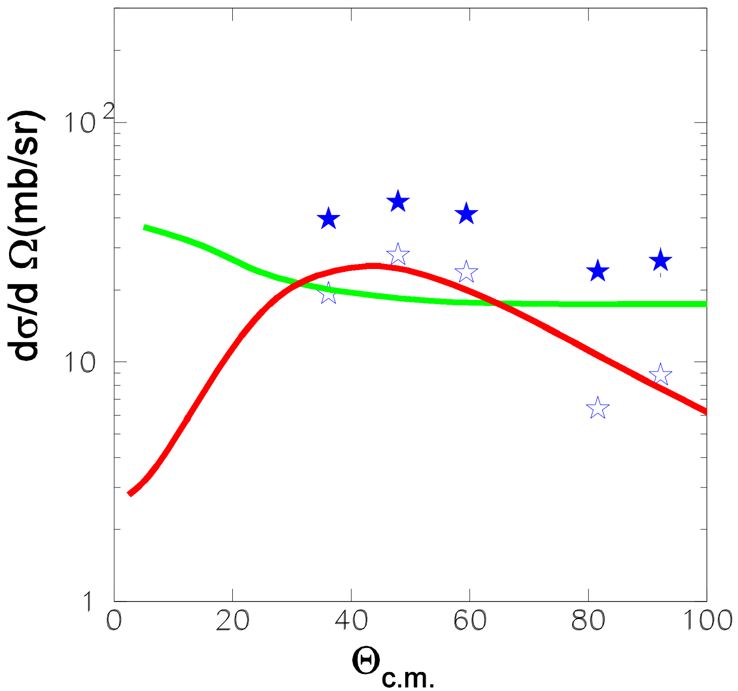
$^{32}S+p+n$

E_{Li}=9MeV

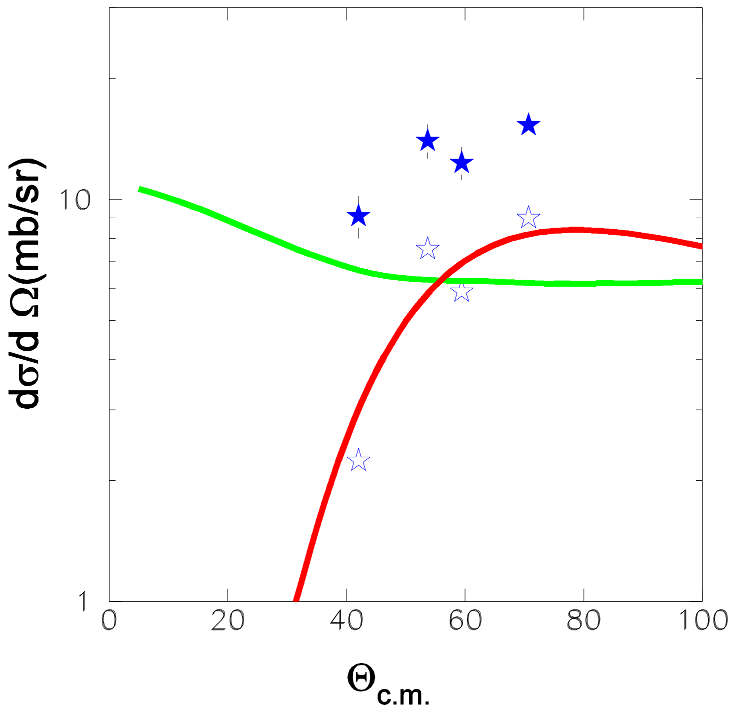
n-transfer versus compound

$^{6}Li + ^{28}Si \rightarrow ^{29}Si + \alpha + p$

13MeV



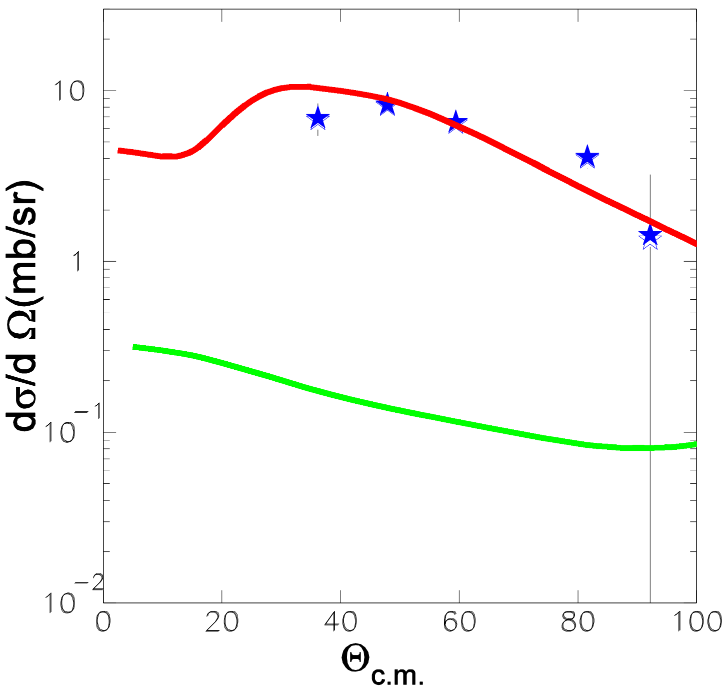
9MeV



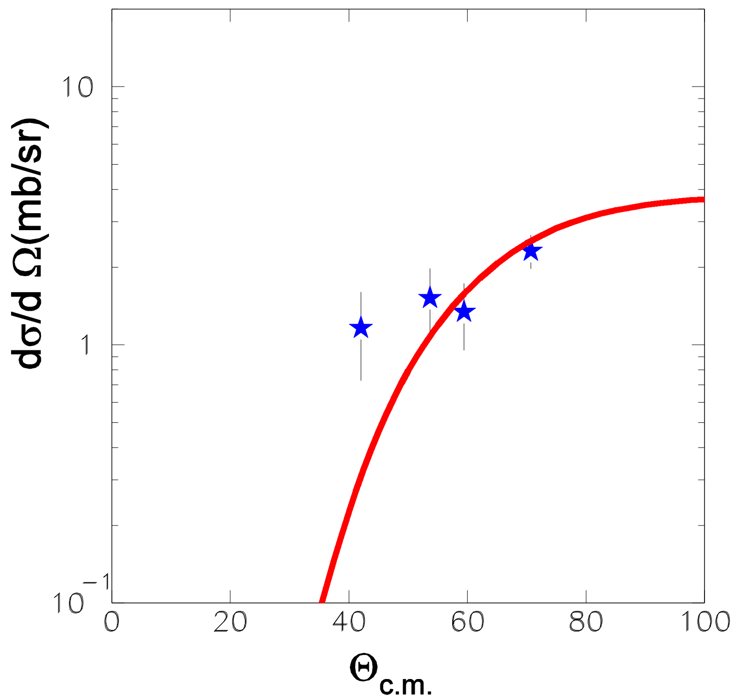
p-transfer versus compound

