Everything is coupled: reactions with weakly bound projectiles

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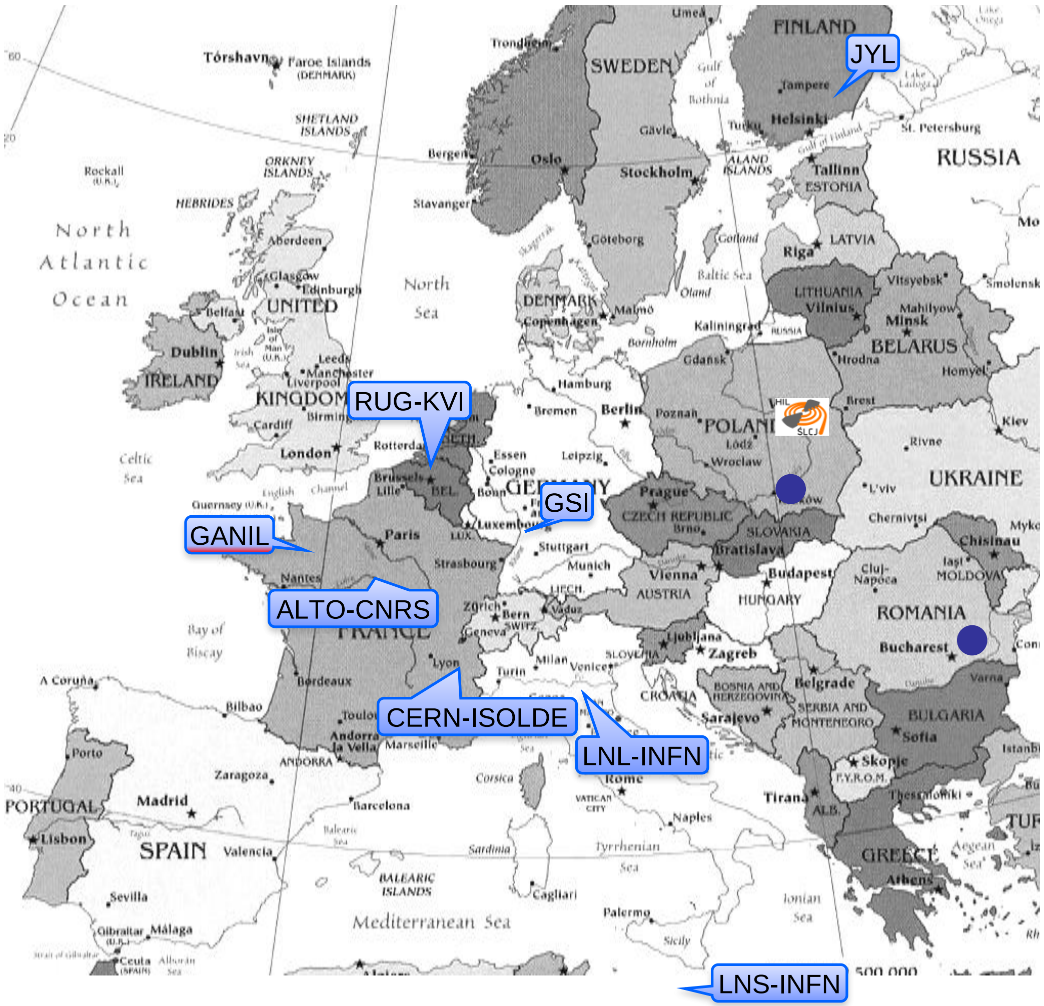
HIL ŚLCJ

Heavy Ion Laboratory, University of Warsaw :

- National nuclear physics laboratory open for external users
- Involved in teaching
- developing medical applications

European Nuclear Science and Applications Research 2 (ENSAR2)



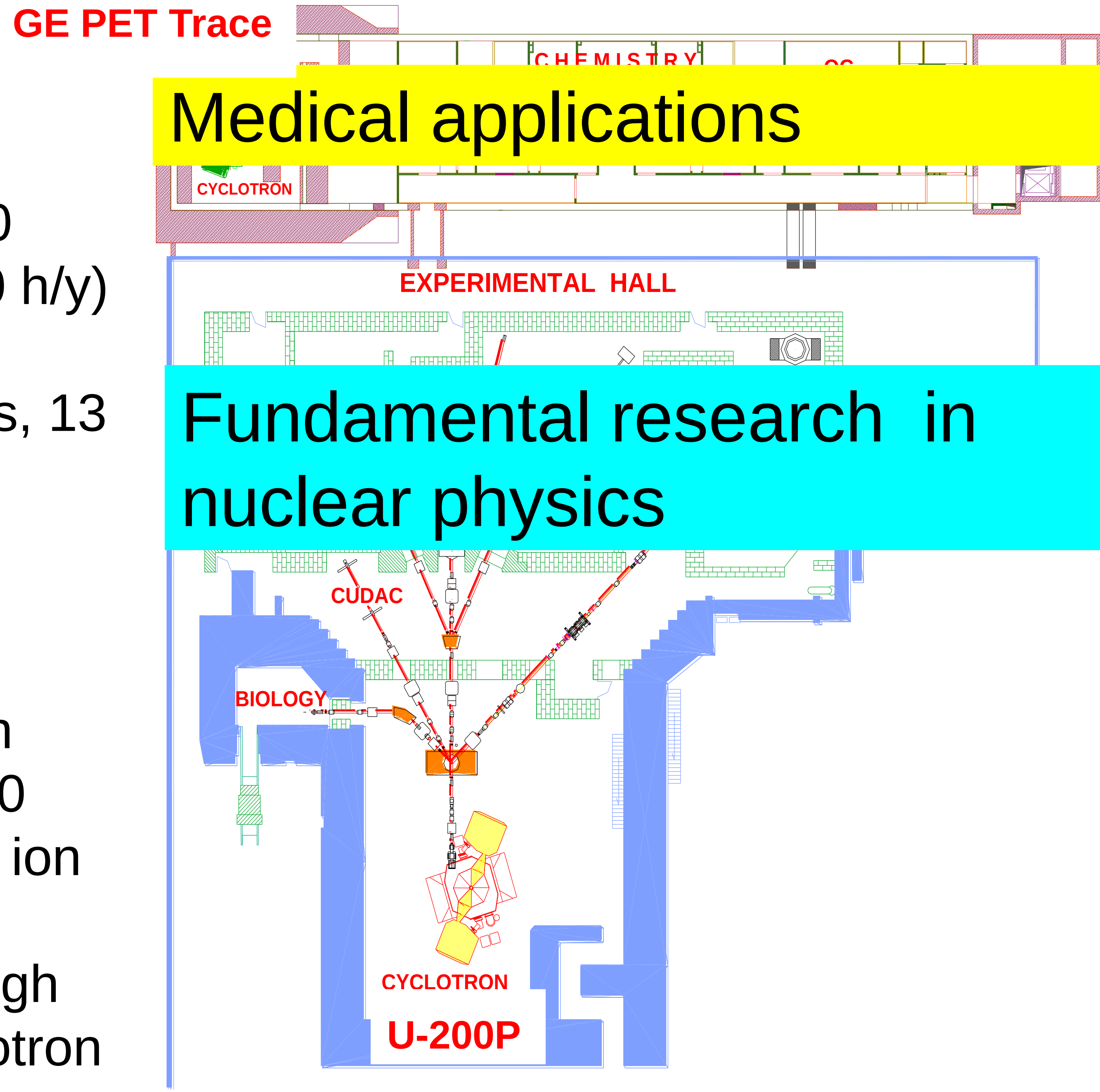
HIL UW duty: 1000 hours of beam, 10 projects (lasting ~one week each), about 50 users eligible for reimbursement

User Facility: ~ 100 users/year (3300 h/y)

Staff: 35 technicians, 13 scientists

Two cyclotrons:

- U-200P heavy-ion cyclotron, up to 10 MeV*A, two ECR ion sources
- GE PET Trace, high intensity p/d cyclotron (16/8 MeV)



Medical applications

Fundamental research in nuclear physics

Overview

Investigation of coupling effects has a long history, as long as nuclear physics, beginning with deuteron induced reactions. This contribution is not meant as a review but rather as a presentation of a few examples where the couplings play an important role.

- Elastic scattering and coupling with the continuum (effect of breakup)

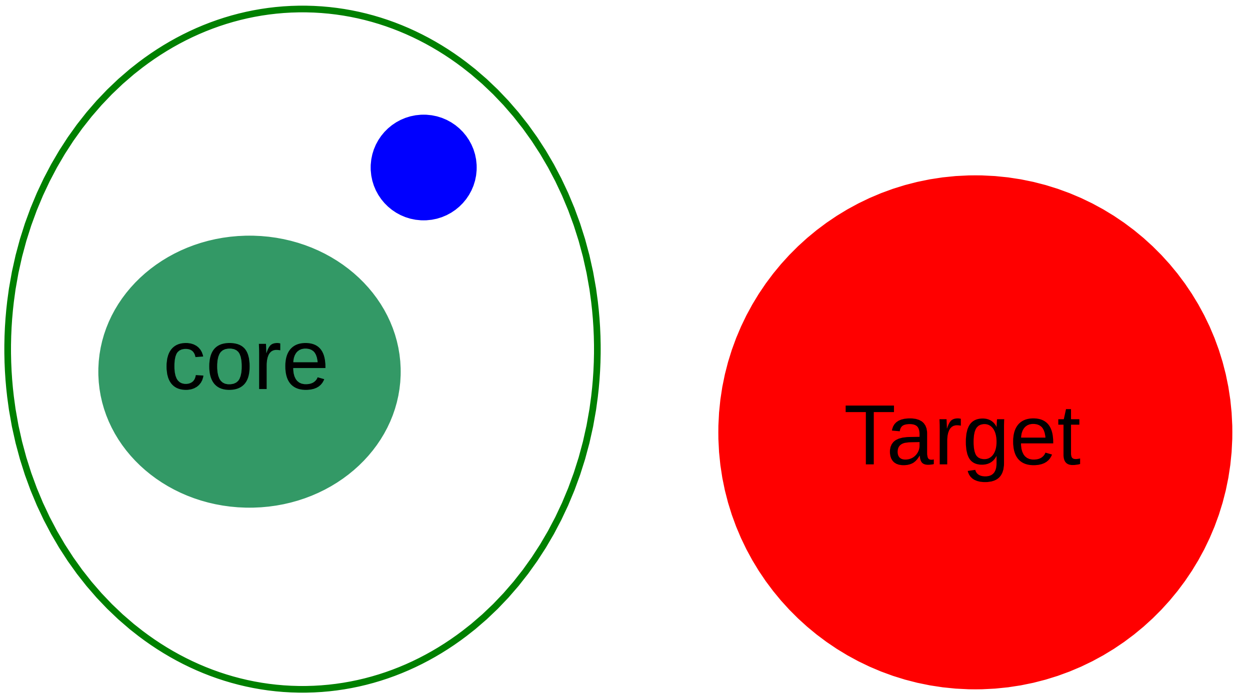
- Elastic scattering and transfer reactions

