A threshold resonance state explains unusual branching ratio and angular distrubitions

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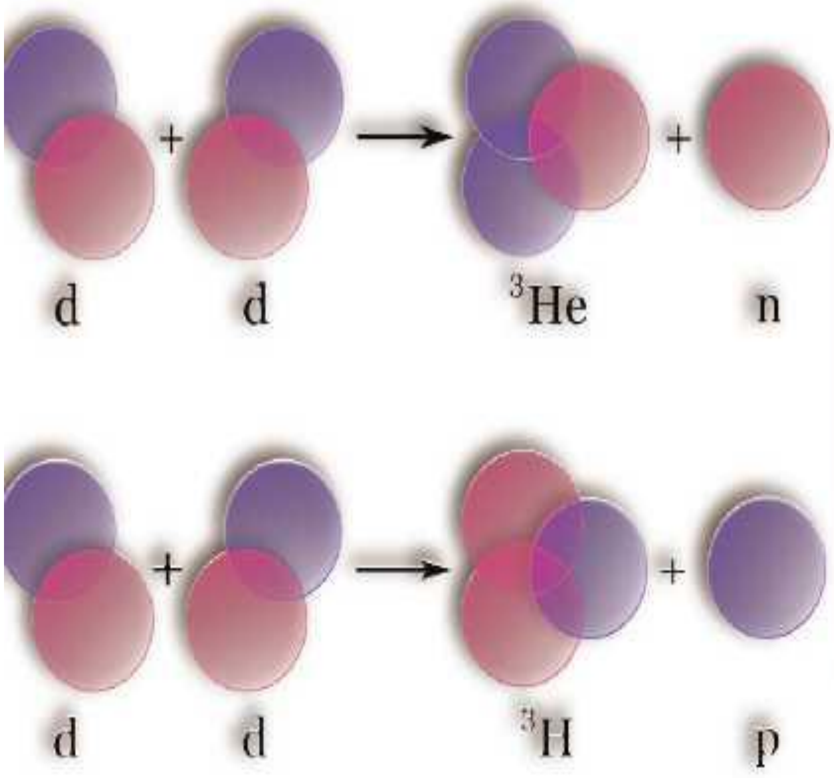
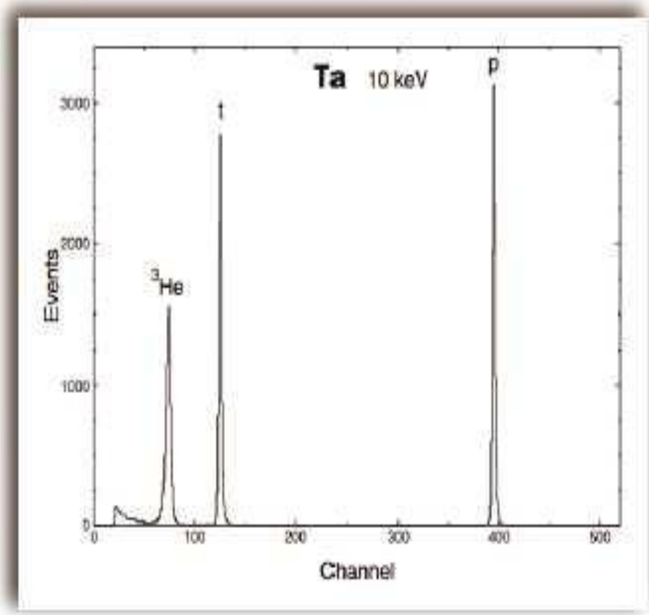
Outline

- General view of D+d reactions- motivation for the study
- Branching ratio and angular distrubitions for The D+d reactions
- Direct reaction and compound nucleus reaction contributions
- Model independent approach
- Experimental results
- 0^+ threshold resonance contribution in He^4 for the D+d reactions