$^{6}Li + {}^{28}Si \rightarrow {}^{29}P + \alpha + n$

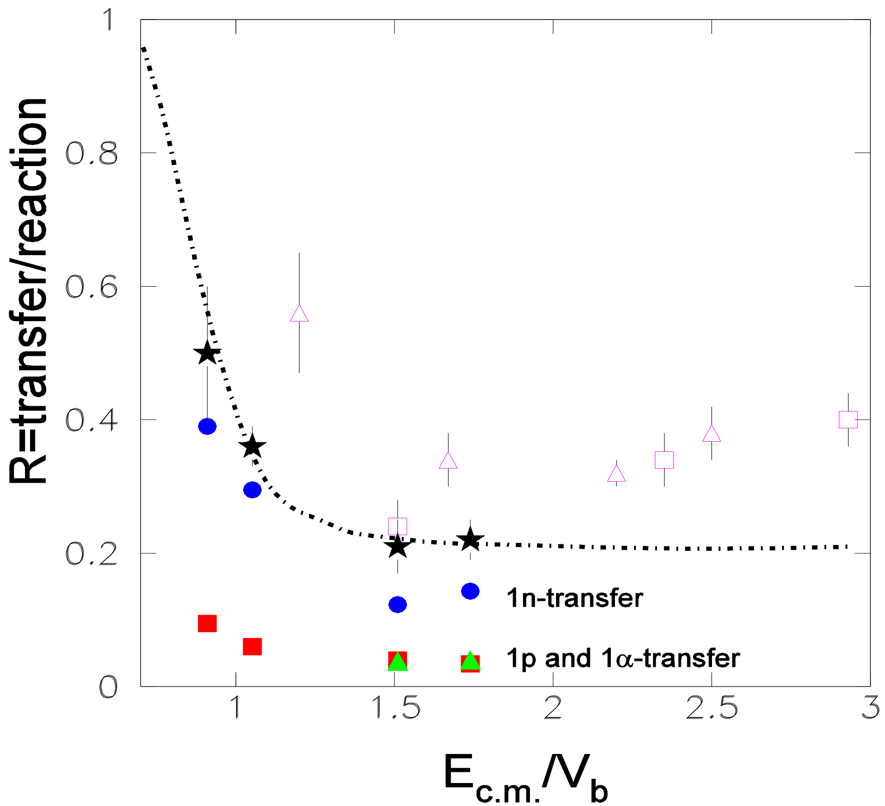
13MeV



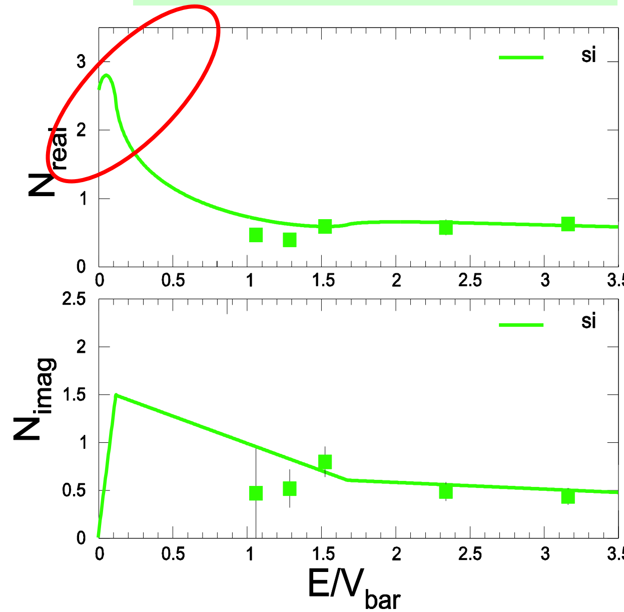
9MeV



Direct to total-$^{6}Li+^{28}Si$



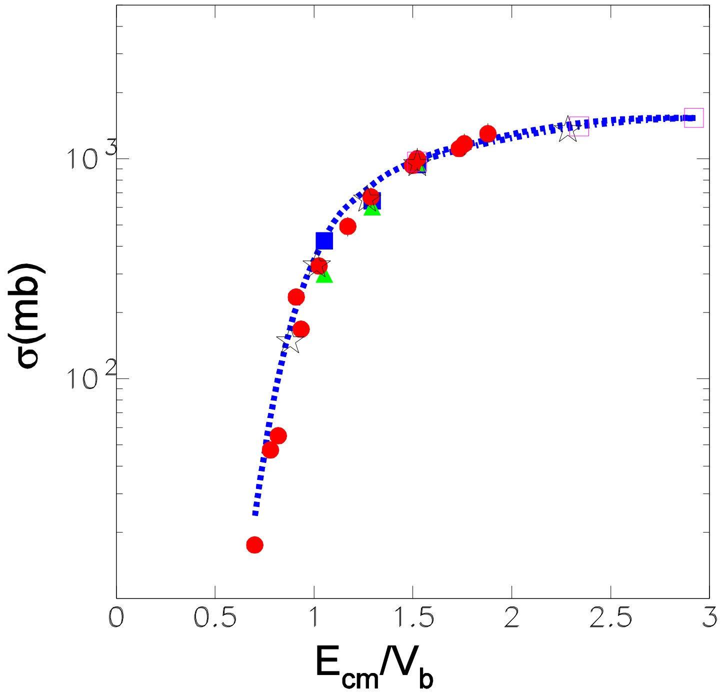
Optical potential



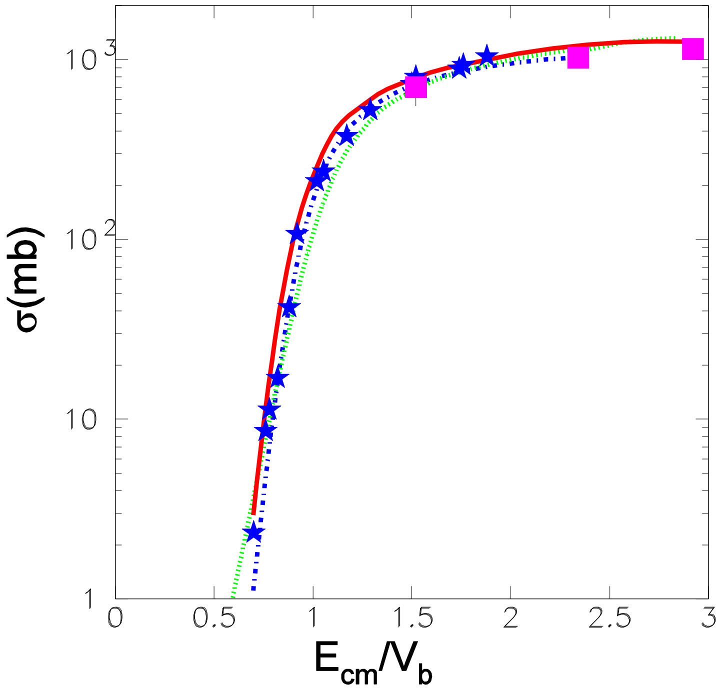
Need for data at deep sub-barrier energies