- Fusion and direct reactions

- Effect on the Coulomb barrier distribution

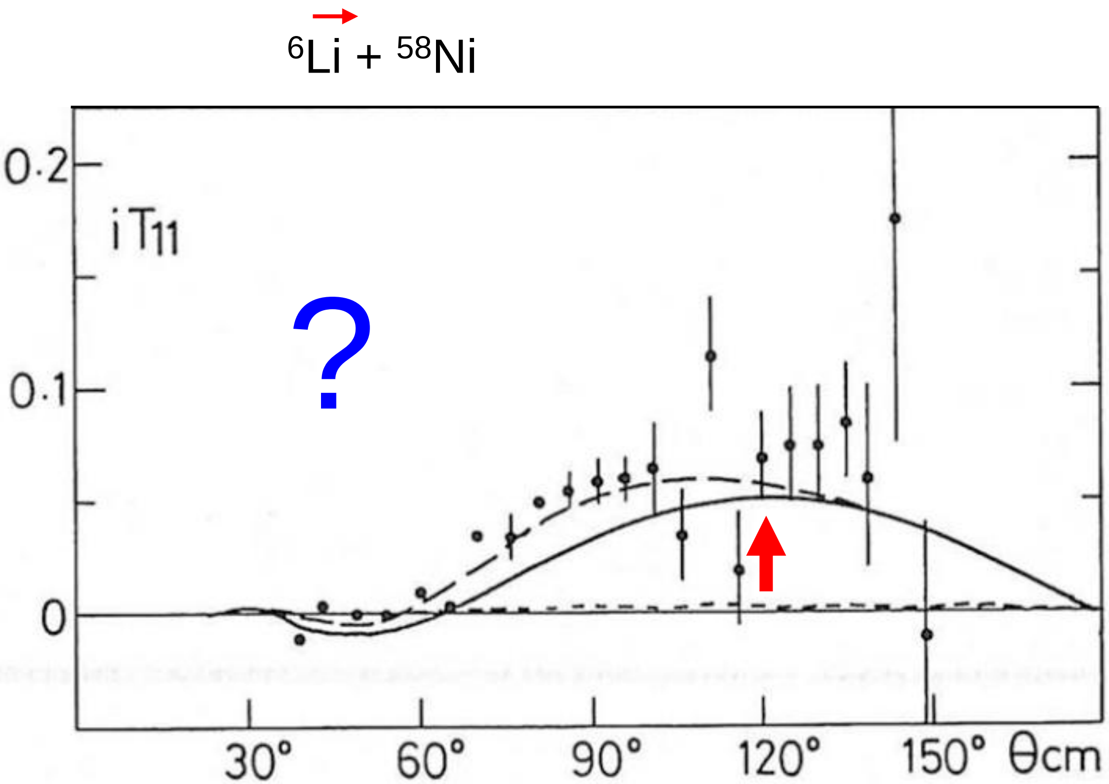
Real and virtual processes

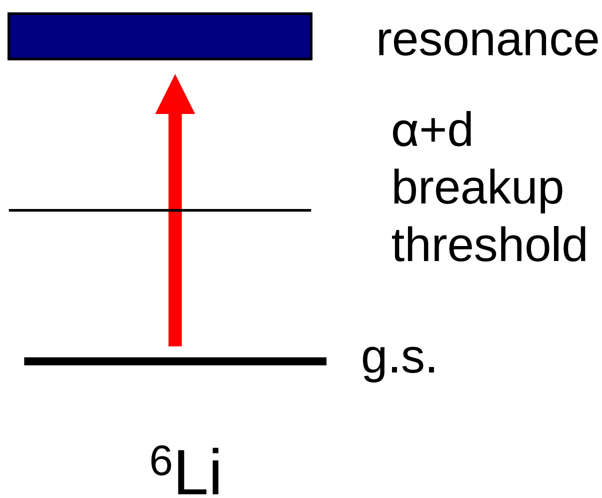
Virtual couplings (polarizability) – processes whereby, for example, the projectile nucleus is raised to an excited state which then decays back to the ground state before the projectile has traversed the field of the target nucleus.



N.Keeley et al. Progress in Particle and Nuclear Physics 63,396 (2009)

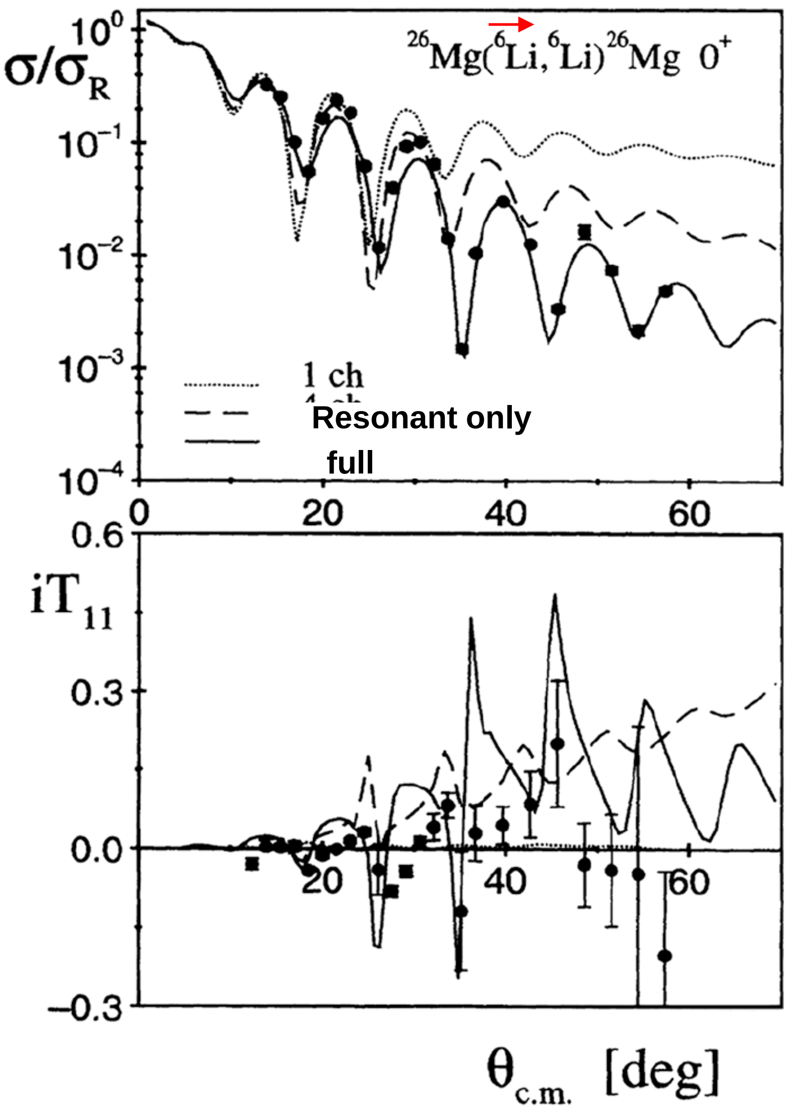
El. scatt. and effect of breakup

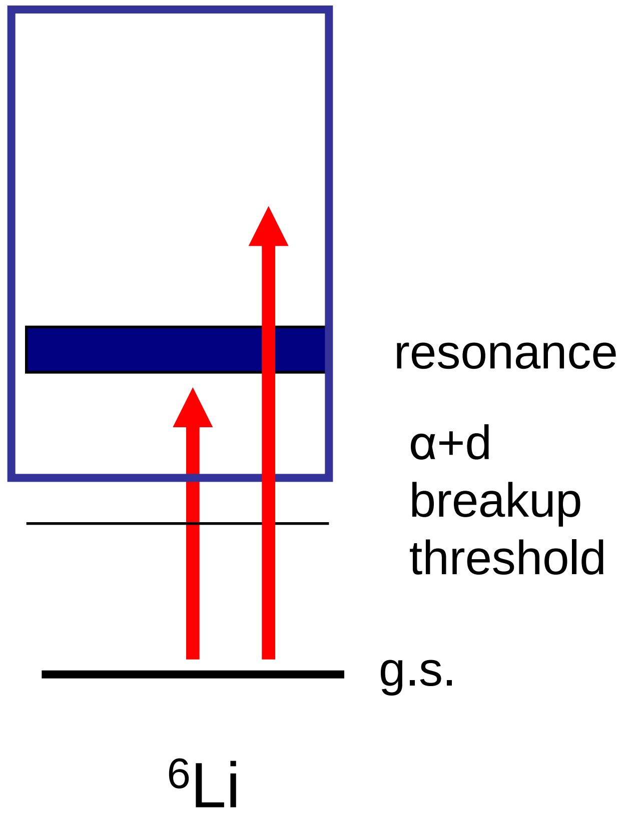




H. Nishioka et al., NPA 415, 230 (1984)

Couplings with resonant and non-resonant states





K.R. et al. PRC 50, 2010 (1994)

^{6}Li - no E1

Electric dipole transition:

$$B(\mathrm{E1};\, j_i \rightarrow j_f) = \frac{3}{4\pi} |\langle j_i - \tfrac{1}{2} 10 | j_f - \tfrac{1}{2} \rangle|^2 \beta_1^2 \langle r \rangle^2$$

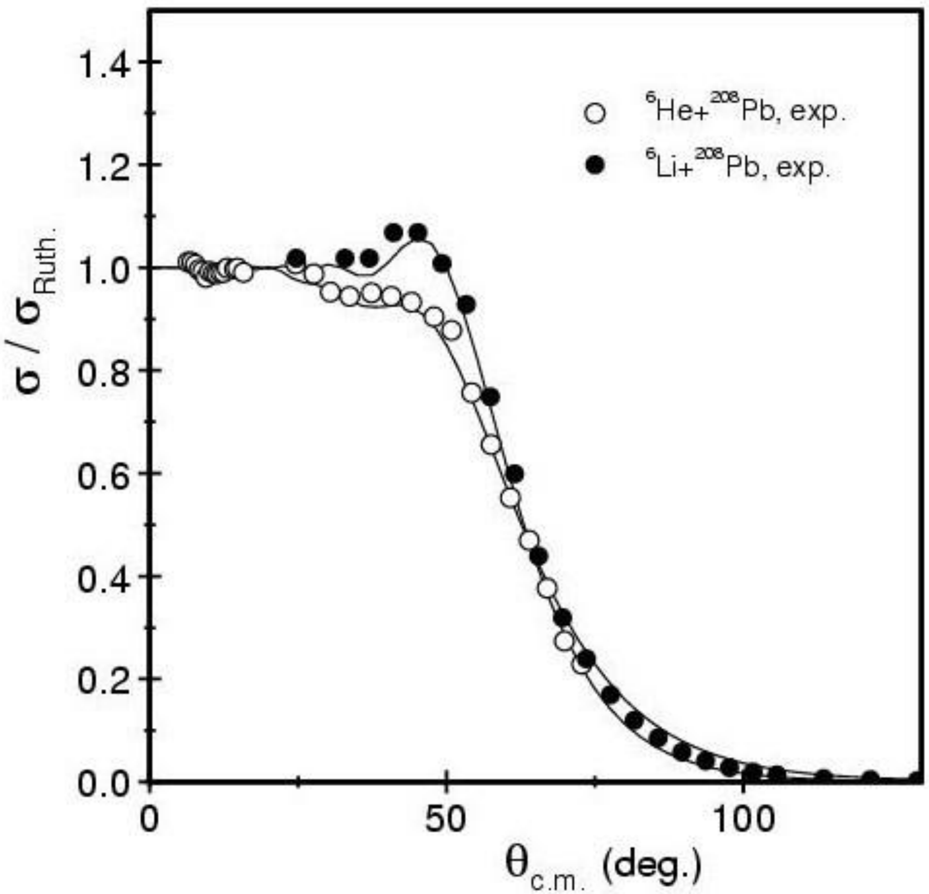
Where „effective charge” is:

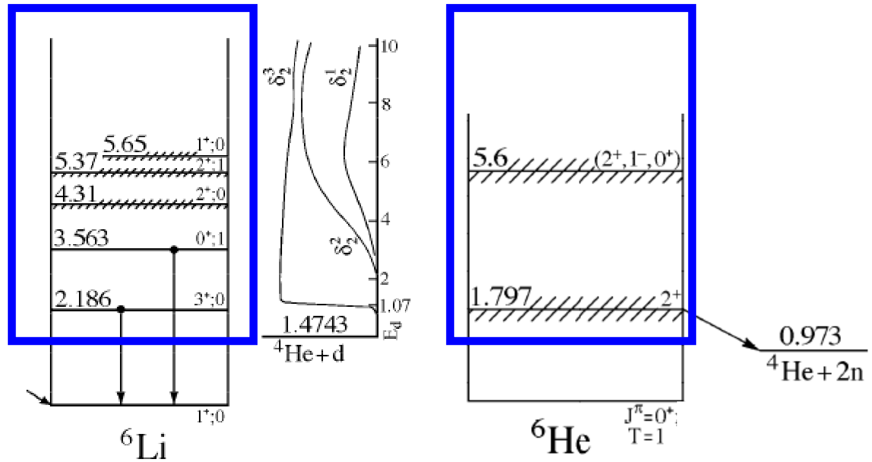
$$\beta_\lambda = \frac{A_1^\lambda Z_2 + (-)^\lambda A_2^\lambda Z_1}{(A_1 + A_2)^\lambda}$$

$= 0$ for $\lambda = 1$

B. Buck, A.A. Pilt, NPA280, 133 (1977)

Comparison of ^{6}Li-^{6}He





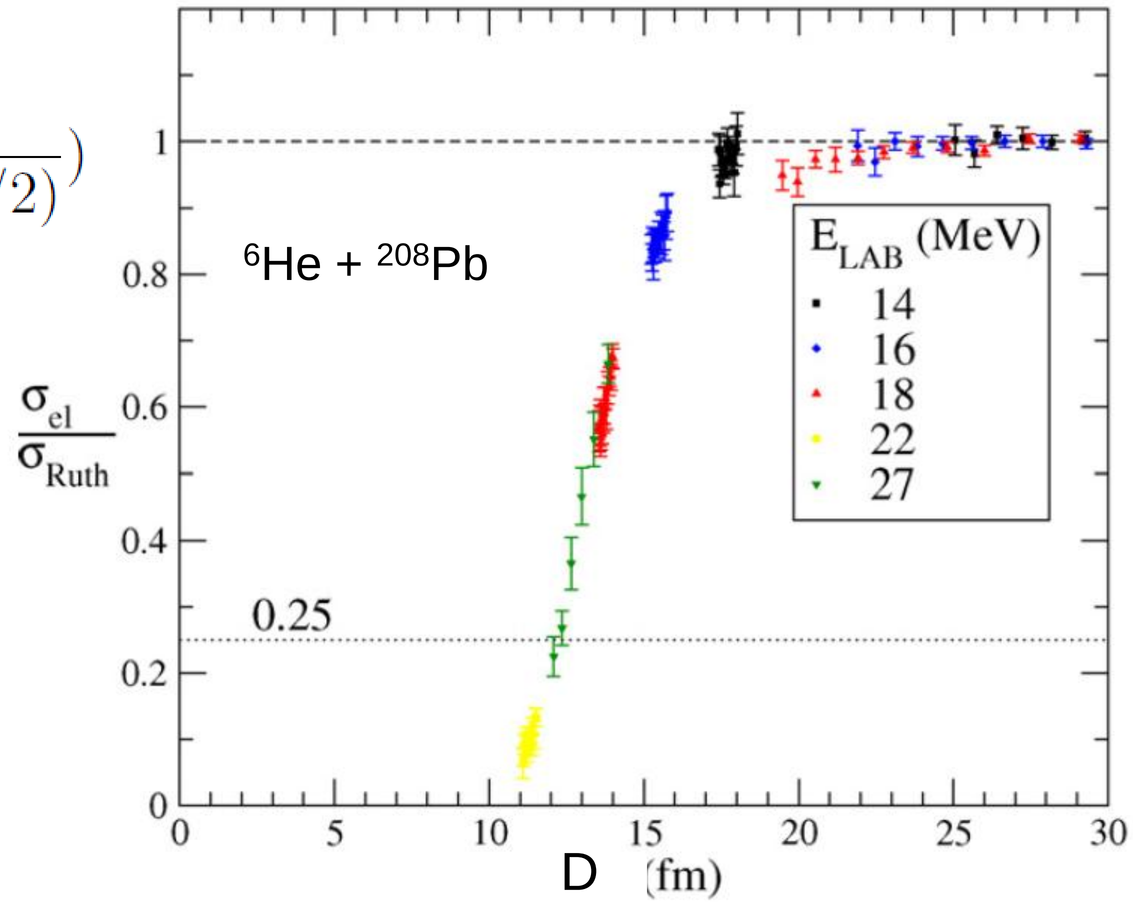
No E1

Reduced Coulomb-nuclear interference peak for ^{6}He, caused by Coulomb dipole couplings to the continuum

Interaction distance from el. scattering

$$D = \frac{Z_a Z_A e^2}{2E_{cm}}\left(1 + \frac{1}{sin(\theta_{cm}/2)}\right)$$

A.M. Sánchez-Benítez et al. / Nuclear Physics A 803 (2008) 30–45



Comparison for various projectiles

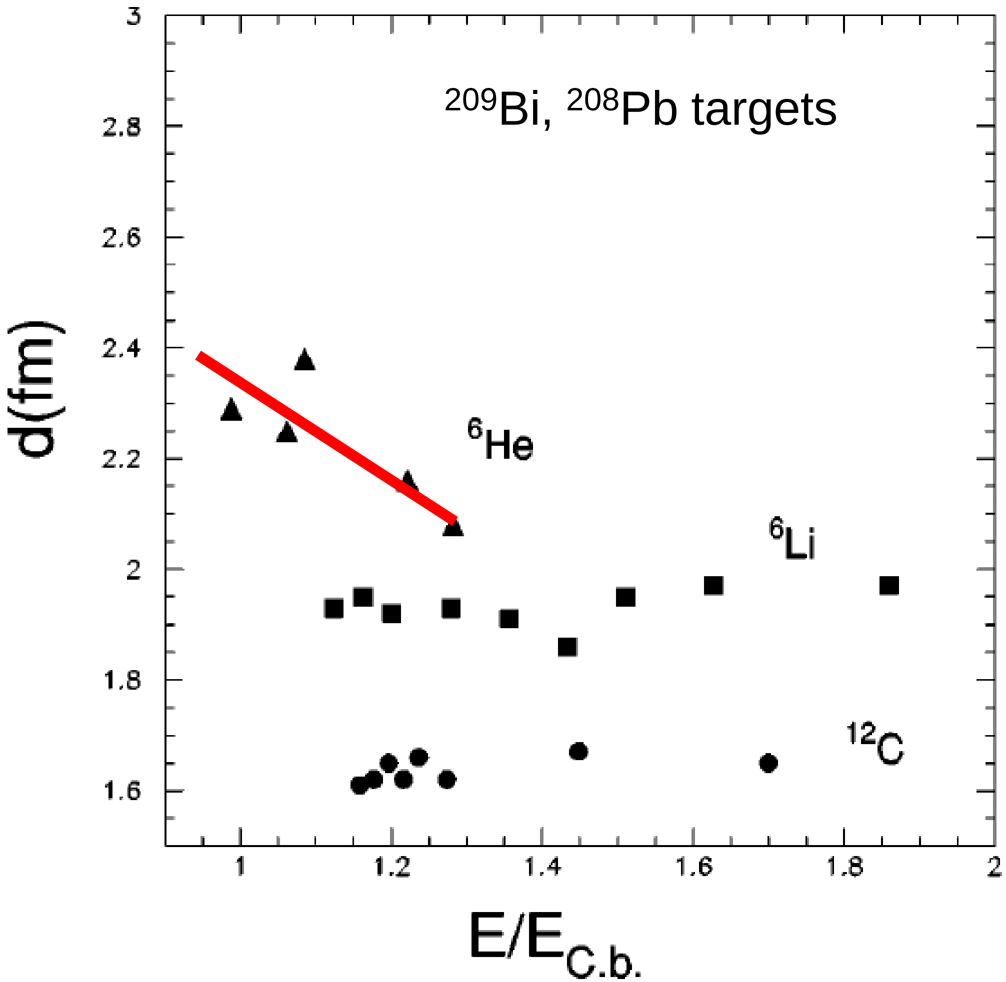
A. Pakou, K.R. PHYSICAL REVIEW C **69**, 057602 (2004)