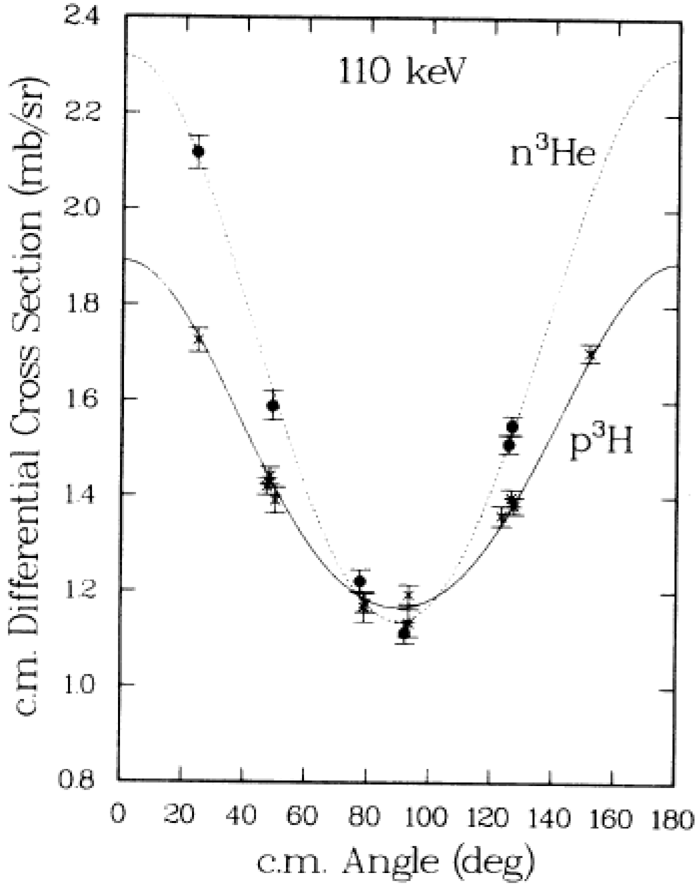
Motivation

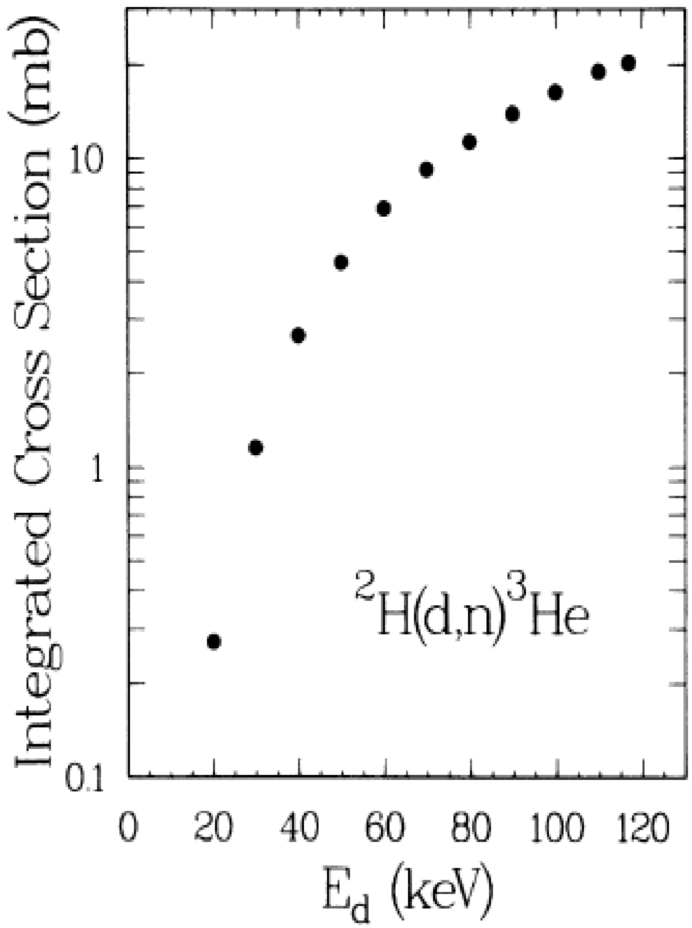
The $^2H(d,n)^3He$ and $^2H(d,p)^3H$ reactions