The $^{6}Li+^{28}Si$ reaction

Total reaction cross section

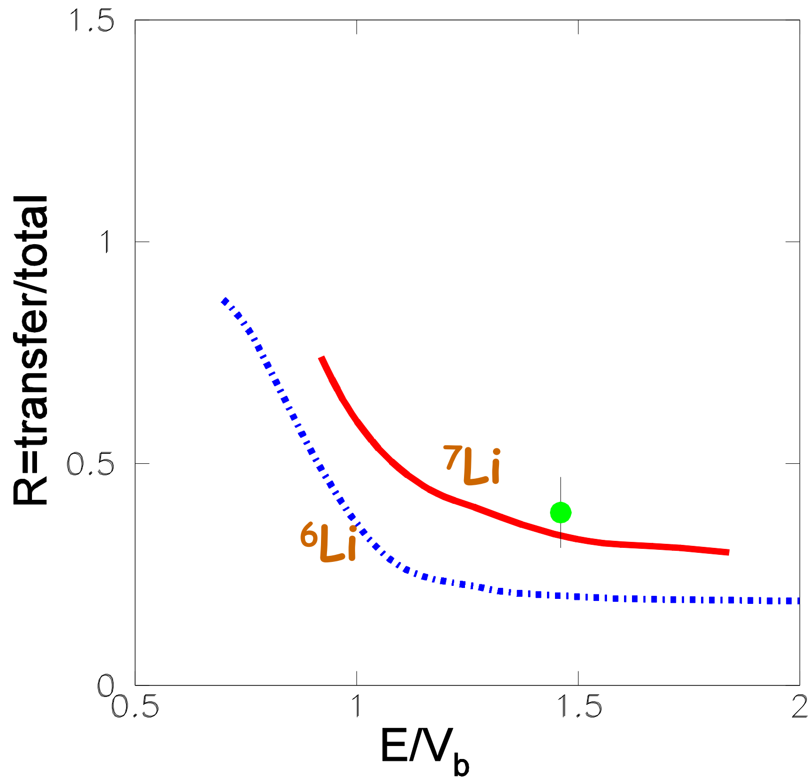


Fusion cross sections



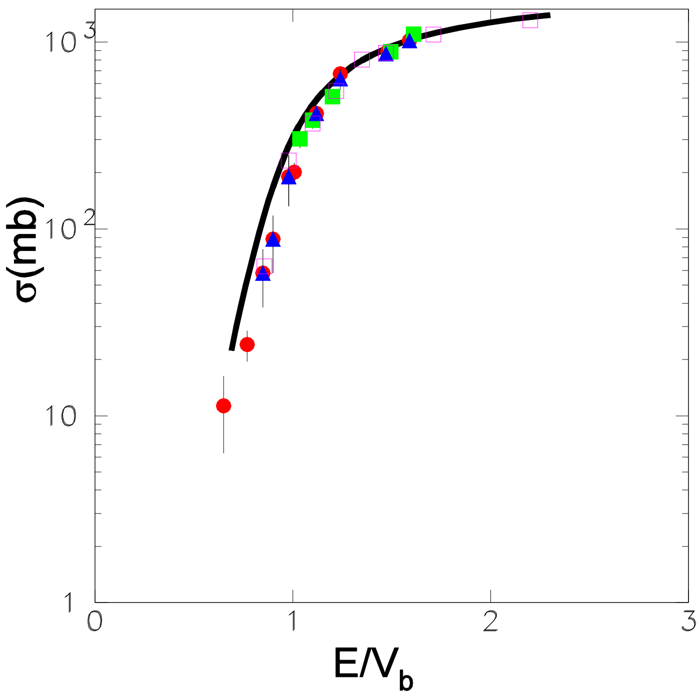
No big changes via breakup couplings

The $^7Li+^{28}Si$ reaction

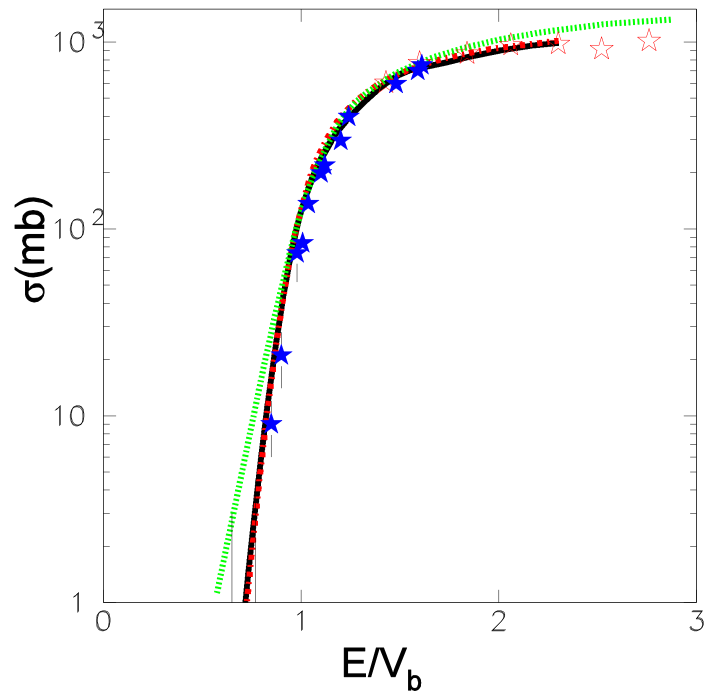


The $^{7}Li+^{28}Si$ reaction

Total reaction cross section



Fusion cross section



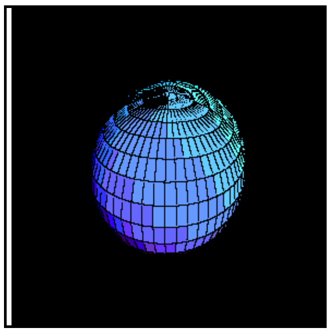
No big changes via breakup couplings

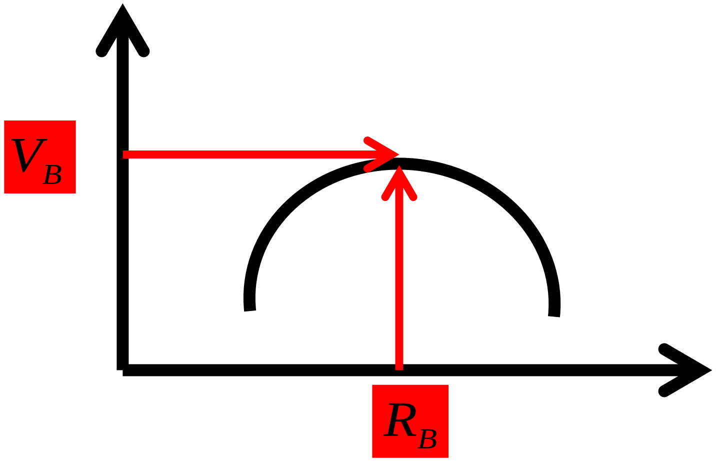
Second conclusion : Referring to almost spherical targets, and light projectiles

If we carefully disentangle the direct from compound contribution then fusion even for weakly bound nuclei can be described by a Wong one barrier penetration model prediction

The Wong formula

Well bound nuclei





PRL 31(1973)766

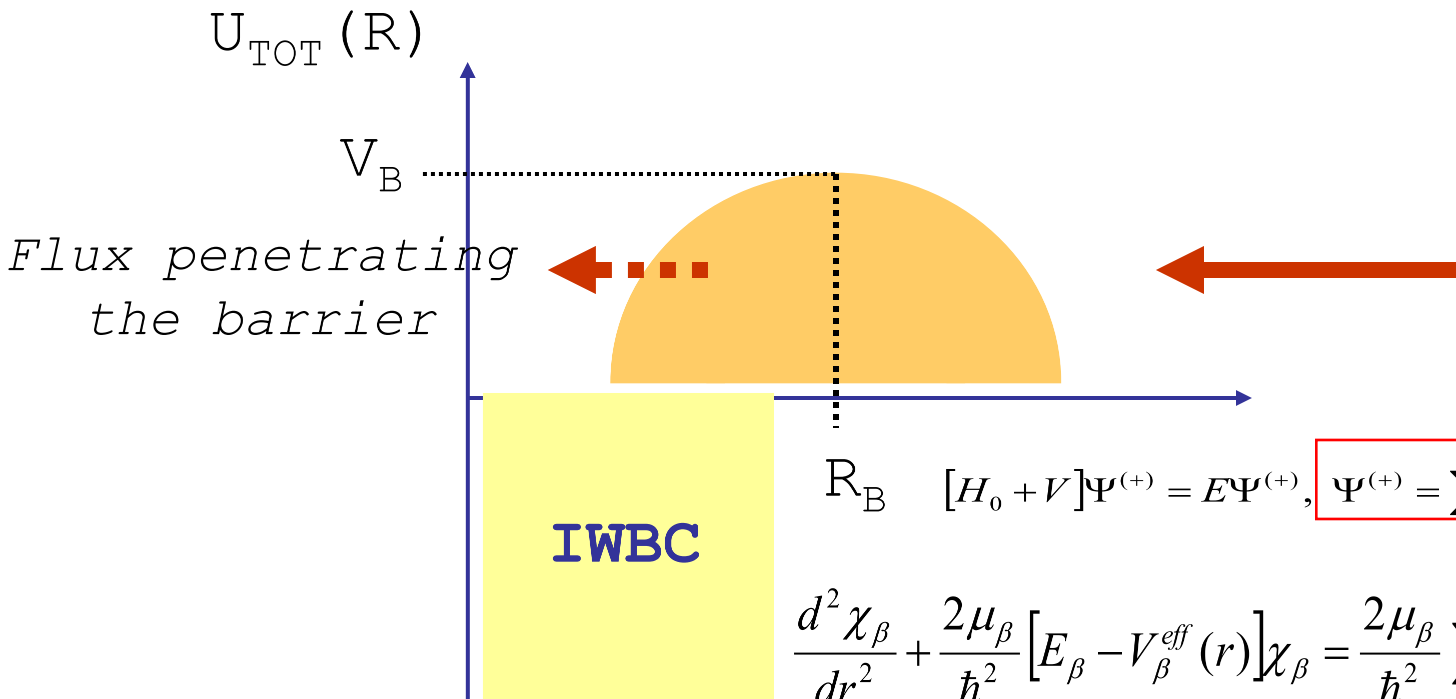
$$\sigma_f = \frac{\hbar\omega R_B^2}{2E}\left[1+\exp\left(\frac{2\pi}{\hbar\omega}(E-V_B)\right)\right]$$