Reduced int. distance

$d = D / (Ap^{1/3}+At^{1/3})$

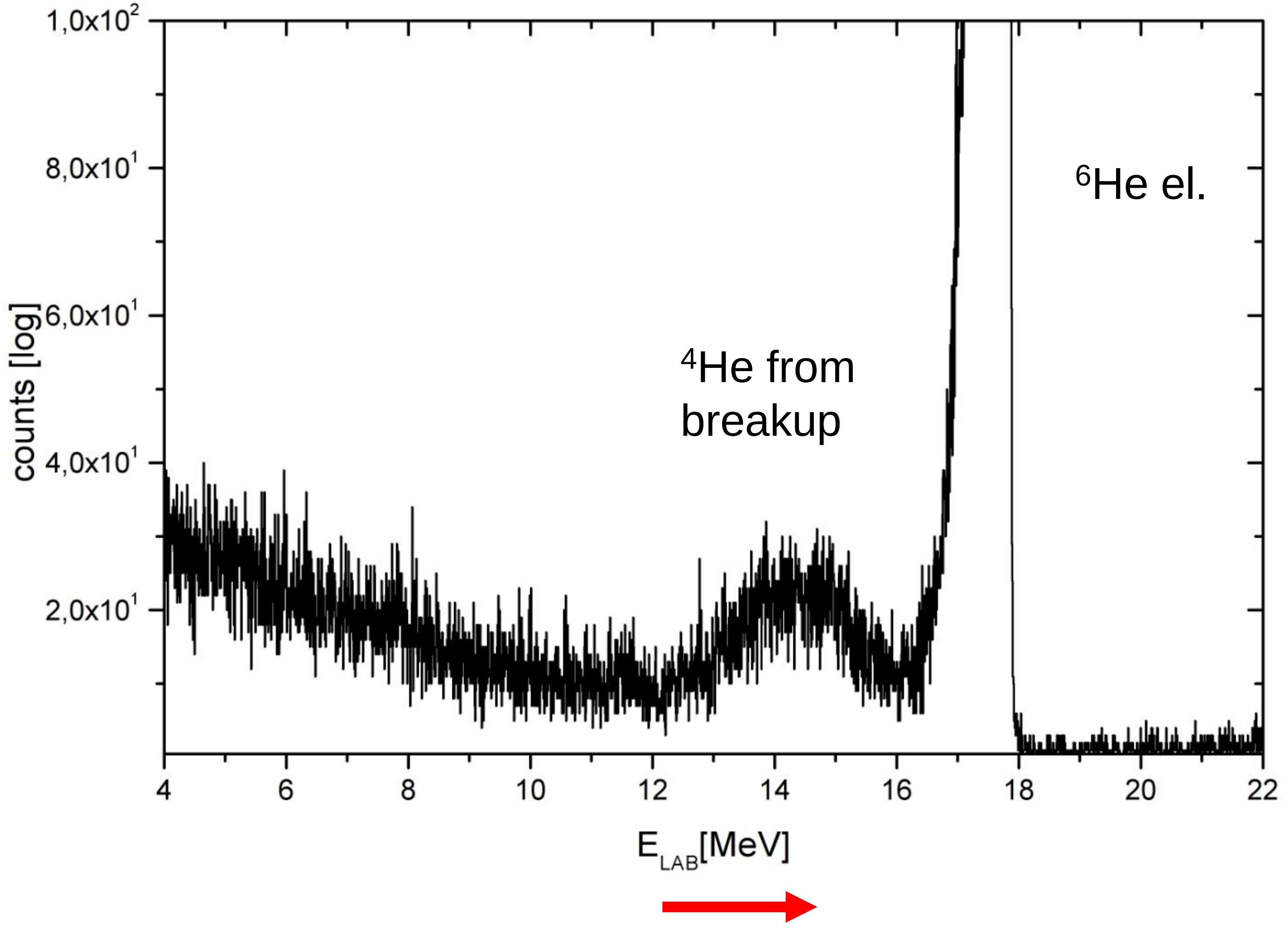
^{6}He: D=18 fm

^{6}Li: D=14.7 fm

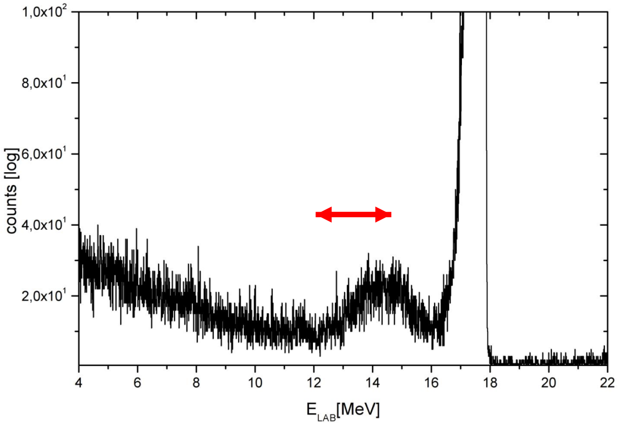


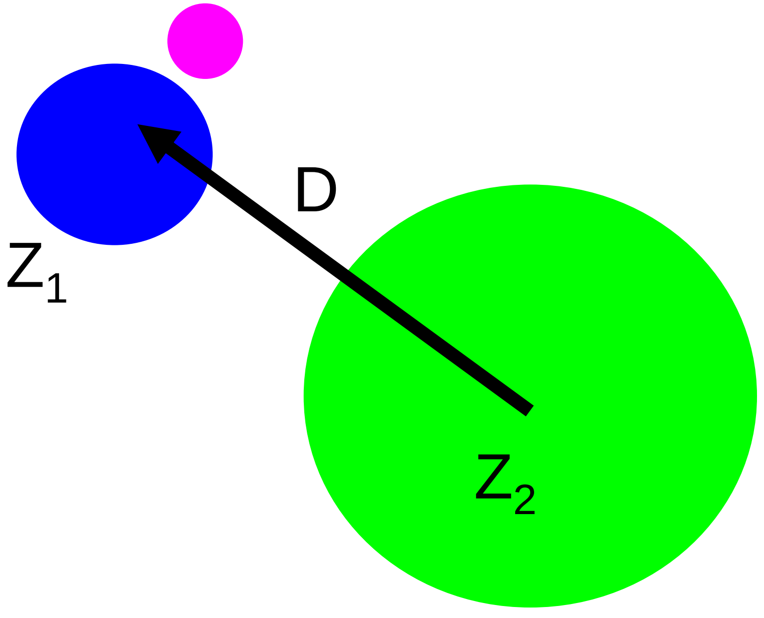
Coulomb post-acceleration

^{6}He + ^{206}Pb at 18 MeV, L. Standylo et al. PRC 87, 064603



Coulomb post-acceleration





^{6}He energy at D:

$E_D = E - Z_1 Z_2 e^2/D$

α energy at the detector:

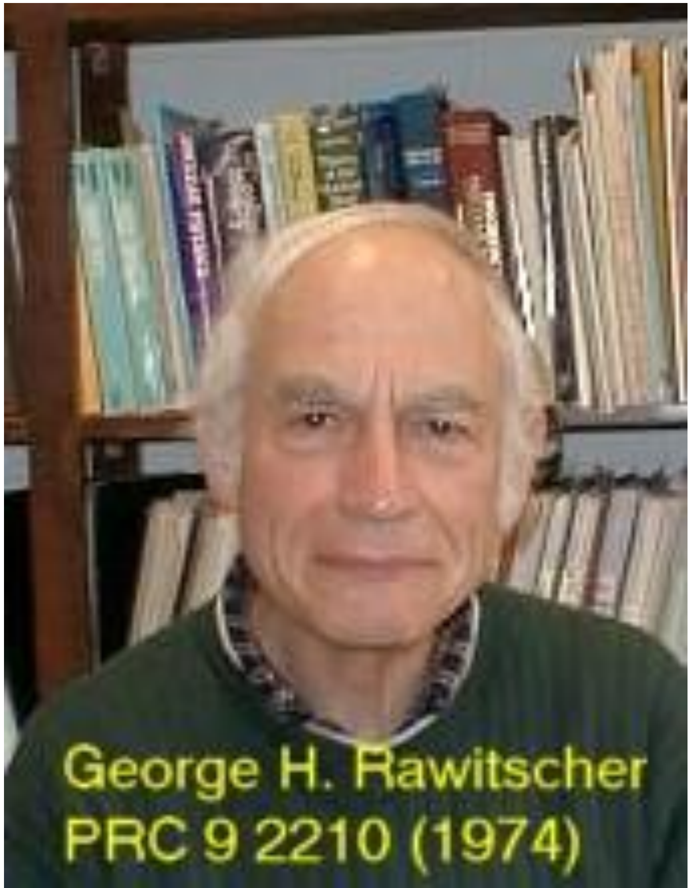
$4/6\ E_D + \ Z_1 Z_2 e^2/D$

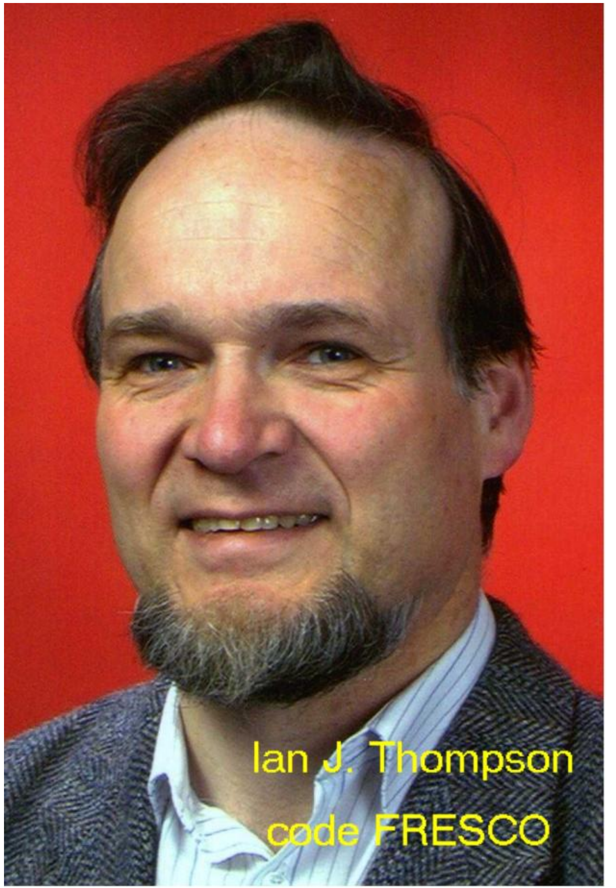
$= 4/6\ E + 1/3\ Z_1 Z_2 e^2/D$ → Breakup occurs at D ~ 25 fm

~3 MeV

Model: Continuum-Discretized Coupled-Channels

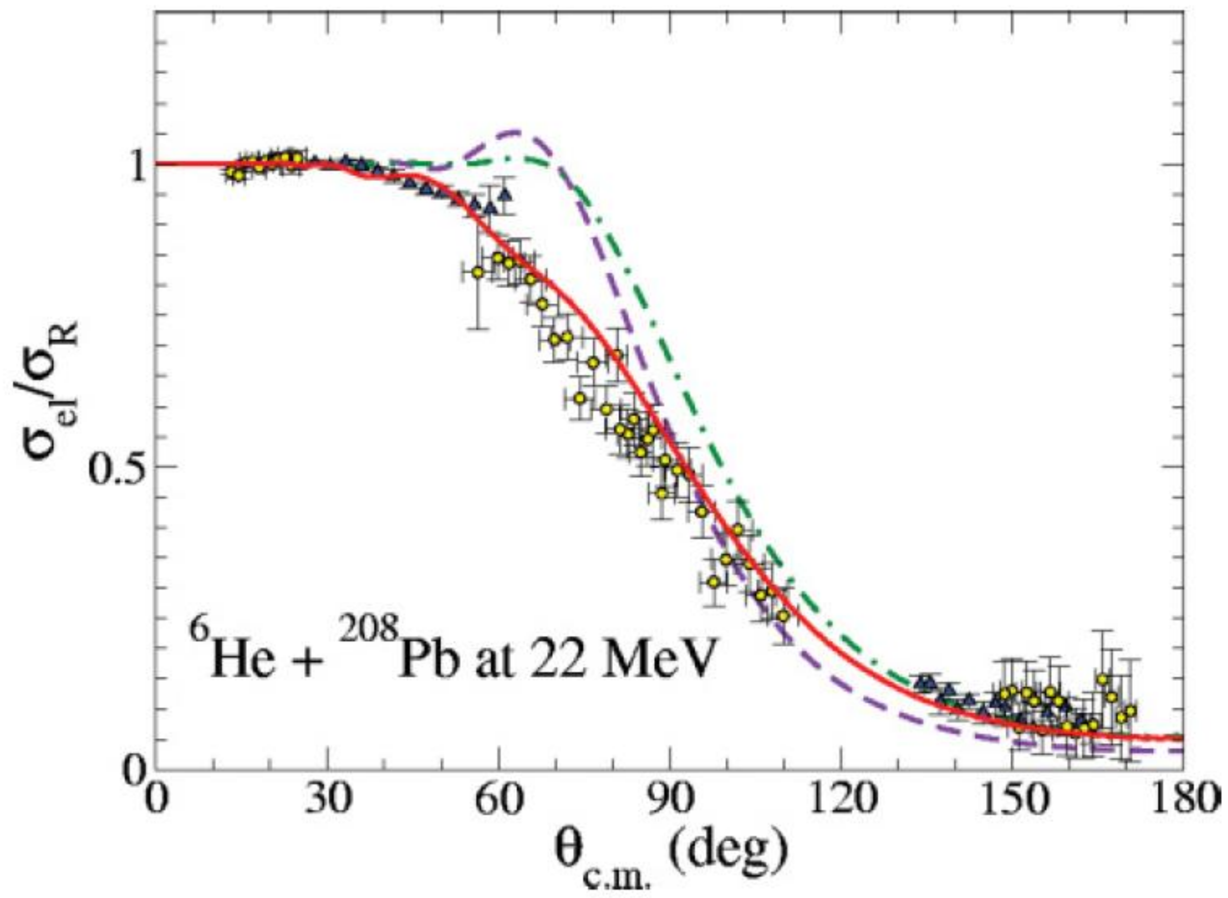
An extension of coupled channels technique to allow the treatment of couplings to unbound states, both resonances and non-resonant continuum. It was first developed to describe the effect of breakup couplings on deuteron elastic scattering.