Angular Distrubition and Cross section for dd reactions in gas target experiment

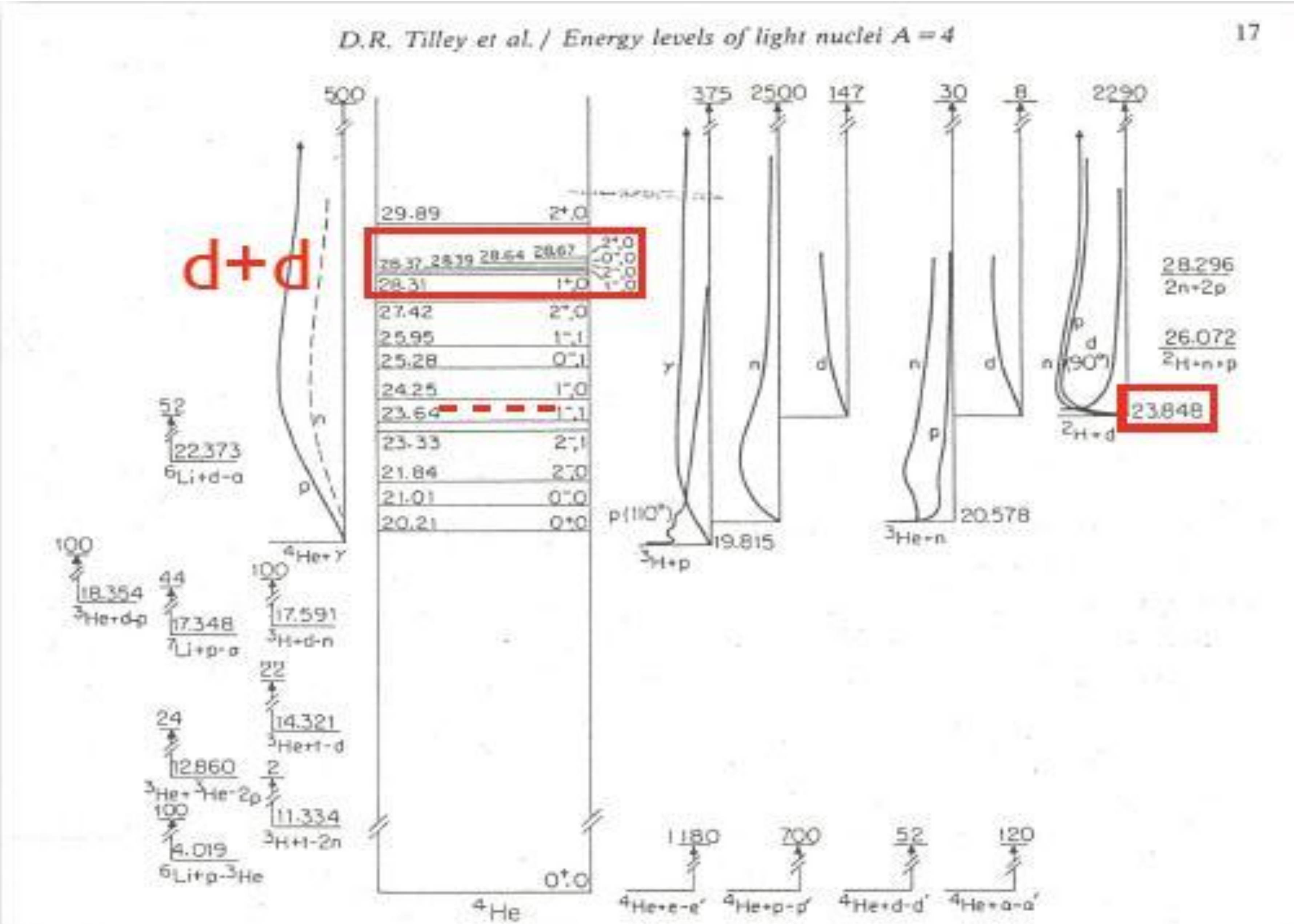




$$\bar{\sigma}(\theta)=a+b\cos^2\theta+c\cos^4\theta.$$

Ronald E.Brown and Nelson Jarmie Phy. Rev.C 1990

Level scheme of He4



Very small cross sections

$$E << E_C \;\rightarrow\; 10^{-18}\ \text{barn} \leq \sigma(E) \leq 10^{-9}\ \text{barn}$$

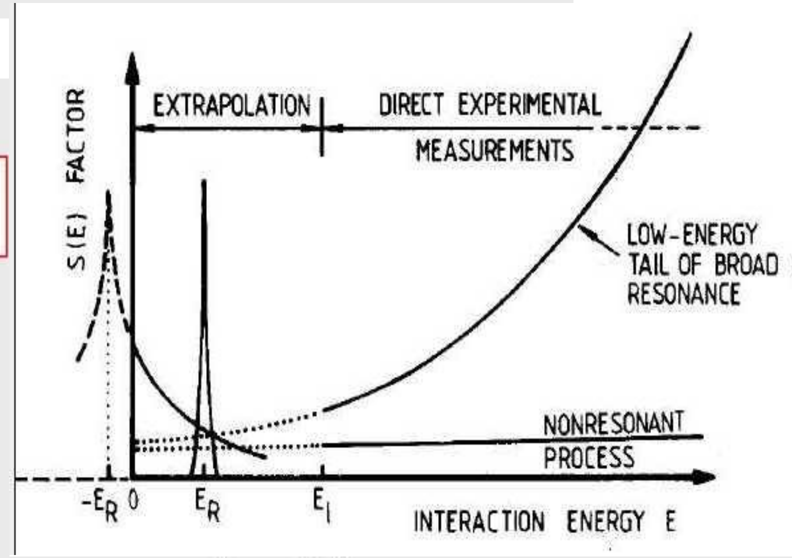
'Nuclear' contribution: the S-factor

Coulomb contribution (strong energy dependence): The Gamow factor

$$\sigma(E) = S(E)\, e^{-2\pi\eta(E)}\, \frac{1}{E}$$

With the Gamow factor: $2\pi\eta(E) = 31.29 Z_1 Z_2 (\mu/E)^{1/2}$

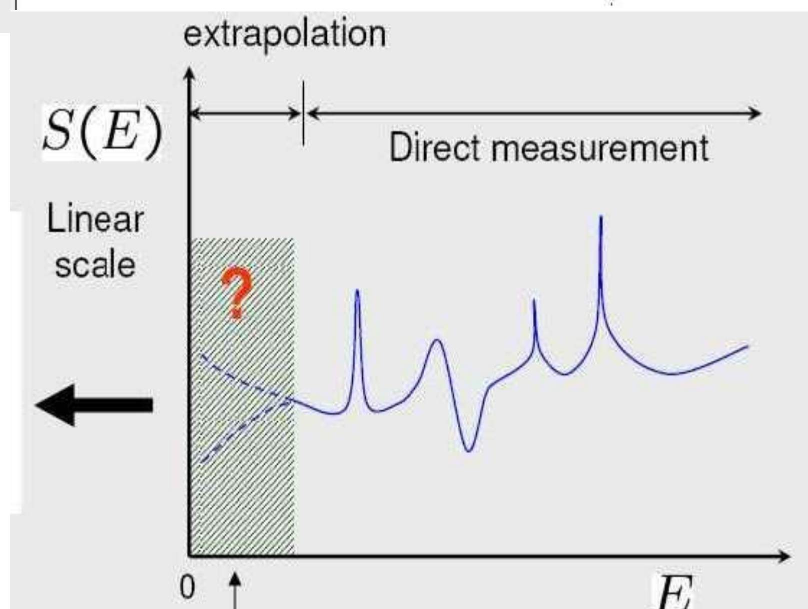
Z_1, Z_2 the charge of the nuclei, μ the reduced mass, E in keV



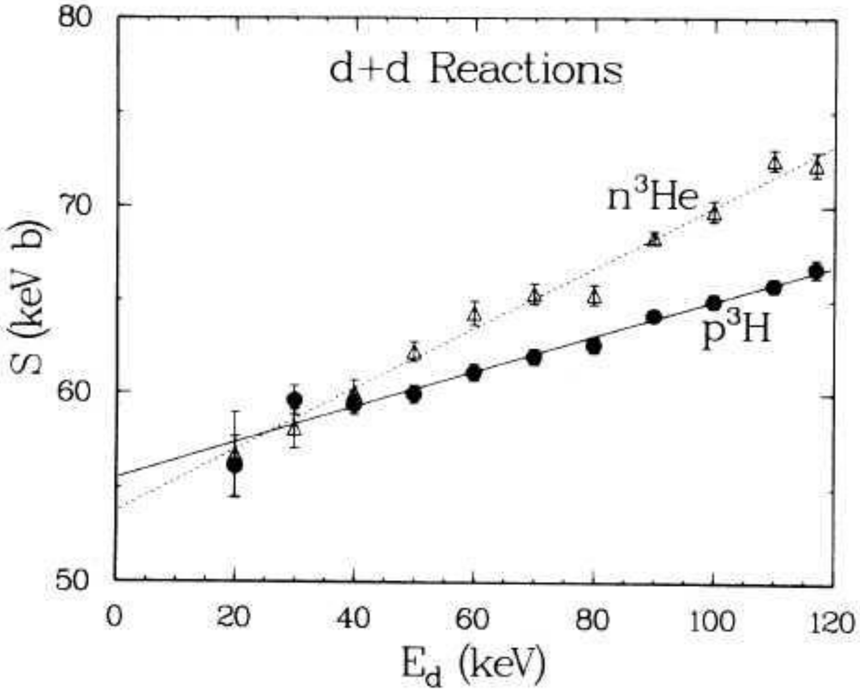
- <u>Procedure</u>
- 1. measurement of cross sections higher energies
- 2.extrapolation to astrophsical energies