Approximate the various barriers for different partial waves by inverted harmonic oscillator potentials of height E_l and frequency ω_l. Subsequently, assume that the barrier position and curvature are independent of l.

CC-model calculations

The sub-barrier fusion in the coupled channel approach

$$U_{TOT}(\vec{R}) = U_C(\vec{R}) + \iint \rho_A(\vec{r}_1)\rho_a(\vec{r}_2)u(\vec{r}_{12})d\vec{r}_1 d\vec{r}_2$$



$$[H_0 + V]\Psi^{(+)} = E\Psi^{(+)}, \quad \Psi^{(+)} = \sum_{\beta} \frac{\chi_\beta(r)}{r}\varphi_\beta$$

$$\frac{d^2\chi_\beta}{dr^2} + \frac{2\mu_\beta}{\hbar^2}\left[E_\beta - V_\beta^{eff}(r)\right]\chi_\beta = \frac{2\mu_\beta}{\hbar^2}\sum_{\alpha\neq\beta} V_{\beta\alpha}^{cpl}(r)\chi_\alpha$$

C. H Dasso, S. Landowne,A. Winther, Nucl. Phys. A405(1983)381;
D. Castro-Rizzo and N.Alamanos, Nucl. Phys. A443 (1985) 525.

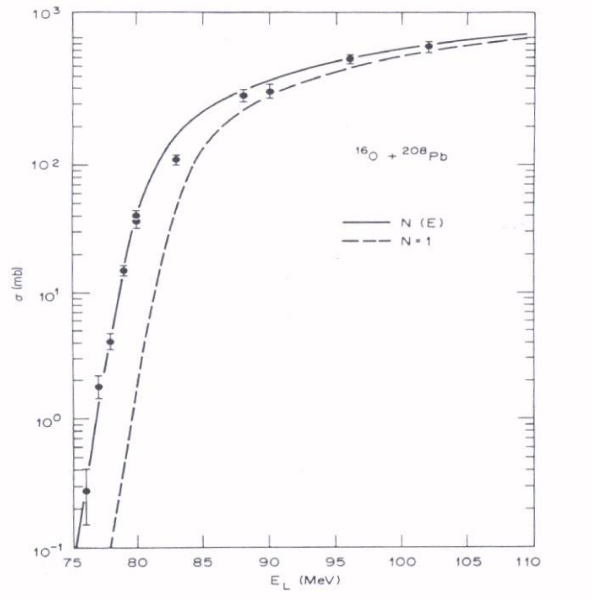
The fusion anomaly can be regarded as another aspect of the optical potential anomaly

It can be treated either via

Coupled-channel calculations OR

an energy dependent optical potential

Satchler, Phys. Rep. 199(1991)147



Fusion cross sections for 8B+28Si at near barrier energies

HINP GROUP

- Athena Pakou - UOI
- Stathis Stiliaris - UOA
- Dina Zerva - UOI
- Akis Sgouros - UOI
- Vassilis Soukeras - UOI

EXOTIC GROUP

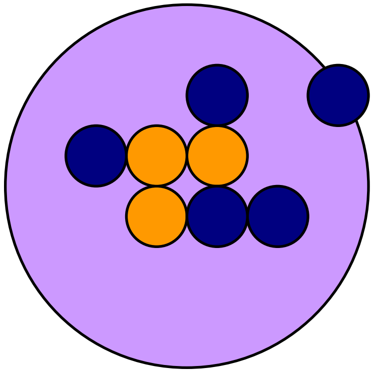
- Dimitra Pierroutsakou- Napoli Italy
- Marco Mazzocco - Padova Italy
- Cosimo Signorini- Padova Italy
- Emanuele Strano- Padova Italy
- A. Boiano- Napoli Italy
- C. Boiano- Milano Italy
- T. Parascandolo- Napoli Italy

Theoretical support

- Nicola Alamanos- Saclay France
- Krzystzof Rusek Warsaw Poland
- Nick Keeley Warsaw Poland
- Andrea Vitturi –Padova Italy