CDCC in action

L. Acosta et al. PHYSICAL REVIEW C **84**, 044604 (2011)



Dot-dashed: no dipole couplings

Dashed: no couplings to the continuum

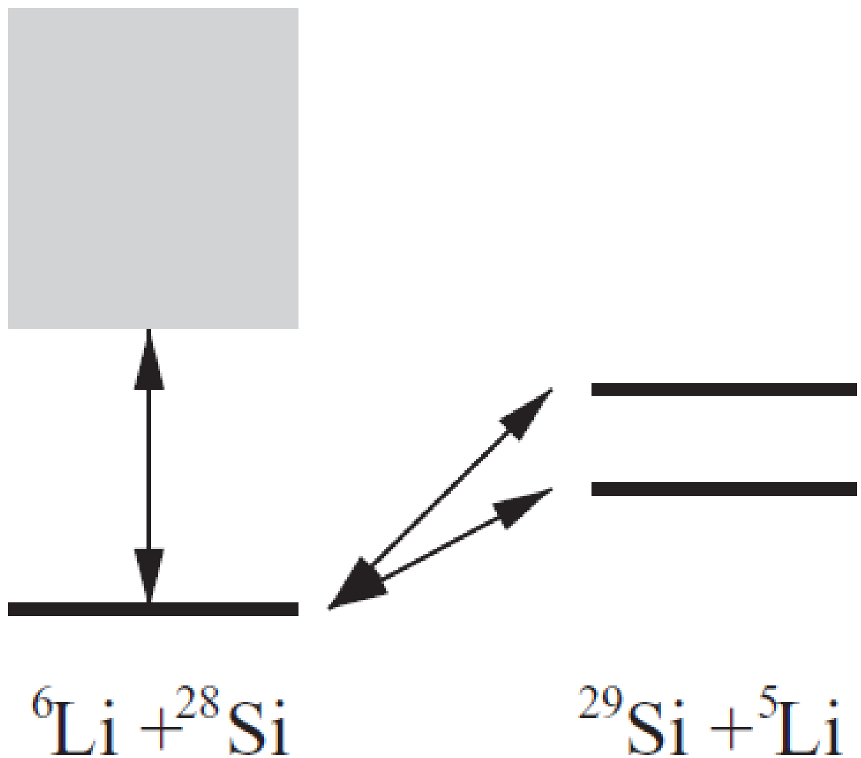
Effect of breakup on el. scattering, summary

Coupling to the continuum is clearly observed in experiments. It affects seriously the elastic scattering cross section and contributes to the generation of analysing powers