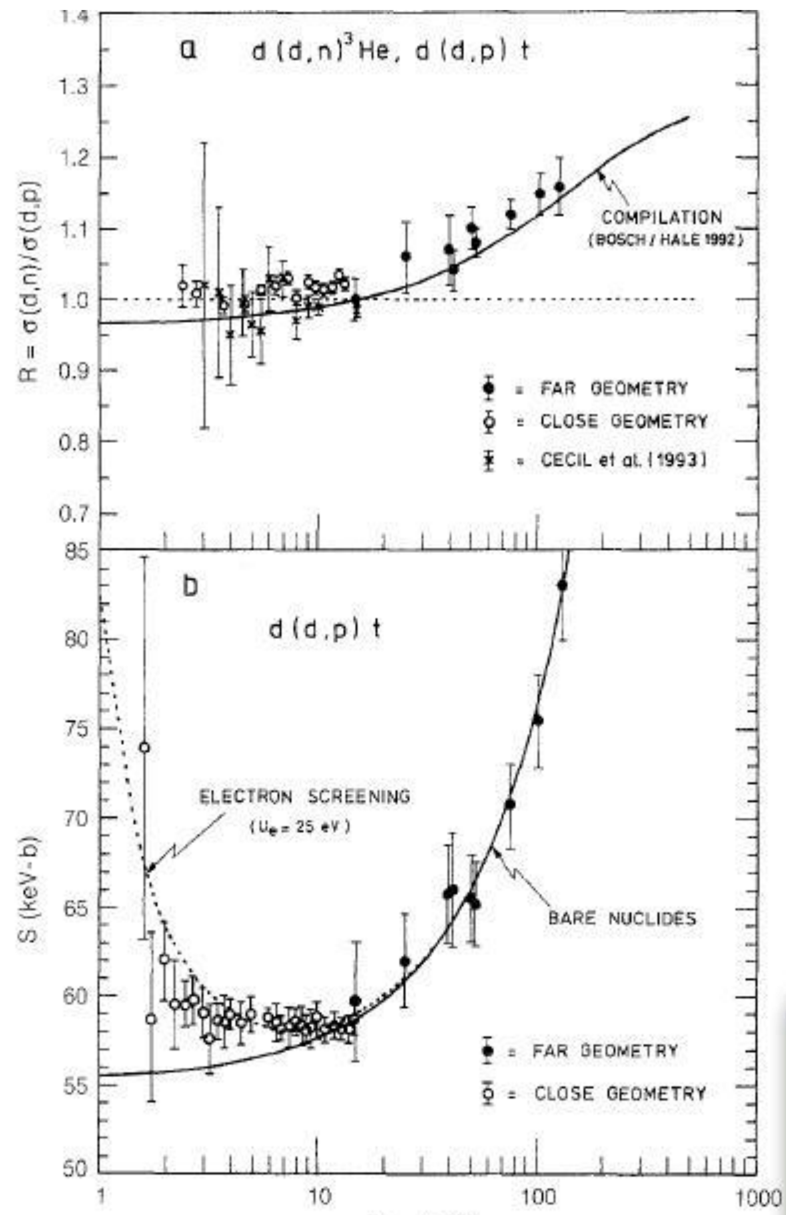
- <u>Need</u>

- low energy measurements (but even though….)
- Use of theoretical methods

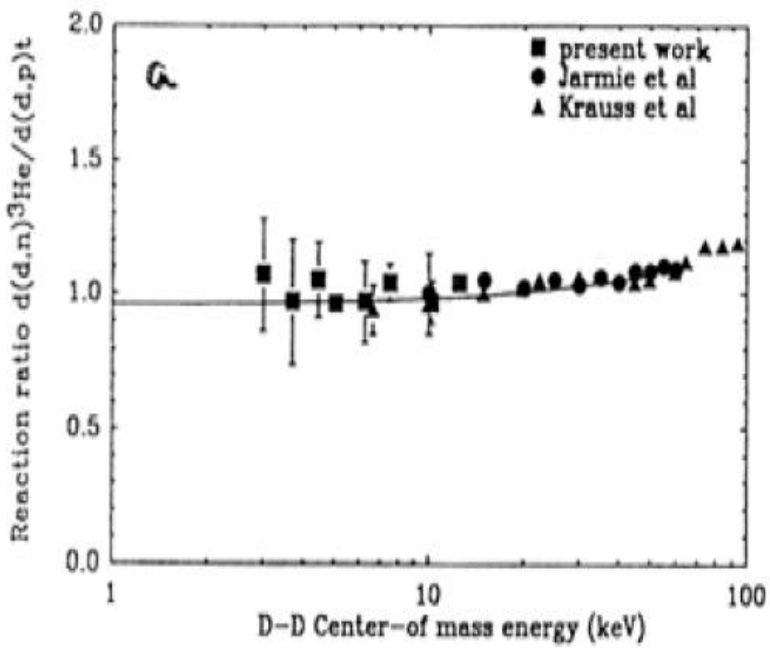


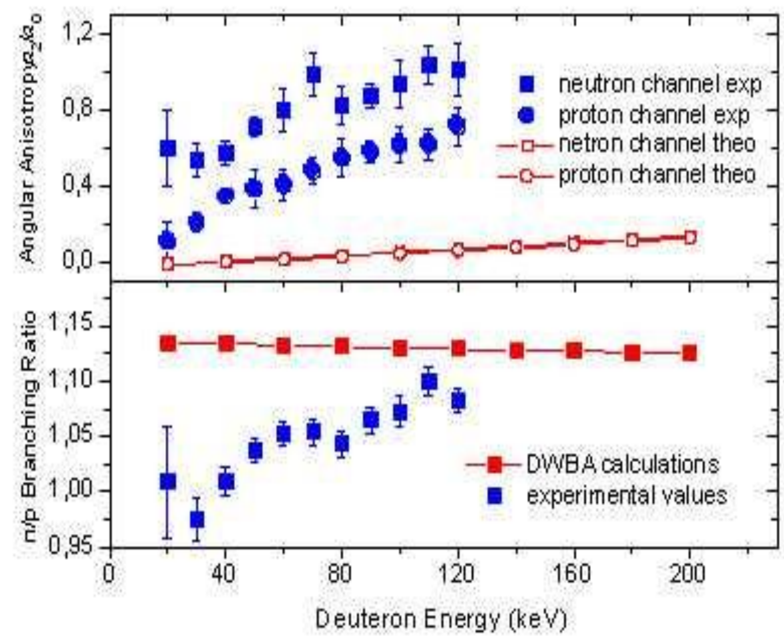
Astrophysical S-factor for d+d





DWBA calculation versus R - Matrix





Cecil, F.E. and G.M. Hale. Measurement of D-D and D-Li6 Nuclear Reactions at Very Low Energies. in Second Annual Conference on Cold Fusion, "The Science of Cold Fusion". 1991.

A.İ.Kılıç, K. Czerski et all Isospin symmetry breaking and branching ratio in the deuteron reactions at Very low energies . International Journal of Modern Physics E Vol. 20, No. 2 (2011)