It is time the above ideas to be confronted by our group using

Weakly bound but radioactive nuclei



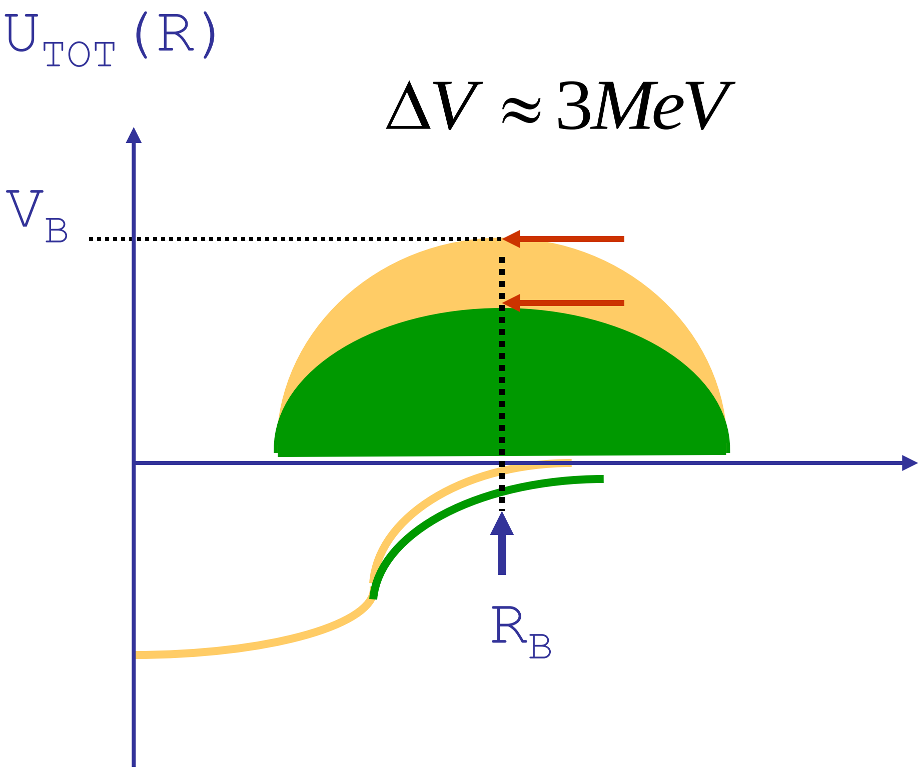
^{8}B

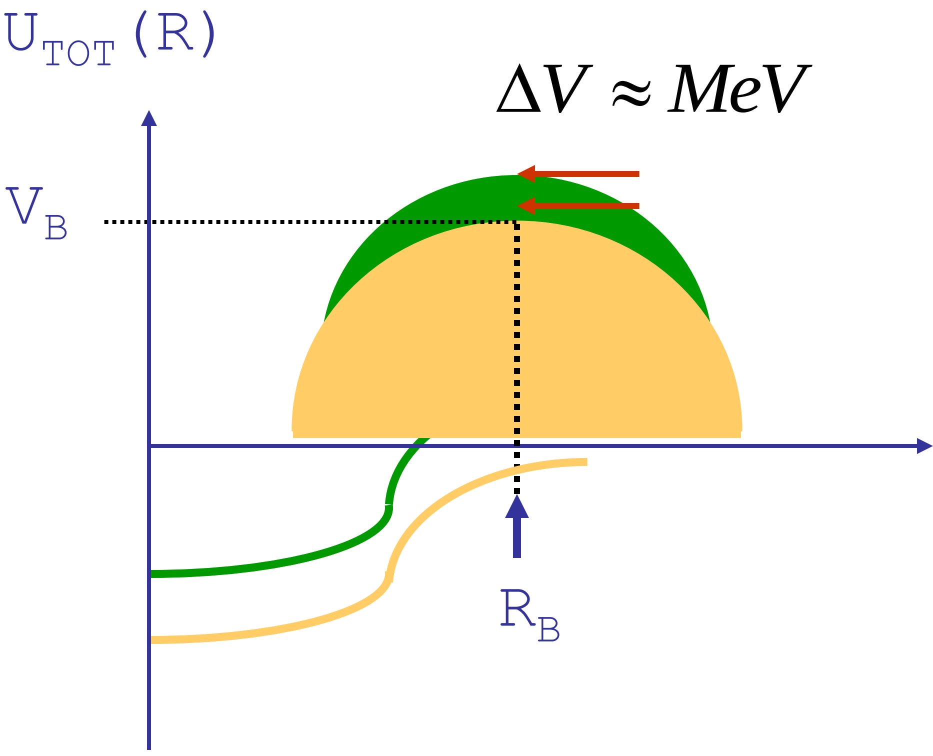
Very promising exotic nucleus but difficult beam