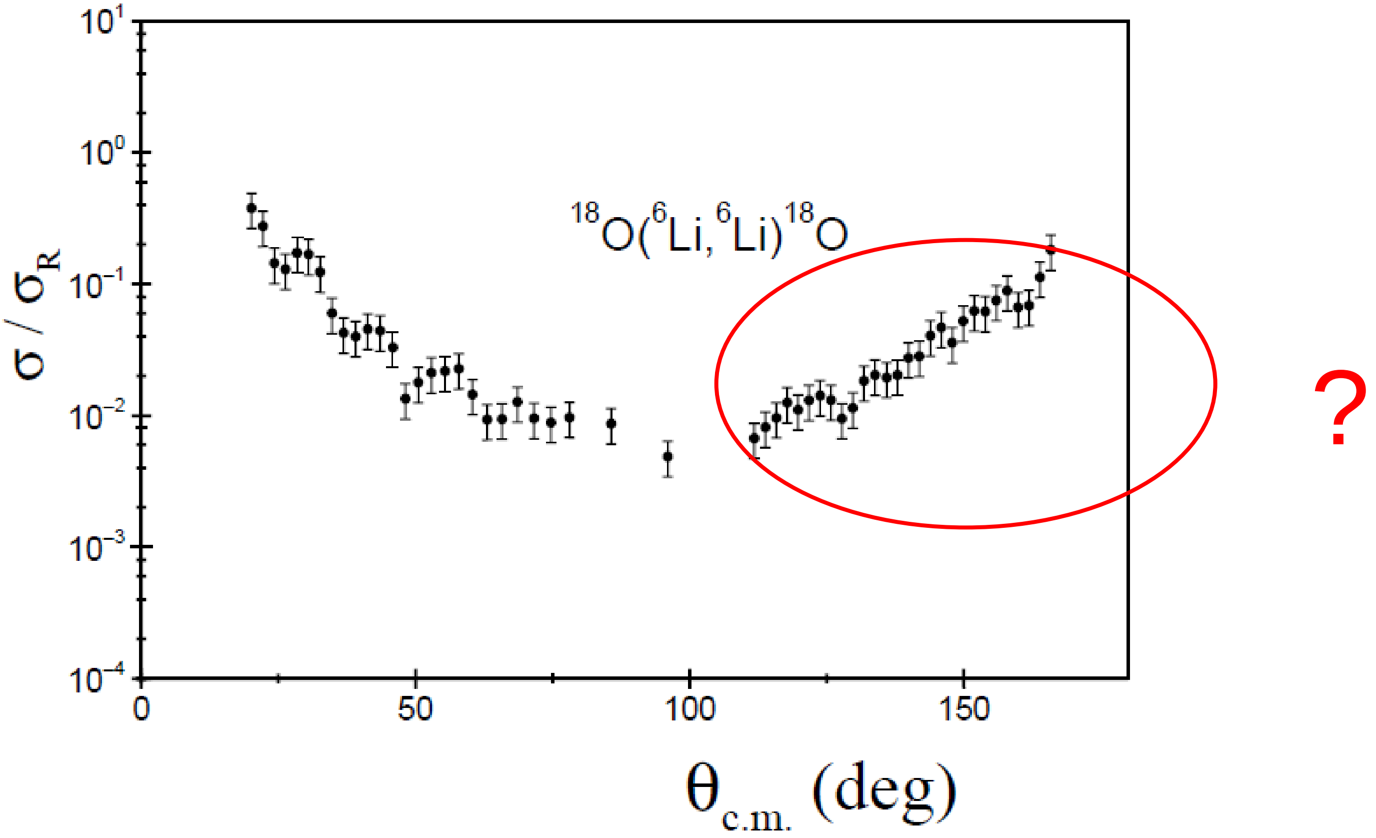
Coupling with reaction channels

Coupled-Reaction-Channels method

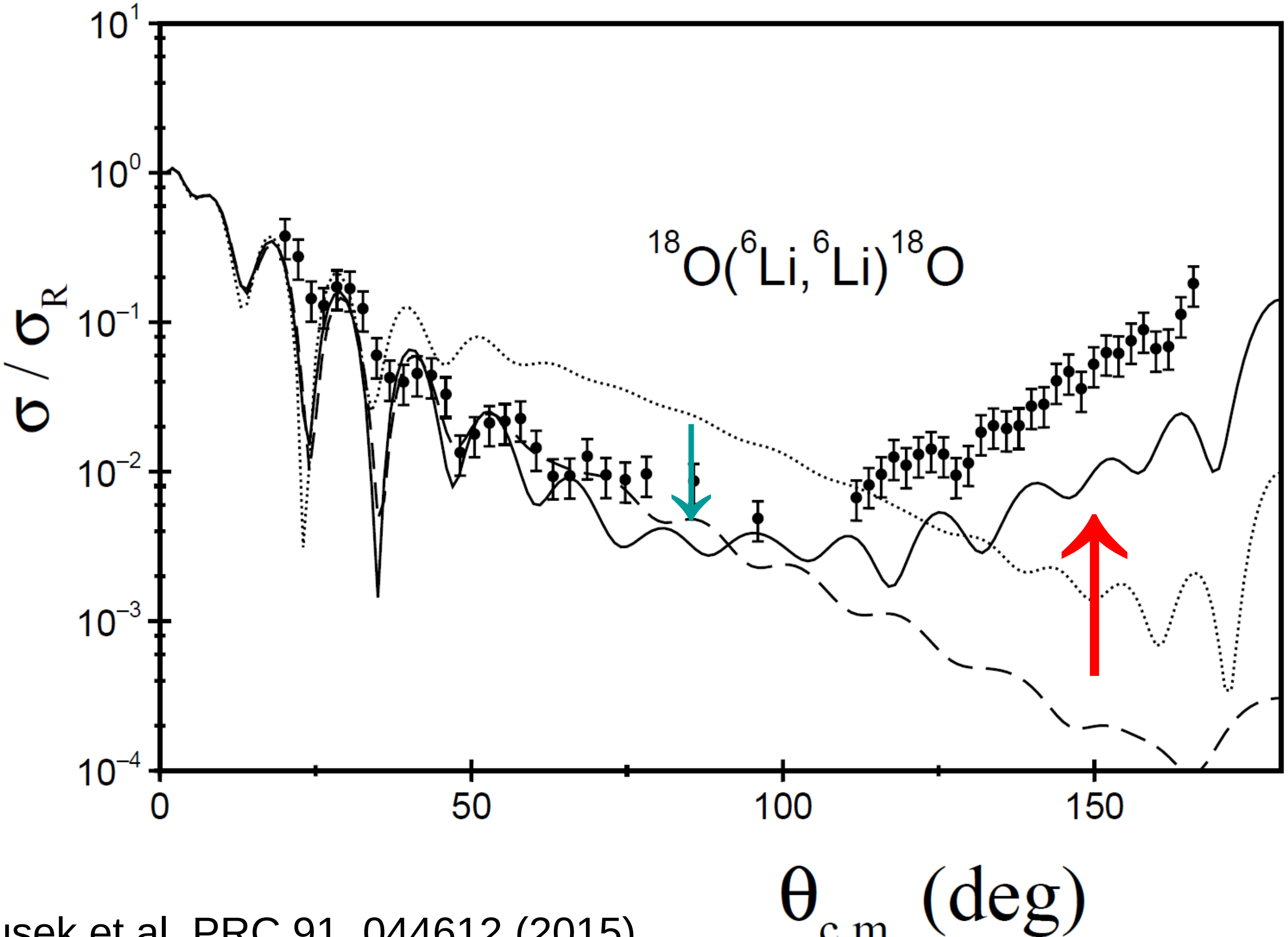
K. Zerva et al. PRC82, 044607



El. scatt. and coupling with reaction channels



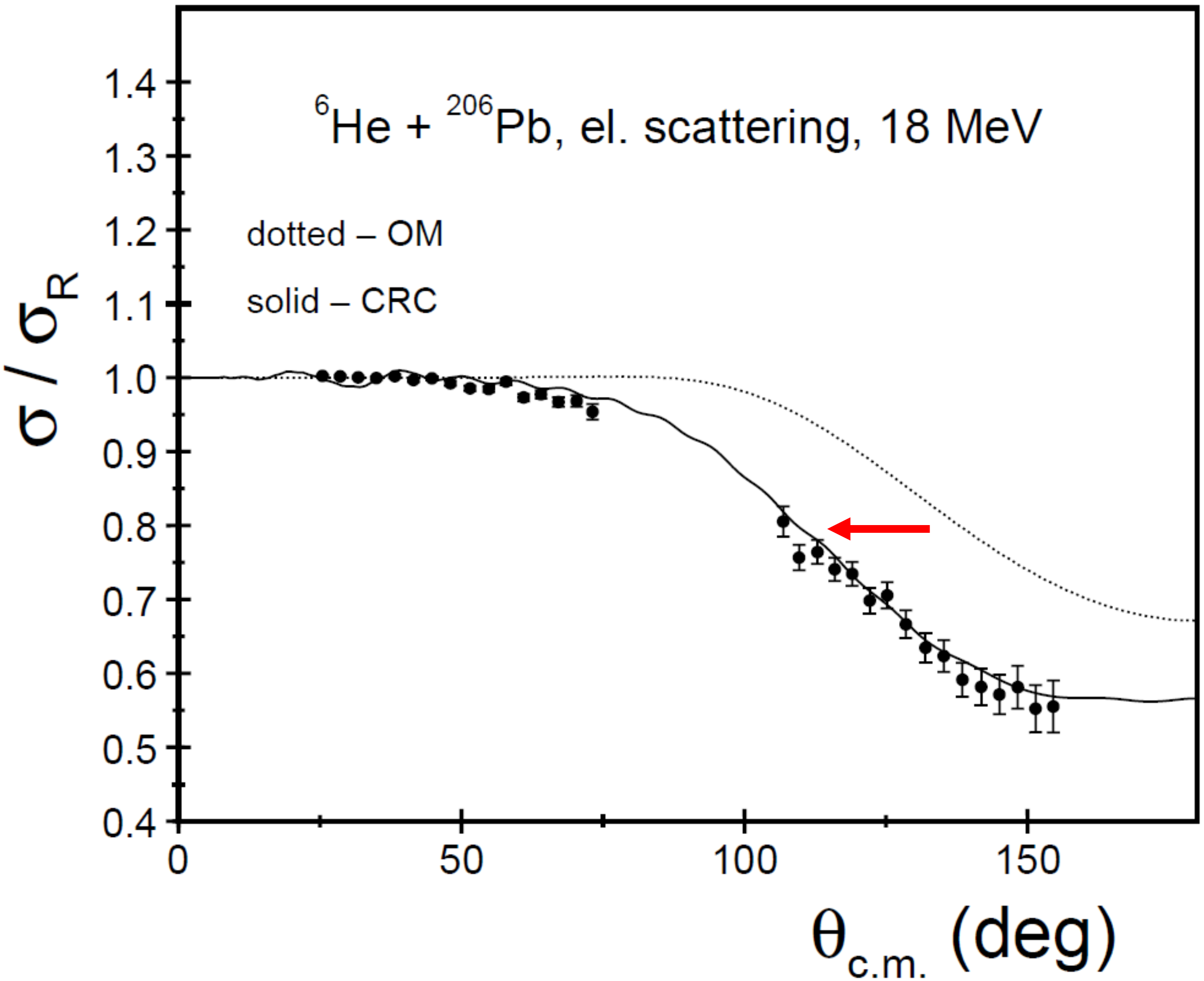
$^{6}Li+^{18}O$ el. scattering - summary



K. Rusek et al. PRC 91, 044612 (2015)

$^{6}He+^{206}Pb$ el. scattering

Coupling effects make ^{6}He look larger.



L. Standylo et al. PRC 87,064603

Effect of transfer on el. scattering, summary

For the cross section, effect of transfer on the elastic scattering is opposite to that of breakup. It is especially strong at backward angles.

Effect on fusion

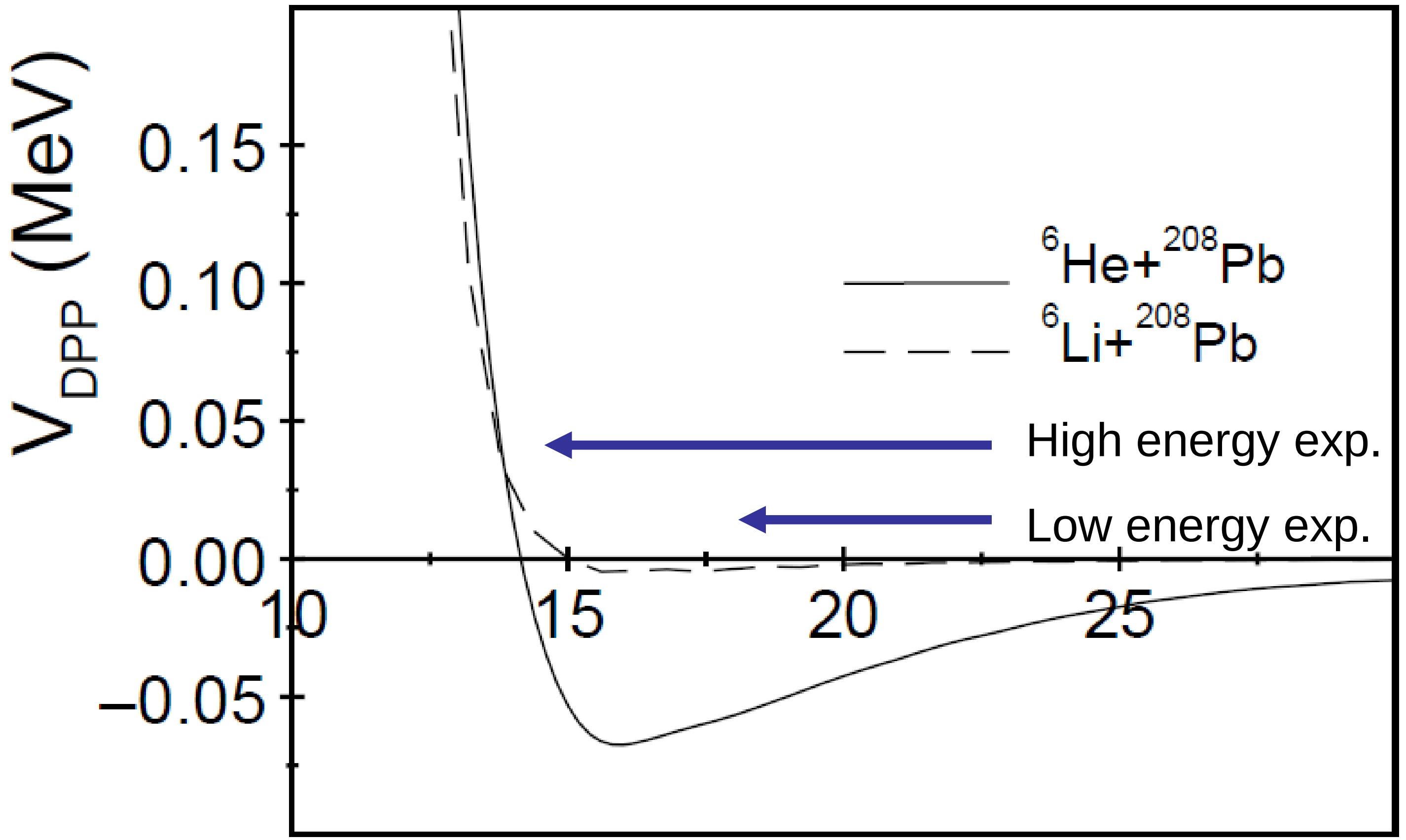
CDCC and CRC models are well suited to calculate direct reactions while fusion cross section is calculated by means of simple potential models, like Wong model. Thus, in order to study an effect of direct reactions on fusion one has to find how the direct reactions affect the effective nucleus-nucleus potential.