Model independent approach

Definition of Transition matrix elements, penetration and penetrabilities for d+d reactions

$$T_{\beta\alpha} = \langle {}^{2S_\alpha+1}\ell_{\alpha J} | J^\pi | {}^{2S_\beta+1}\ell_{\beta J} \rangle$$

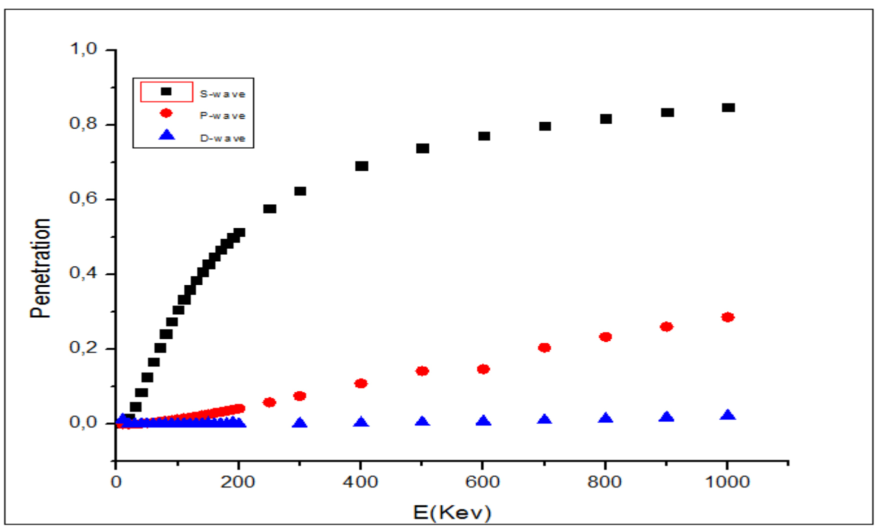
α: entrance channel; β: exit channel.

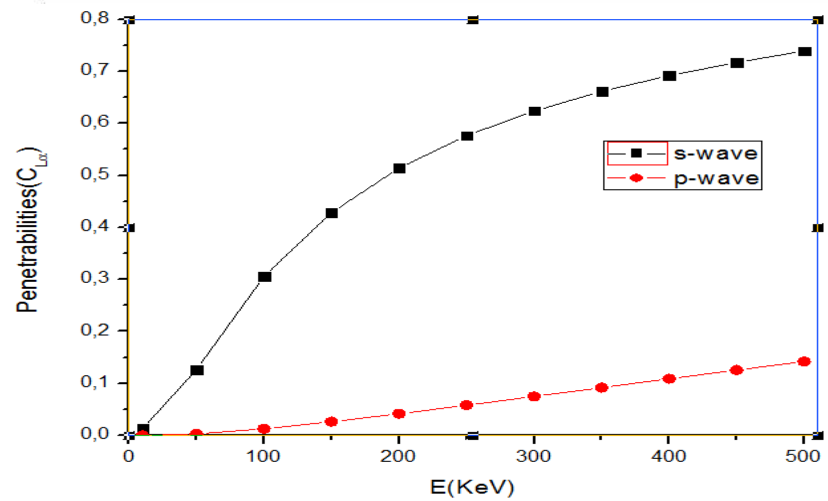
$$T_{\beta\alpha}(E) = C_{\ell_\alpha}(E)\ \hat{T}_{\beta\alpha}$$

$$C_{\ell_\alpha}(E) = \sqrt{P_{\ell_\alpha}(E)}\ \exp[i(\delta_{\ell_\alpha} + \varphi_{\ell_\alpha})]$$