New measurement : $^{8}B+^{28}Si$ fusion at near barrier energies

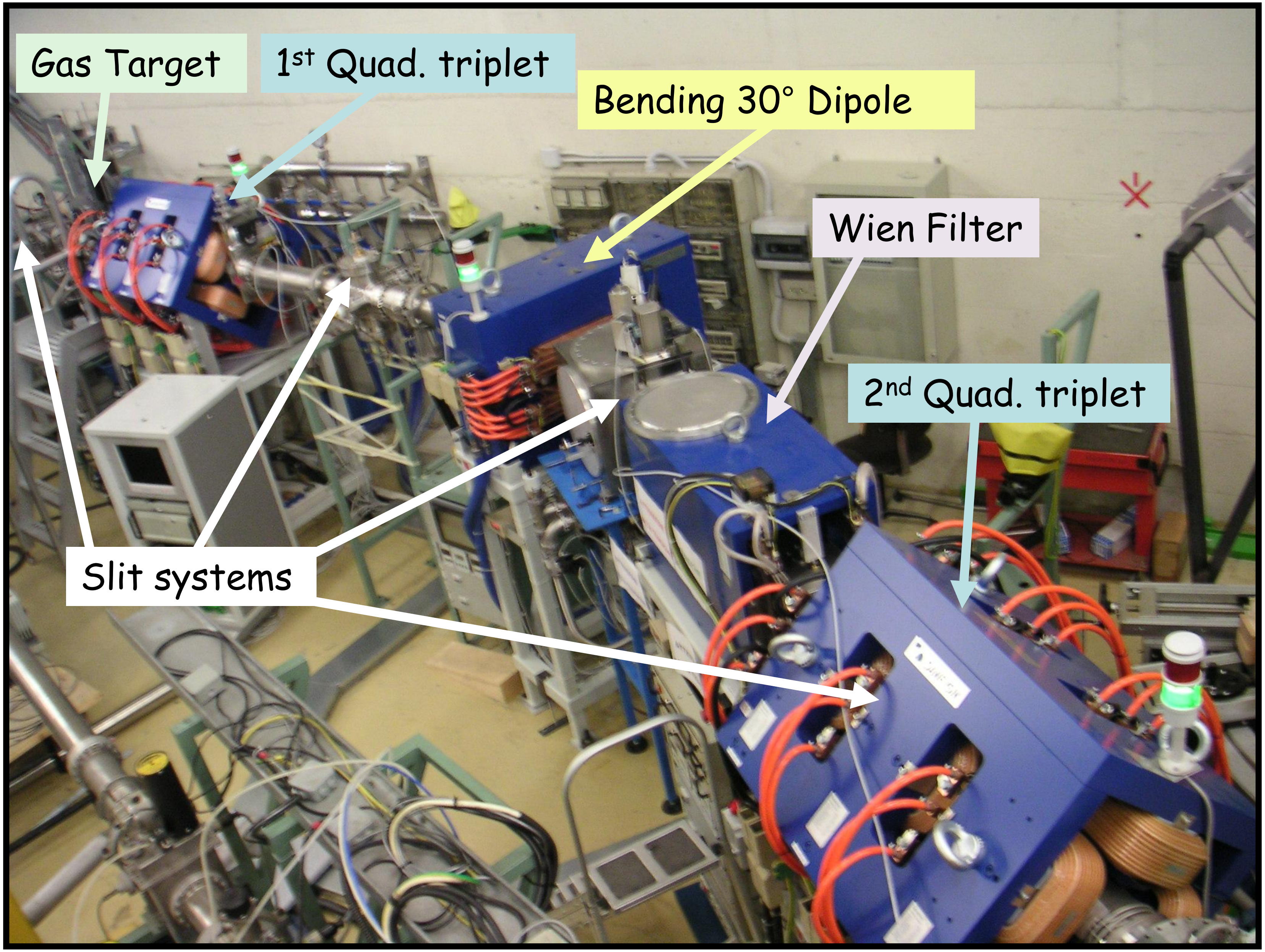
The halo effect

The dynamic polarization potential effect

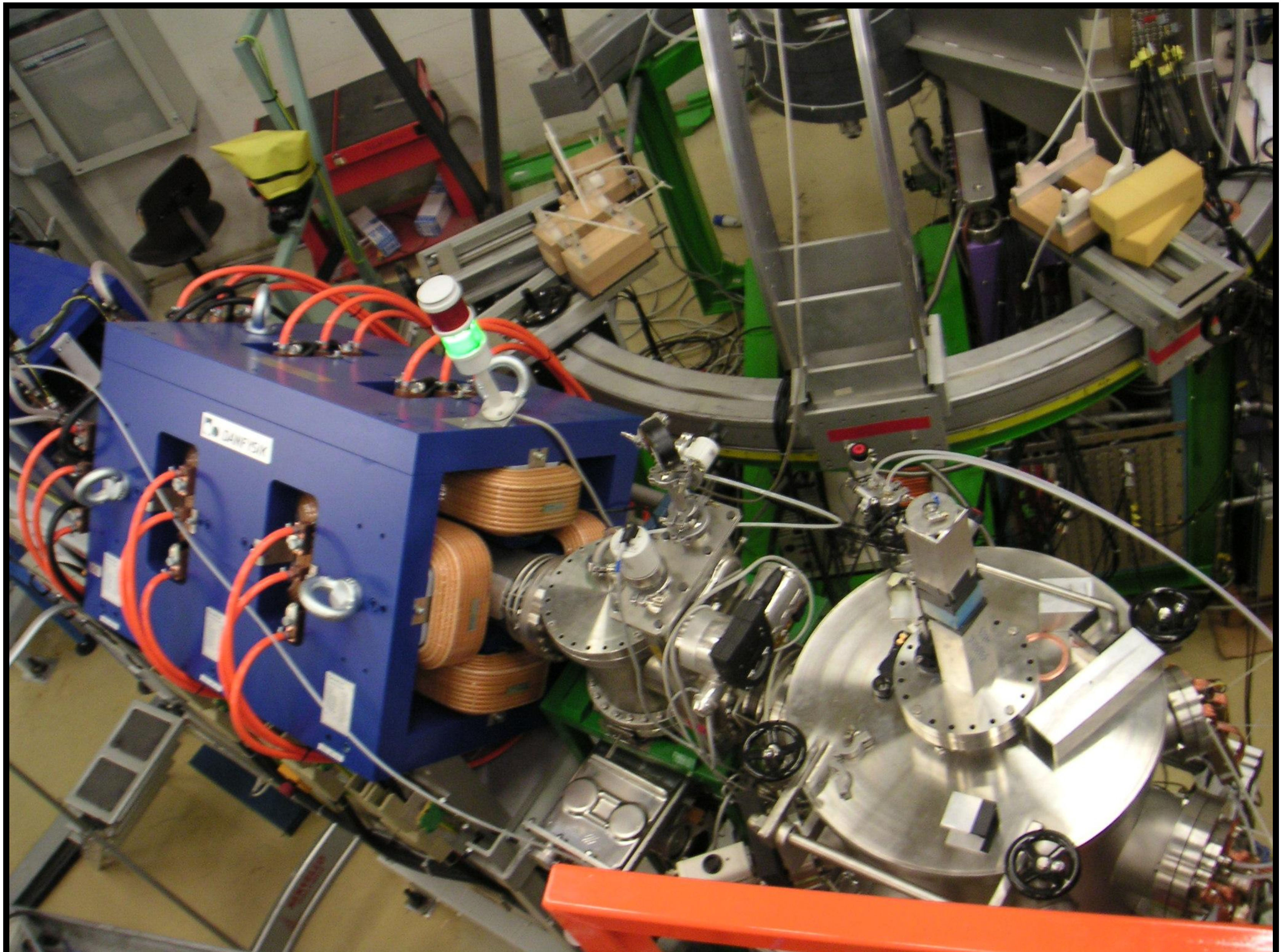




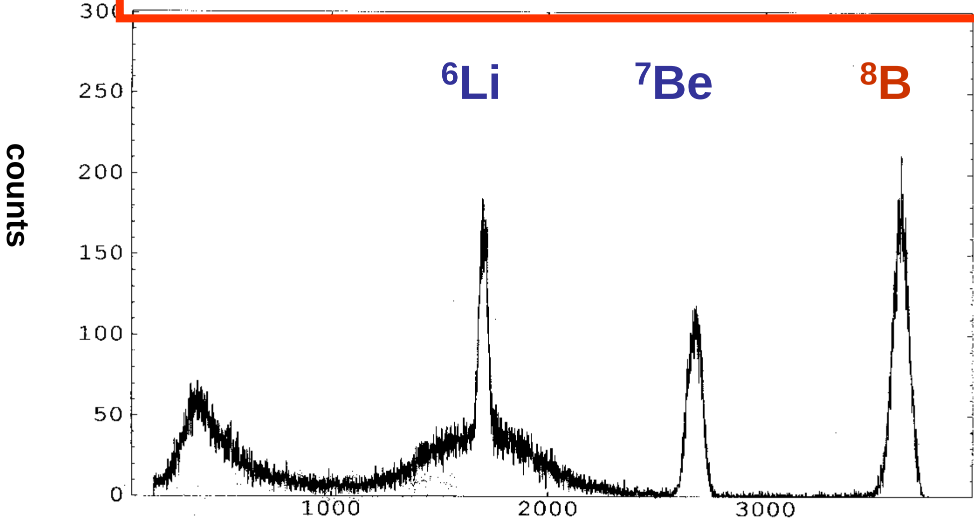
EXOTIC beam line-LNL ITALY

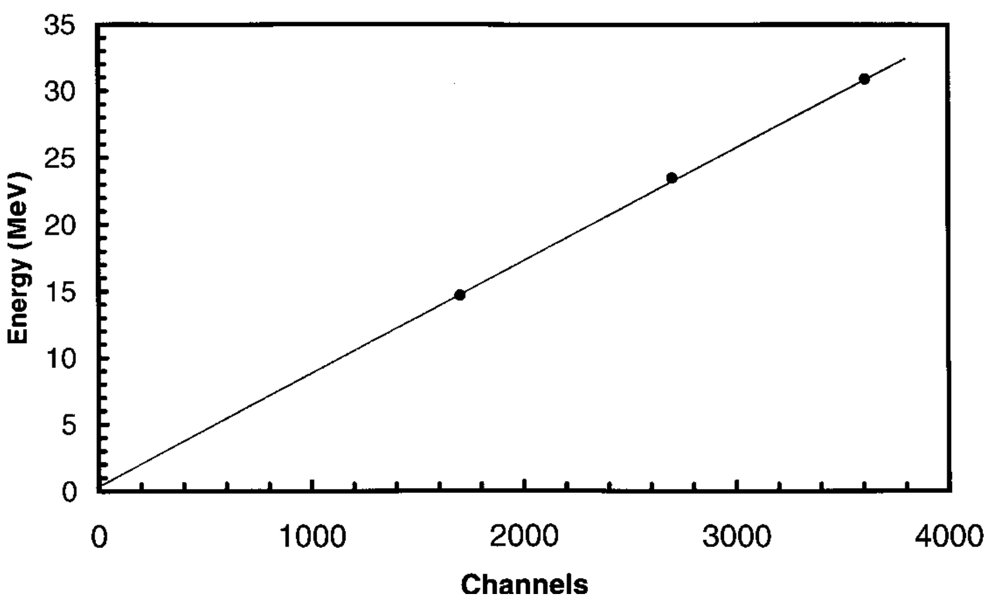


2nd 4-pole triplet and final measuring point



EXOTIC beam line: production of a ^{8}B beam





Primary beam:

^{6}Li @ 41 MeV   I = 3 nA

Gas Target: ^{3}He; P=800 mbar;

T= 300K

Dipole magnetic field B = 0.863 T

$B\rho$ = 0.471 Tm

Wien Filter 30%

Secondary beams:

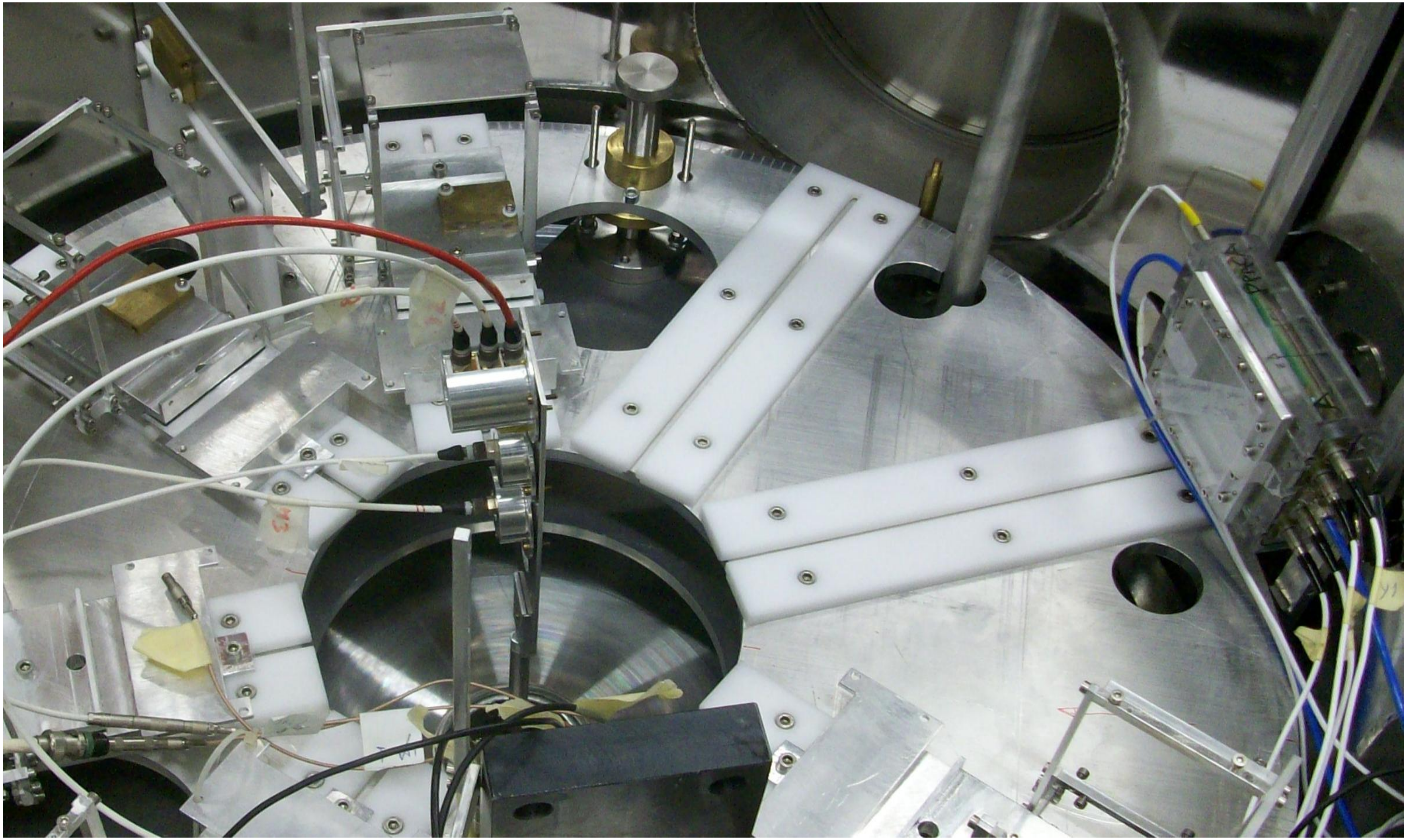
^{8}B E_{res} = 30.9 MeV; E = 33.3MeV

^{7}Be E_{res} = 23.4 MeV; E = 24.4 MeV

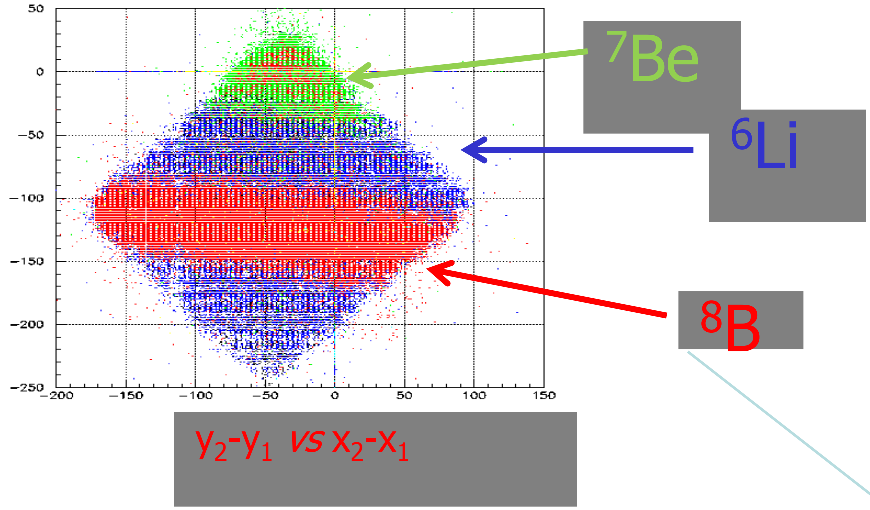
Residual primary beam:

^{6}Li E_{res} = 14.7 MeV; E = 16 MeV

$^{8}B+^{28}Si$: set up



$^{8}B+^{28}Si$

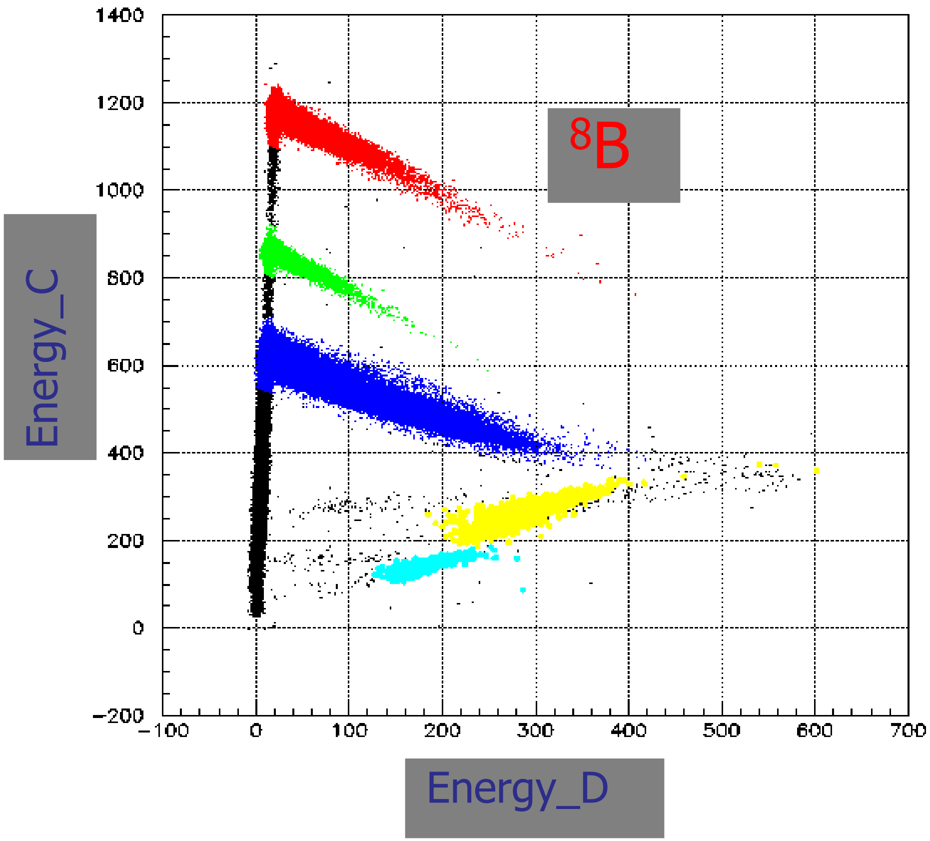


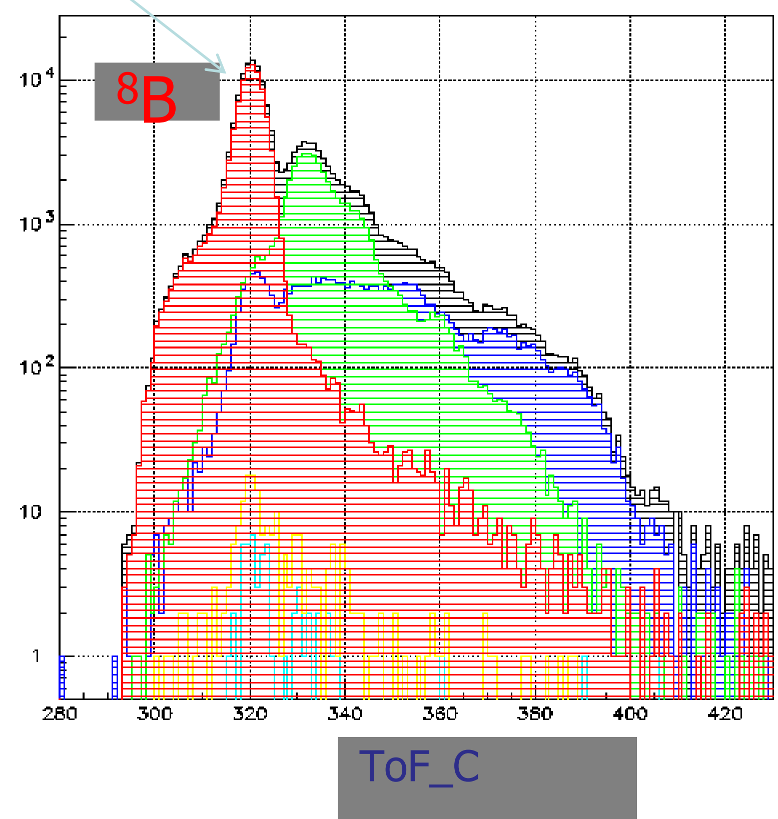
Target stack

C: 45 μm

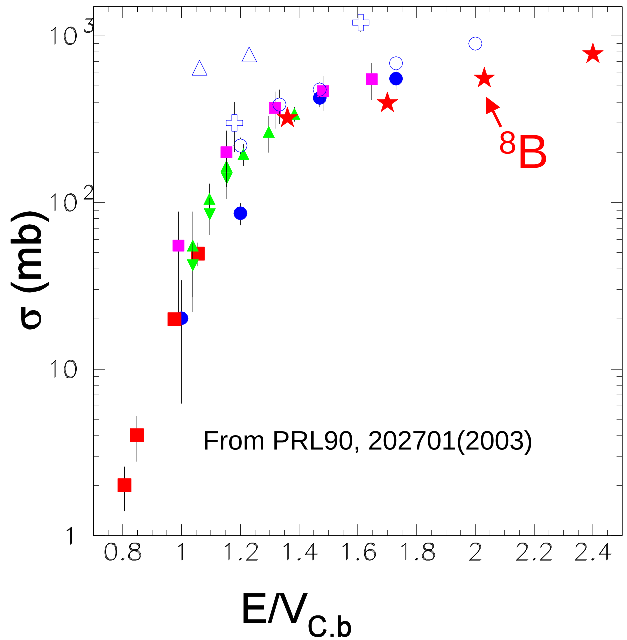
D: 45 μm

E: 2000 μm

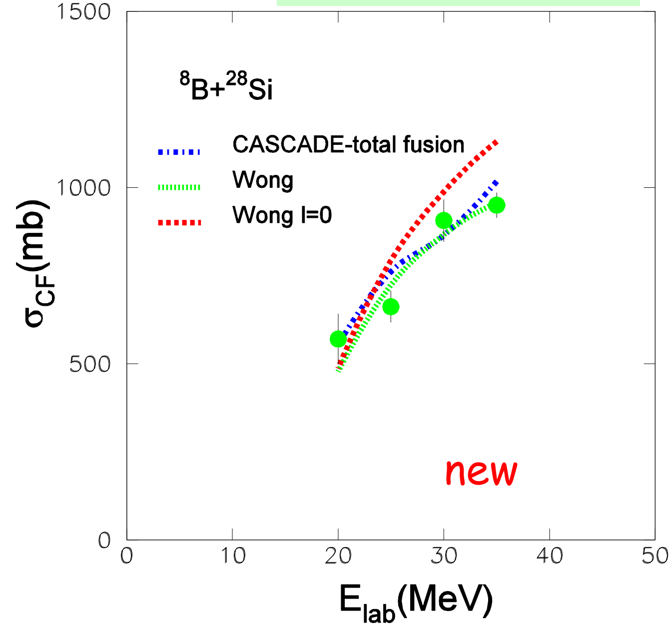




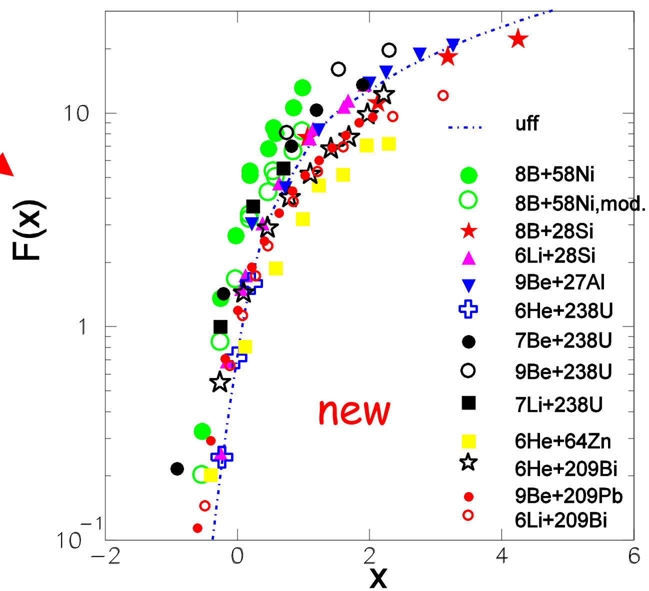
α-production



8B+28Si fusion



Fusion functions for various weakly bound stable and exotic projectiles on various targets



$$F(x)=\sigma*2*E_{c.m.}/R^2*\hbar\omega$$

$$x=E_{cm}-V_b/\hbar\omega$$

Conclusion:

8B although a very special proton rich nucleus fuses with silicon in the same way as other weakly bound but stable light nuclei

Future perspectives and the life tree

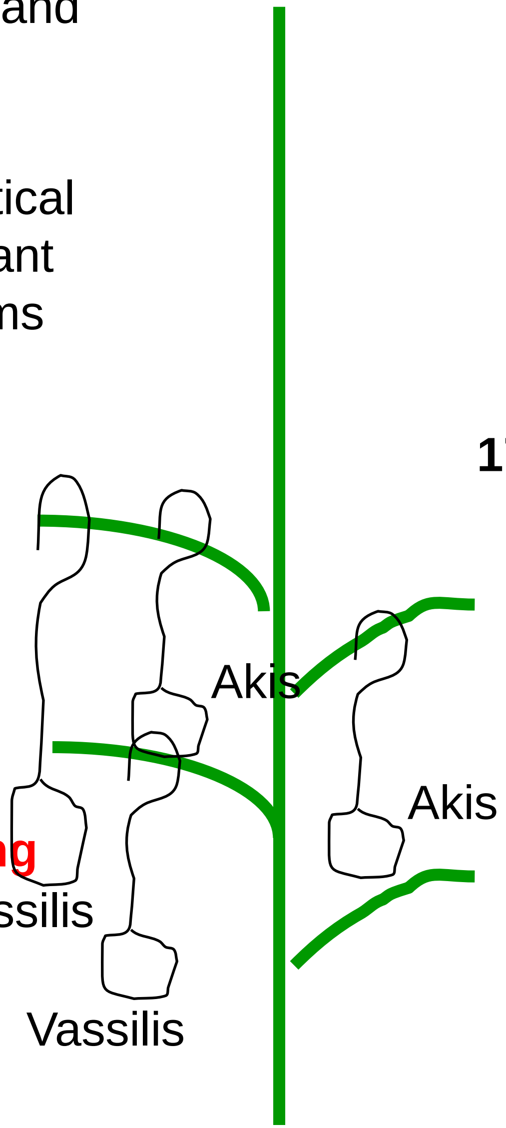
Nucleus-Nucleus optical potential, and relevant reaction mechanisms

6,7Li+28Si

^{8}B, ^{7}Be, ^{6}He +^{28}Si

^{20}Ne+^{28}Si-

inverse kinematics probing clustering effects



Proton-Nucleus optical potential

17F+p off resonances

6Li+p inclusion of compound couplings

18Ne+p inclusion of clustering effects