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

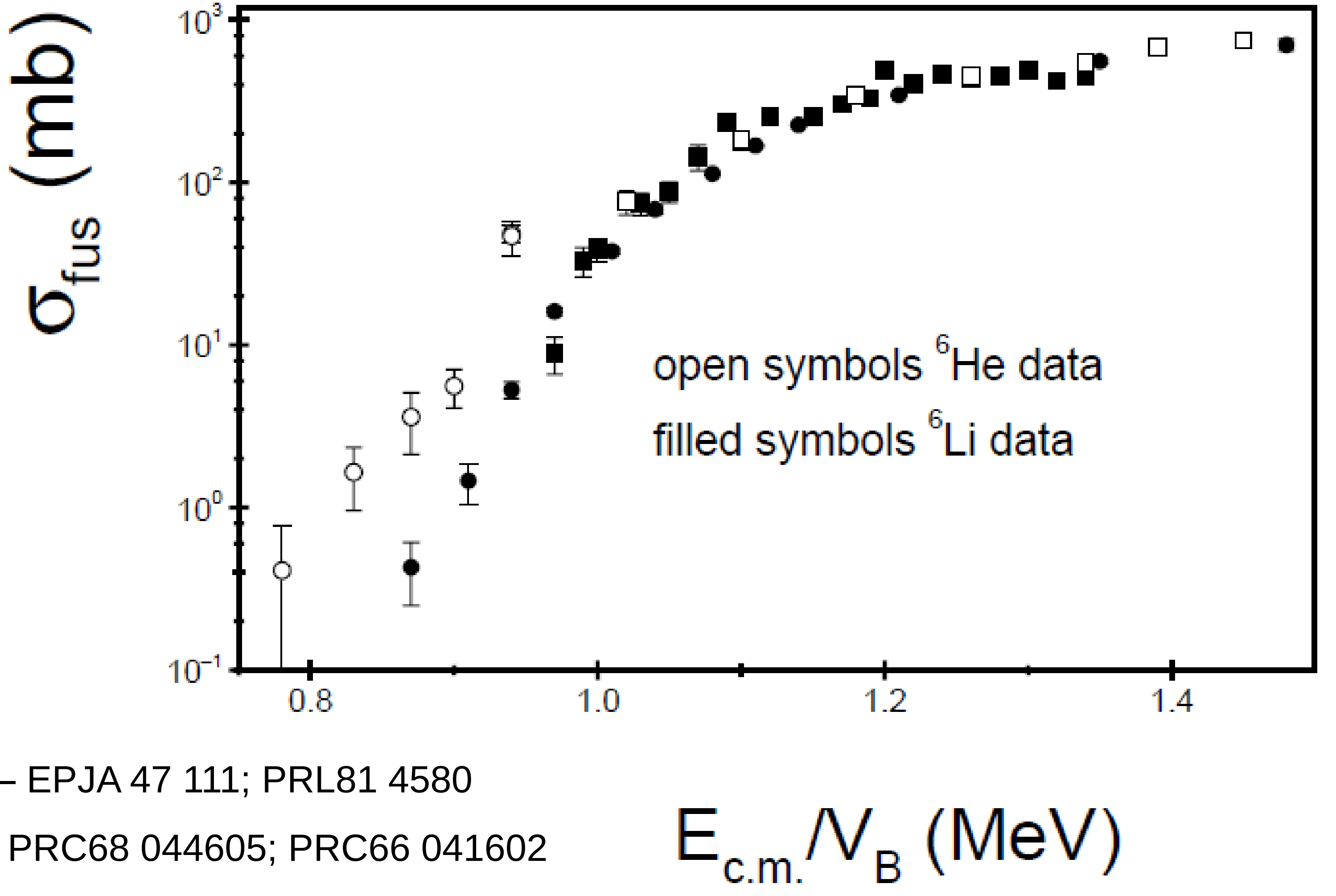
Dynamic Polarization Potential

V = Vo + i W + DPP

From CDCC, CRC calculations



Fusion – an enhancement below the Coulomb barrier



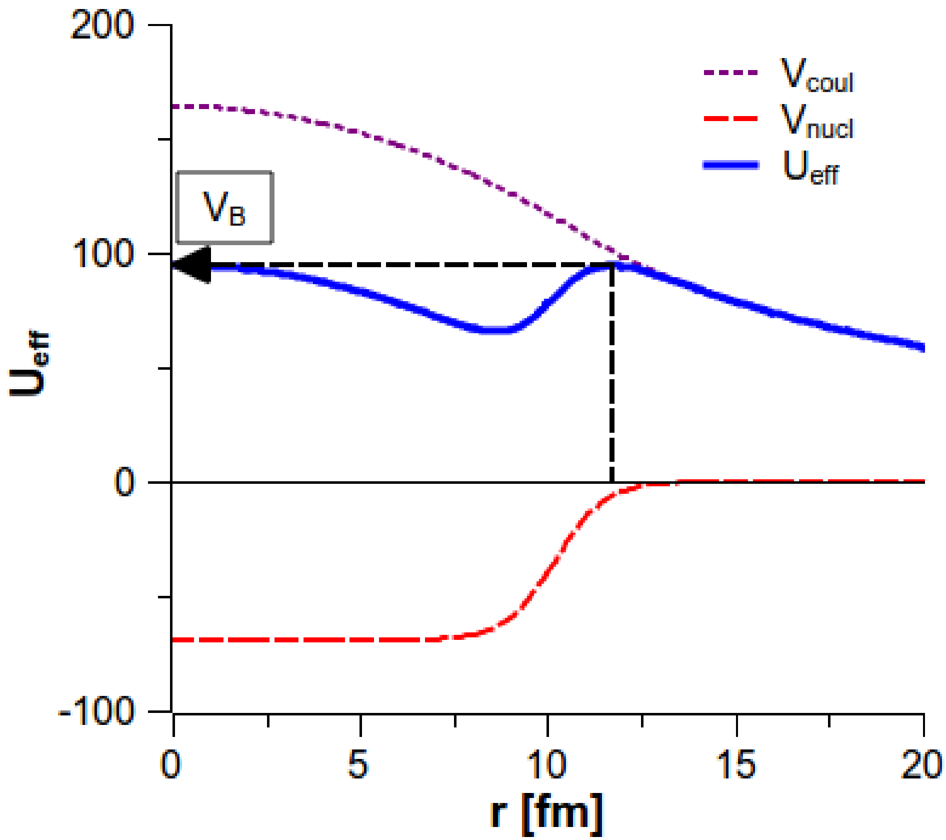
6He – EPJA 47 111; PRL81 4580

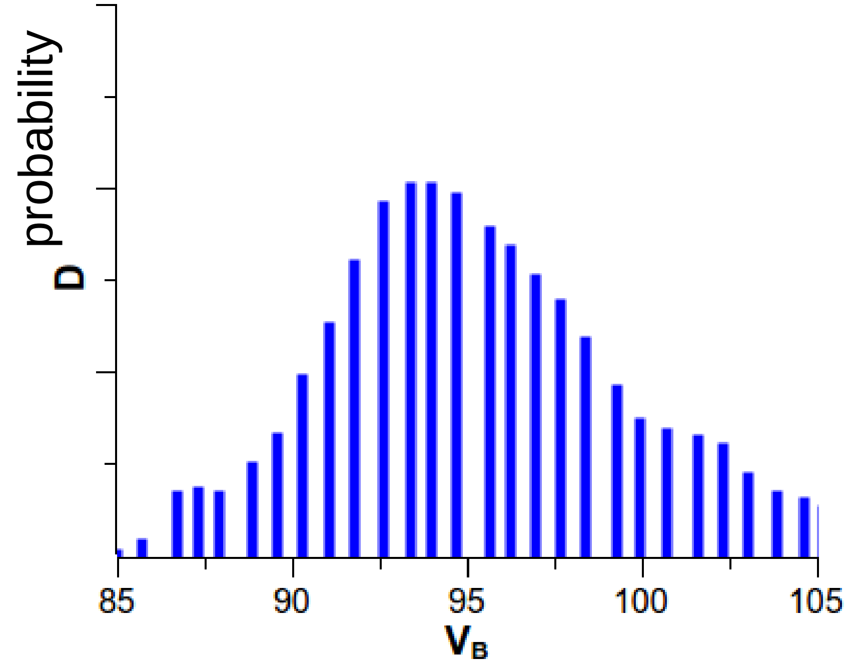
6Li – PRC68 044605; PRC66 041602

Effect on fusion, summary

Direct reaction channels (breakup, transfer) may significantly affect the fusion cross section with respect to the predictions based on a simple potential model (e.g. enhance the fusion c.s. below the Coulomb barrier and suppress it above).

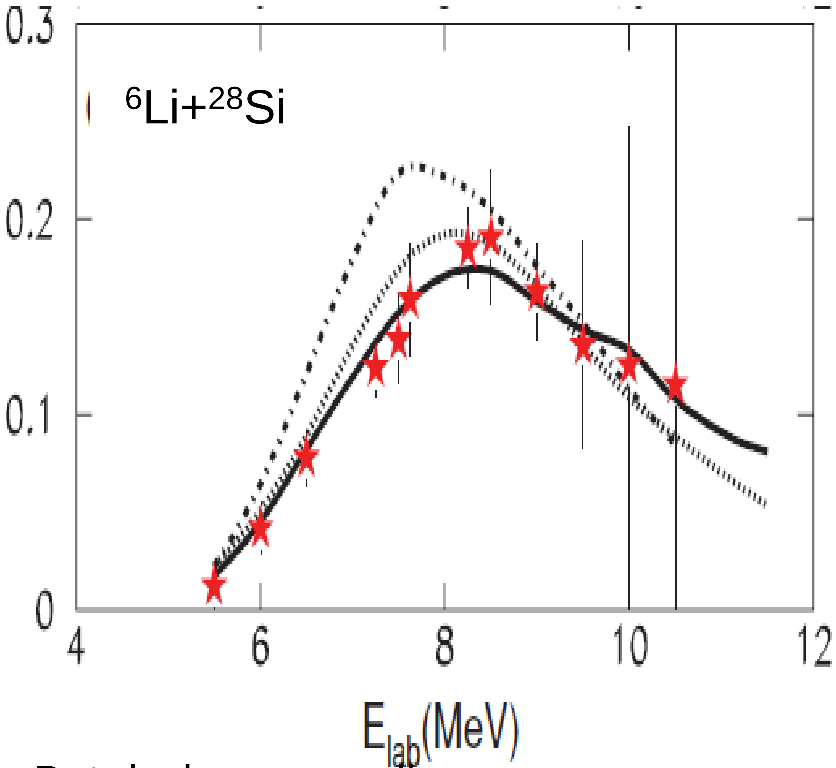
Effect on the Coulomb barrier distribution





Effect on the Coulomb barrier distributions

K. Zerva et al. PRC 82, 044607

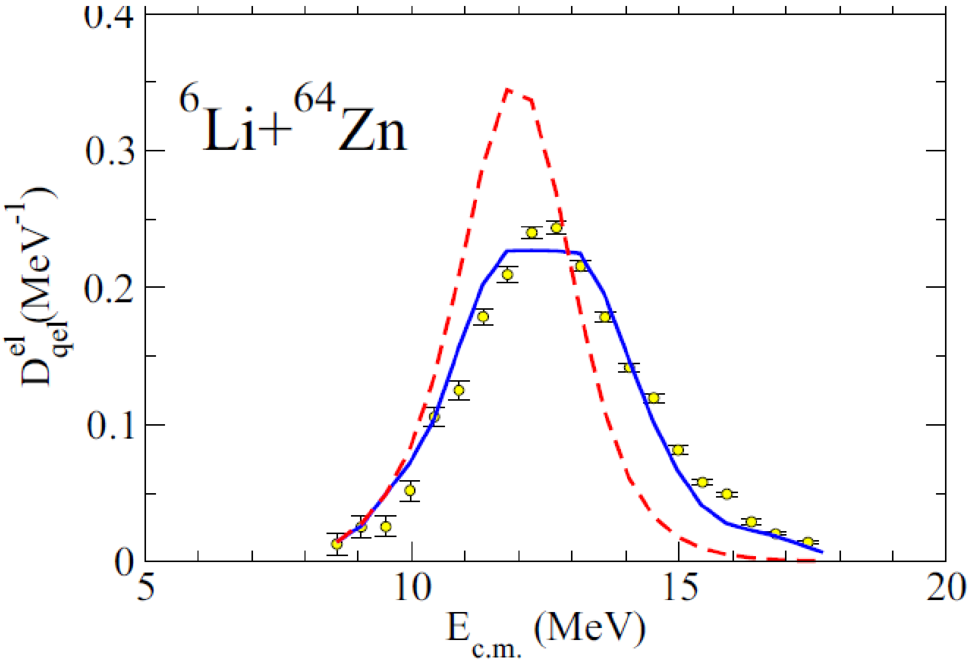


Dot-dash - no coupling

Solid – coupl. to breakup only

Dotted – coupl. to breakup and transf.

J.P. Fernandez-Garcia et al. PRC 92, 054602



Dashed- no coupling

Solid – coupl. to breakup only

Effect on barrier distribution, summary

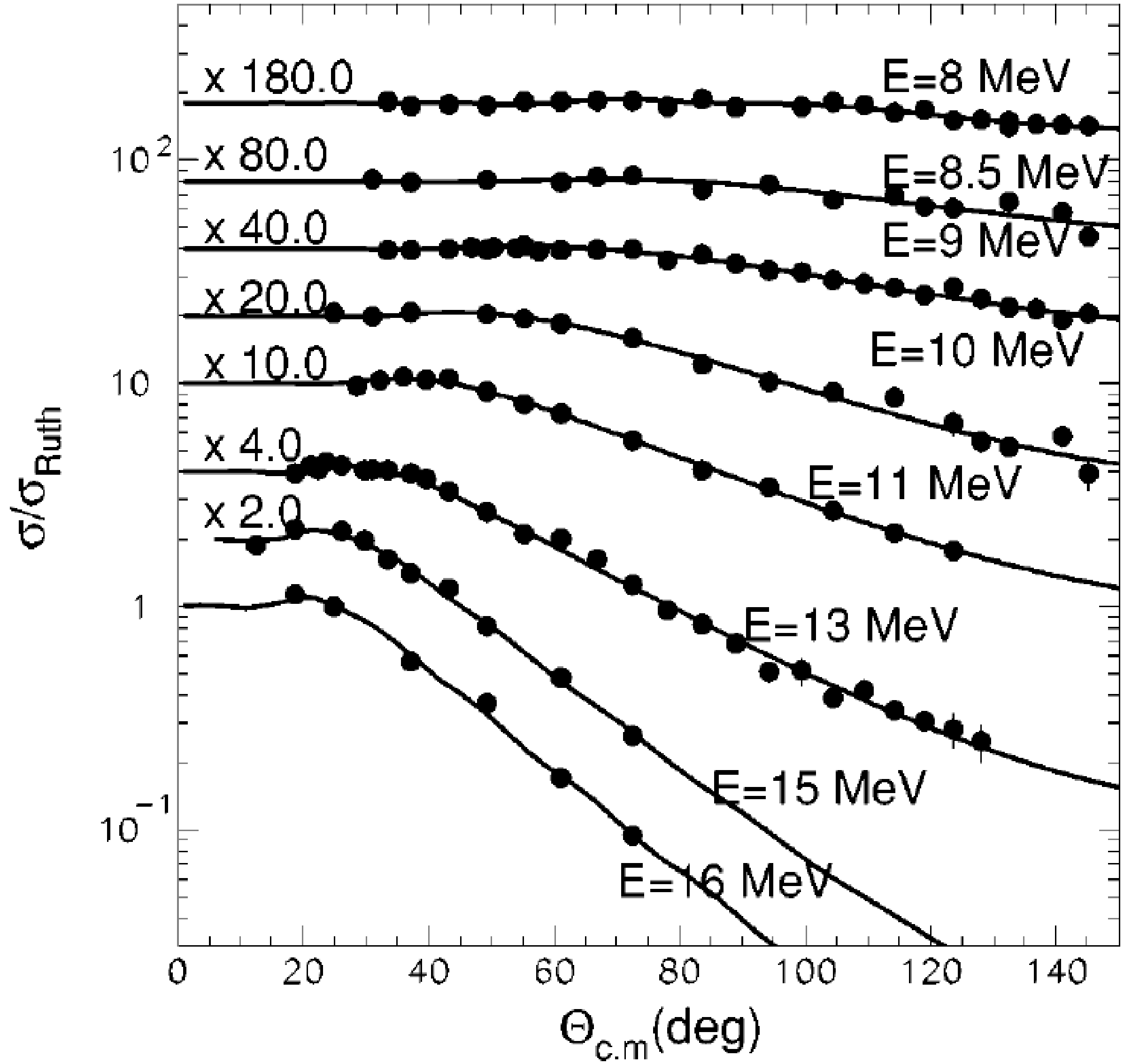
Breakup tends to broaden the barrier distribution and to increase its average energy while the transfer acts opposite, similar as it was observed for elastic scattering.