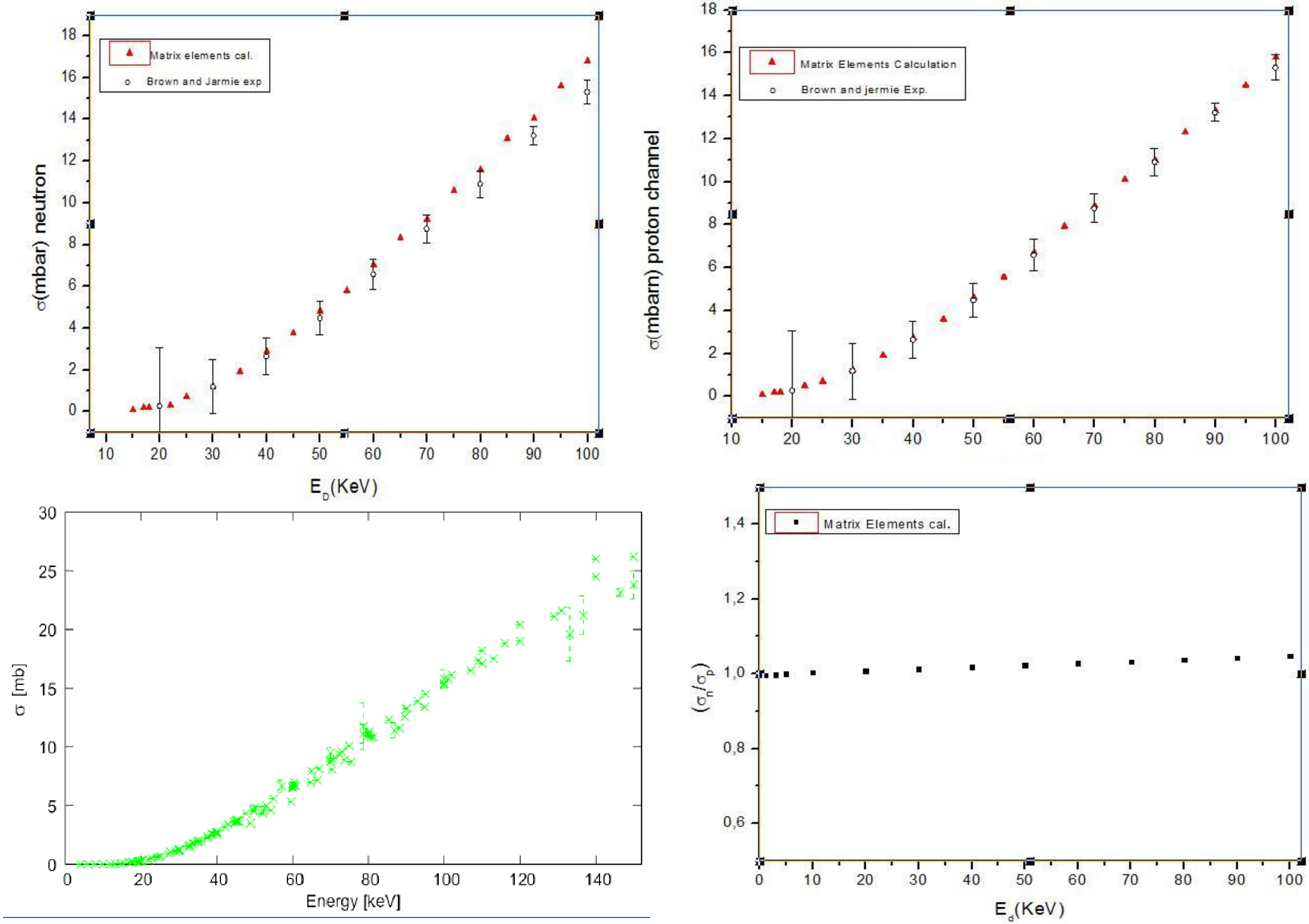
$$P_{\ell_\alpha}(E) = \frac{1}{F_{\ell_\alpha}(E)^2 + G_{\ell_\alpha}(E)^2}$$

	$S_\alpha = 0$ (Singlet)	$S_\alpha = 1$ (Triplet)	$S_\alpha = 2$ (Quintet)
$\ell_\alpha = 0$	$\alpha_0 = \langle {}^1S_0 \| 0^+ \| {}^1S_0 \rangle$		$\gamma_1 = \langle {}^5S_2 \| 2^+ \| {}^1D_2 \rangle$ $\delta_1 = \langle {}^5S_2 \| 2^+ \| {}^3D_2 \rangle$
$\ell_\alpha = 1$		$\alpha_{10} = \langle {}^3P_0 \| 0^- \| {}^3P_0 \rangle$ $\beta_{11} = \langle {}^3P_1 \| 1^- \| {}^1P_1 \rangle$ $\alpha_{11} = \langle {}^3P_1 \| 1^- \| {}^3P_1 \rangle$ $\alpha_{12} = \langle {}^3P_2 \| 2^- \| {}^3P_2 \rangle$ $\alpha_3 = \langle {}^3P_2 \| 2^- \| {}^3F_2 \rangle$	
$\ell_\alpha = 2$	$\alpha_2 = \langle {}^1D_2 \| 2^+ \| {}^1D_2 \rangle$ $\beta_2 = \langle {}^1D_2 \| 2^+ \| {}^3D_2 \rangle$		$\gamma_2 = \langle {}^5D_0 \| 0^+ \| {}^1S_0 \rangle$ $\gamma_3 = \langle {}^5D_2 \| 2^+ \| {}^1D_2 \rangle$ $\delta_2 = \langle {}^5D_1 \| 1^+ \| {}^3S_1 \rangle$ $\delta_3 = \langle {}^5D_1 \| 1^+ \| {}^3D_1 \rangle$ $\delta_4 = \langle {}^5D_3 \| 3^+ \| {}^3D_3 \rangle$ $\delta_5 = \langle {}^5D_2 \| 2^+ \| {}^3D_2 \rangle$