Weakly bound light nuclei are ideal to study coupling effects. These effects are clearly observed in experiments measuring elastic scattering, transfer reactions and fusion providing that the measurements are precise. It helps, if such a study is complex – a set of experiments devoted to different processes. In fact there are not many data sets existing that cover all possible reaction channels for a given pair of scattered nuclei. Good example of such a set is the data for $^{6,7}Li + ^{28}Si$ collected in complementary experiments by **Prof. Athena Pakou and her team.**

$^7Li + ^{28}Si$

A. Pakou et al. PHYSICAL REVIEW C **69**, 054602 (2004)

El. scattering

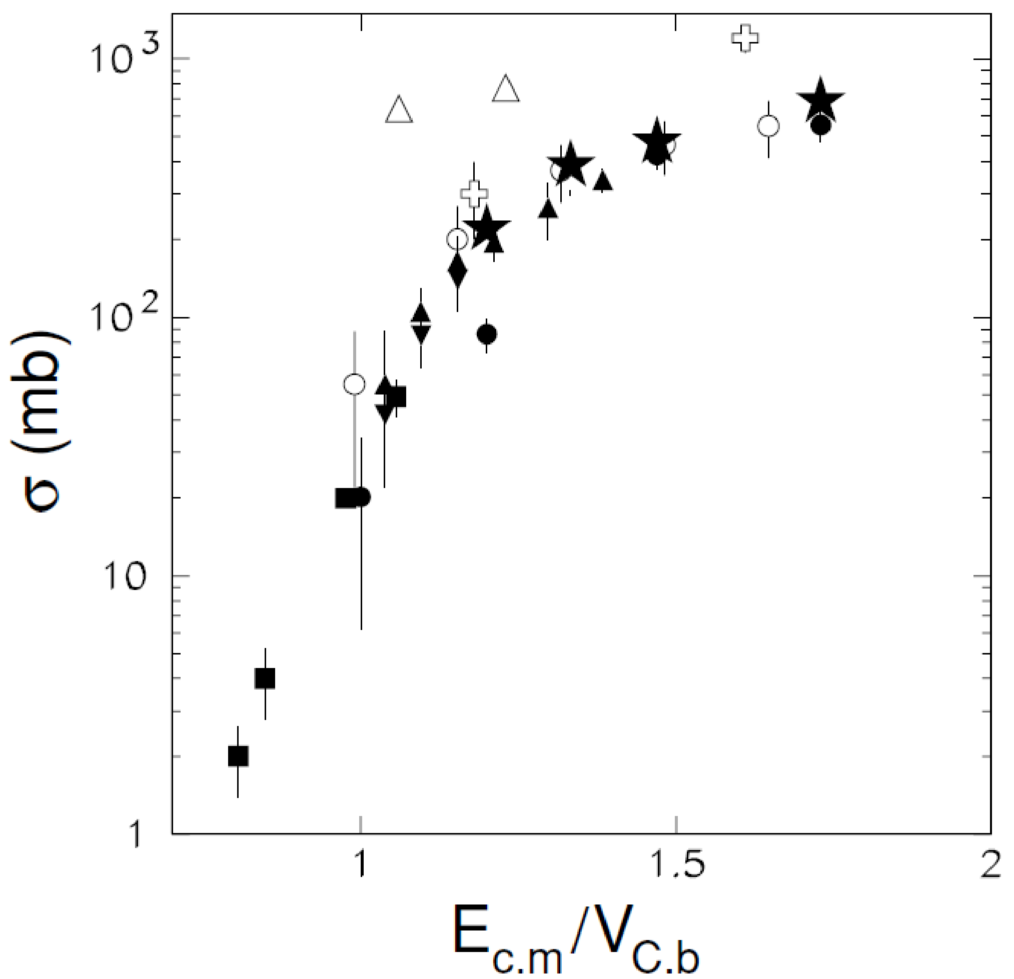


Alpha-production c.s.

A.Pakou et al. PRC71, 064602

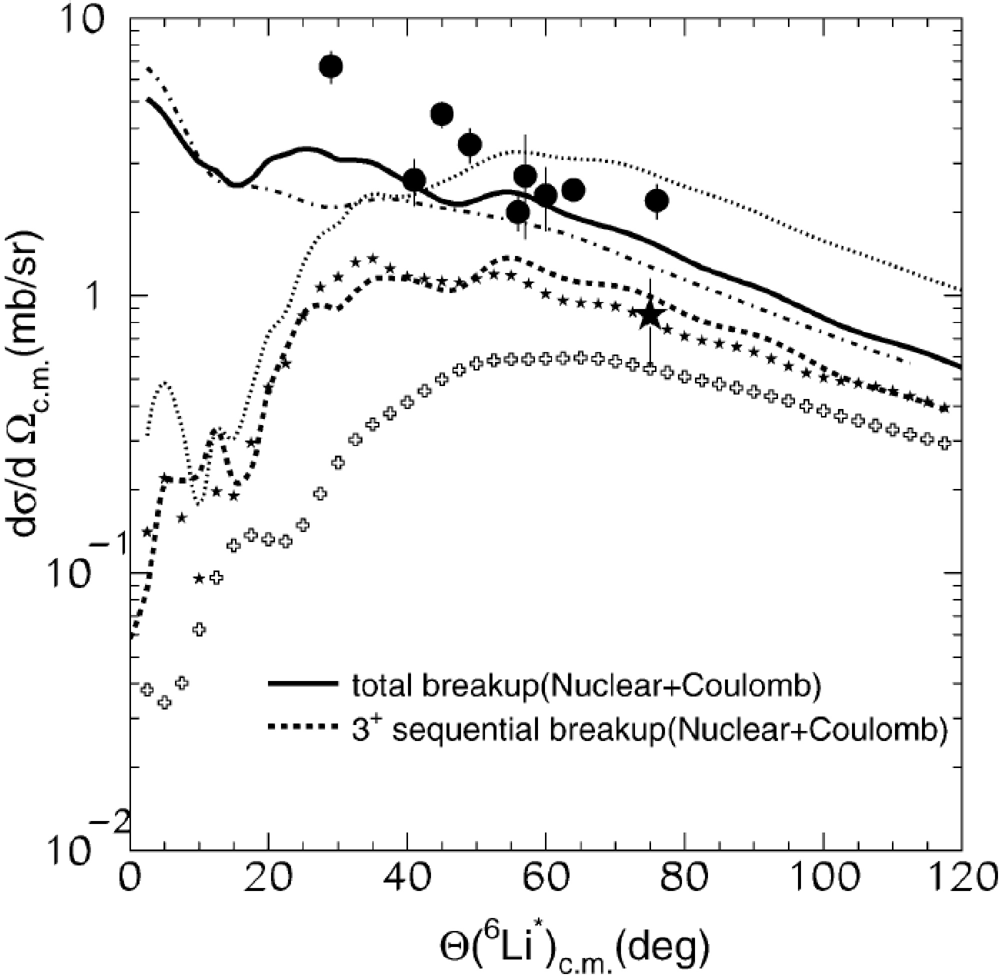
Open triangles and crosses - ^{6}He,

Other symbols – $^{6,7}Li$



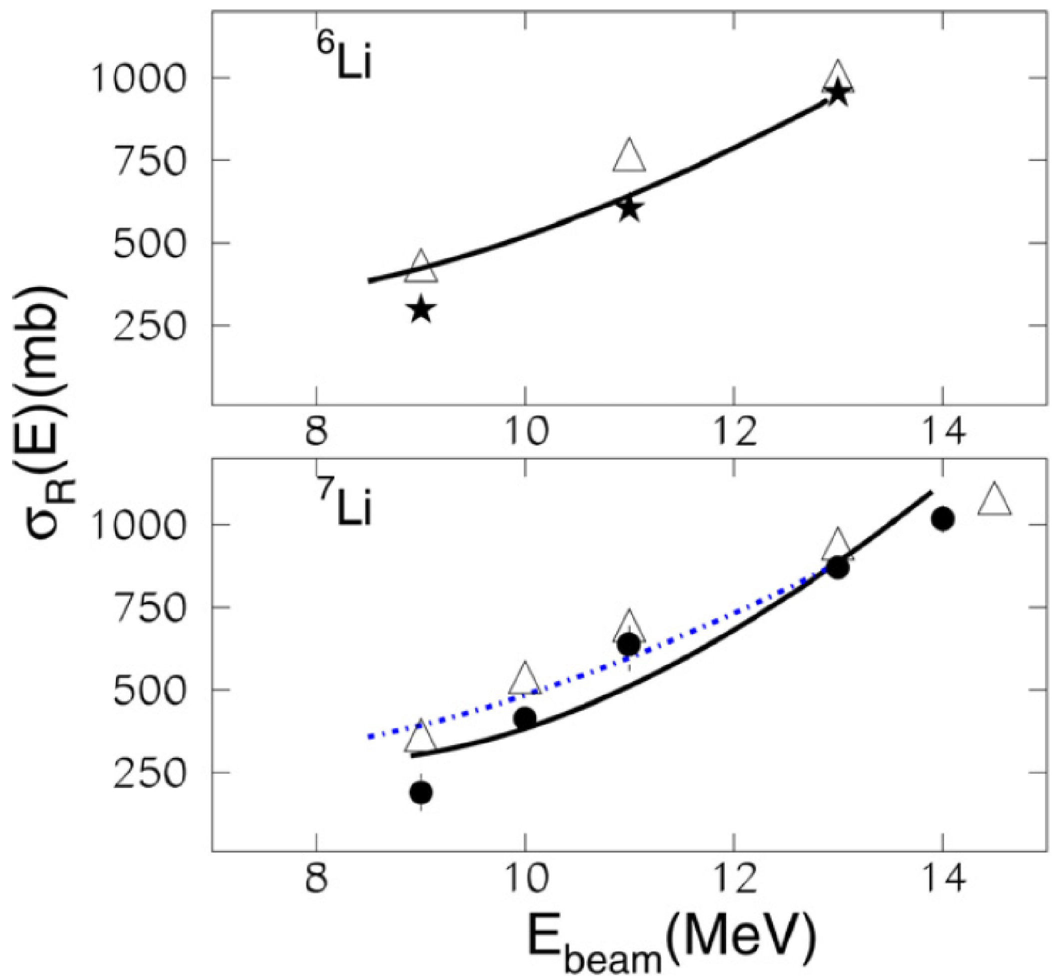
^{6}Li exclusive breakup

A. Pakou et al. PLB 633, 691



Reaction cross section

A. Pakou et al. / Nuclear Physics A 784 (2007) 13–24



Triangles – theory

Symbols – el. scattering

Solid curves - experiment

Thank you all for your attention and for the invitation to this meeting

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