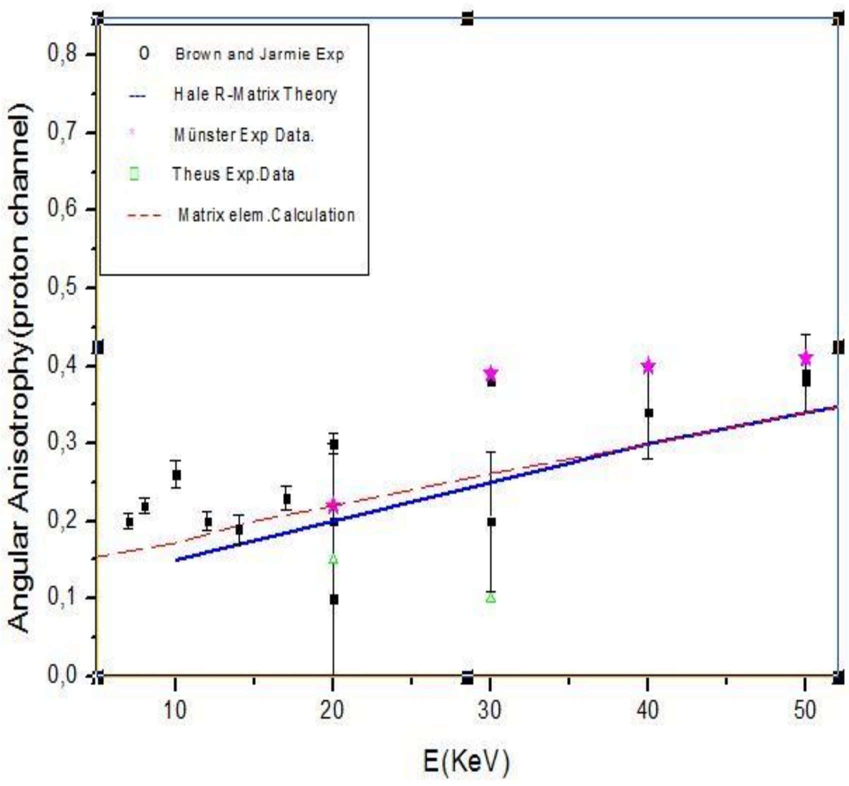


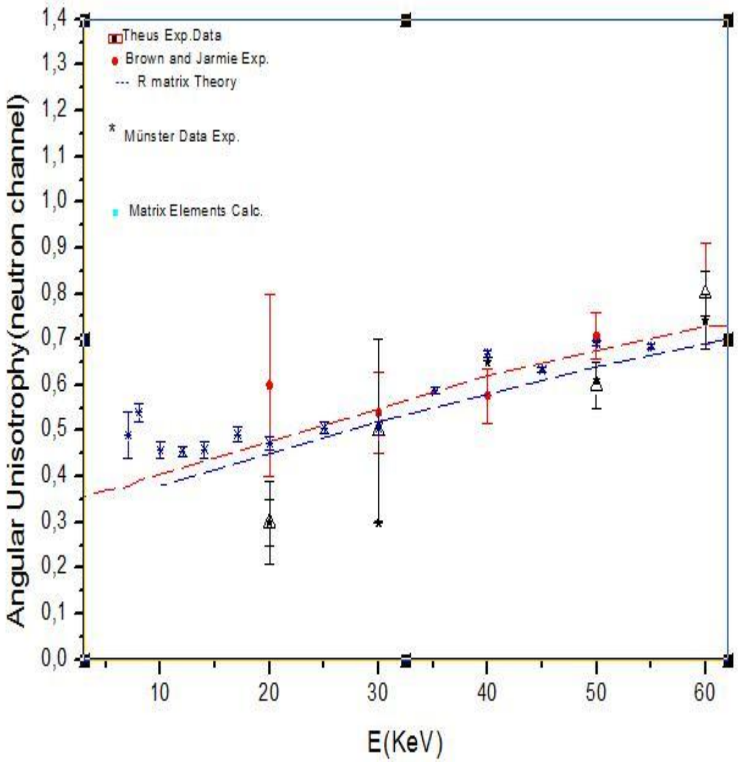


Cross sections for d+d reactions



Usual angular distrubiutions for d+d reactions





Electron screening

$$f_{lab}(E) = \frac{S_{screen}(E)}{S_{bare}(E)} \sim \exp(\pi\eta U_e/E)$$

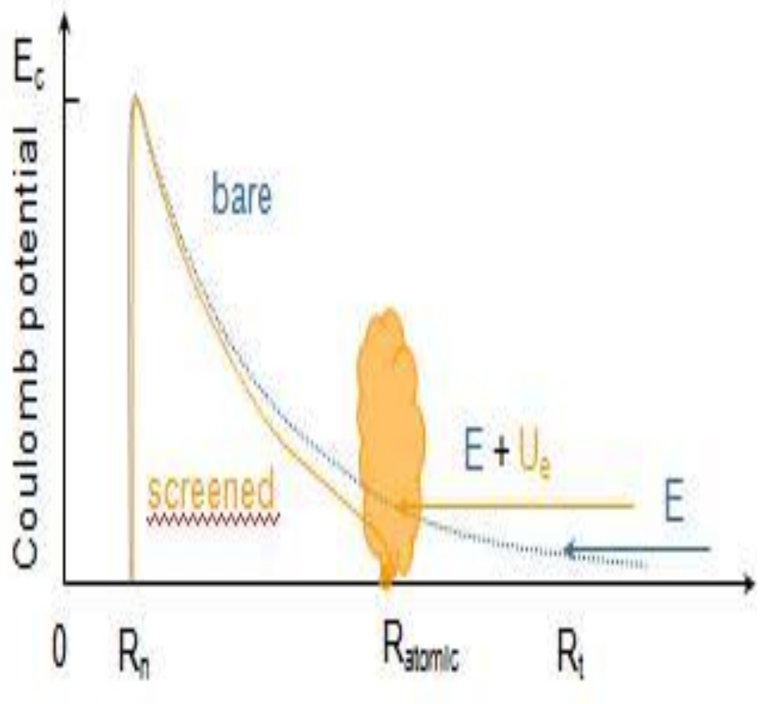
$$V(r) = \frac{Z_1 Z_2 e^2}{r}\phi(r)$$

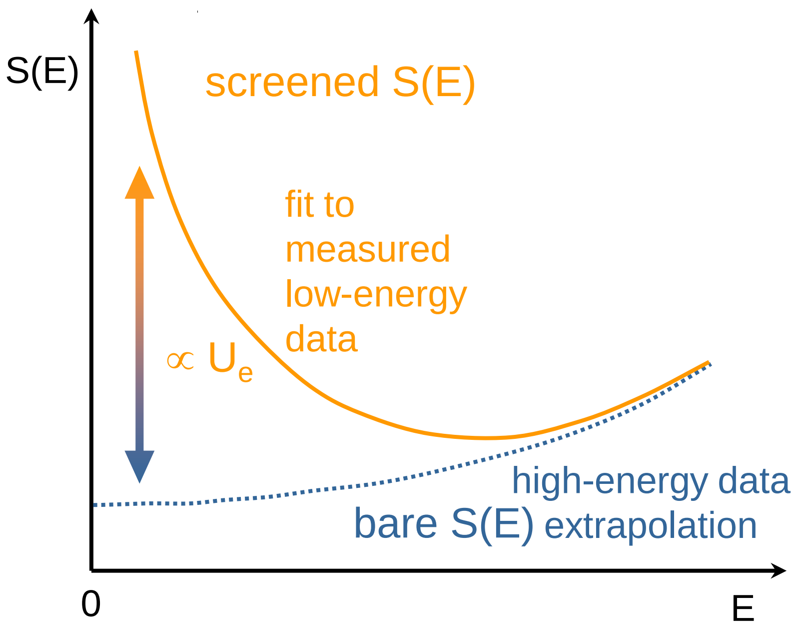
$$\phi(r) = e^{-\frac{r}{a}}$$

$$V(r) = \frac{Z_1 Z_2 e^2}{r}\left(1 - \frac{r}{a}\right) =$$

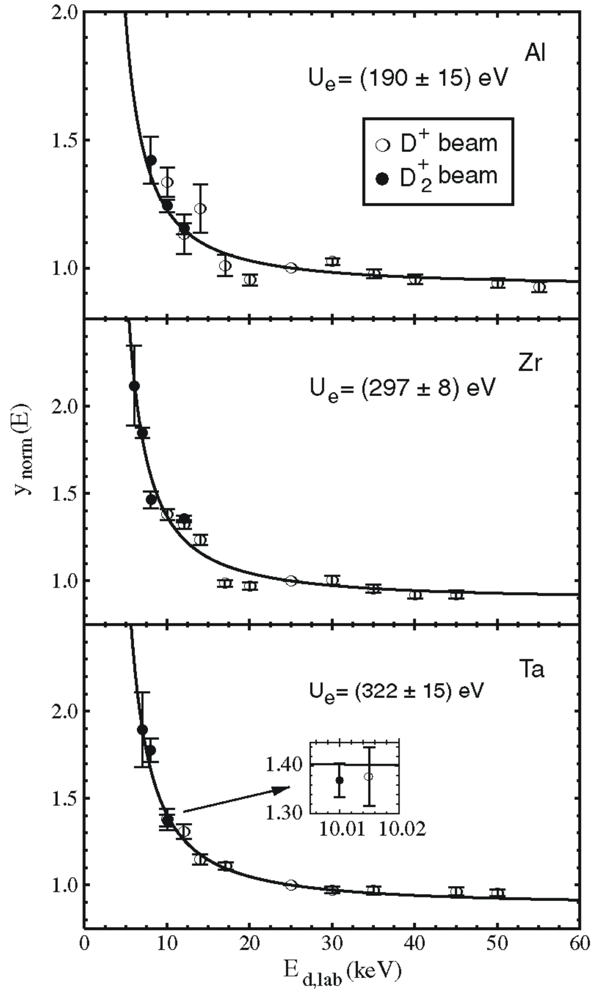
$$= \frac{Z_1 Z_2 e^2}{r} - \underbrace{\frac{Z_1 Z_2 e^2}{a}}_{U_e}$$

$$E_{eff} = E + U_e$$





Experimantal screening



d + d ⟶ ^{3}He + n

d + d ⟶ ^{3}H + p

metal target

NIC 1998, p. 152
Europhys. Lett. 54 (2001) 449

Similar results:

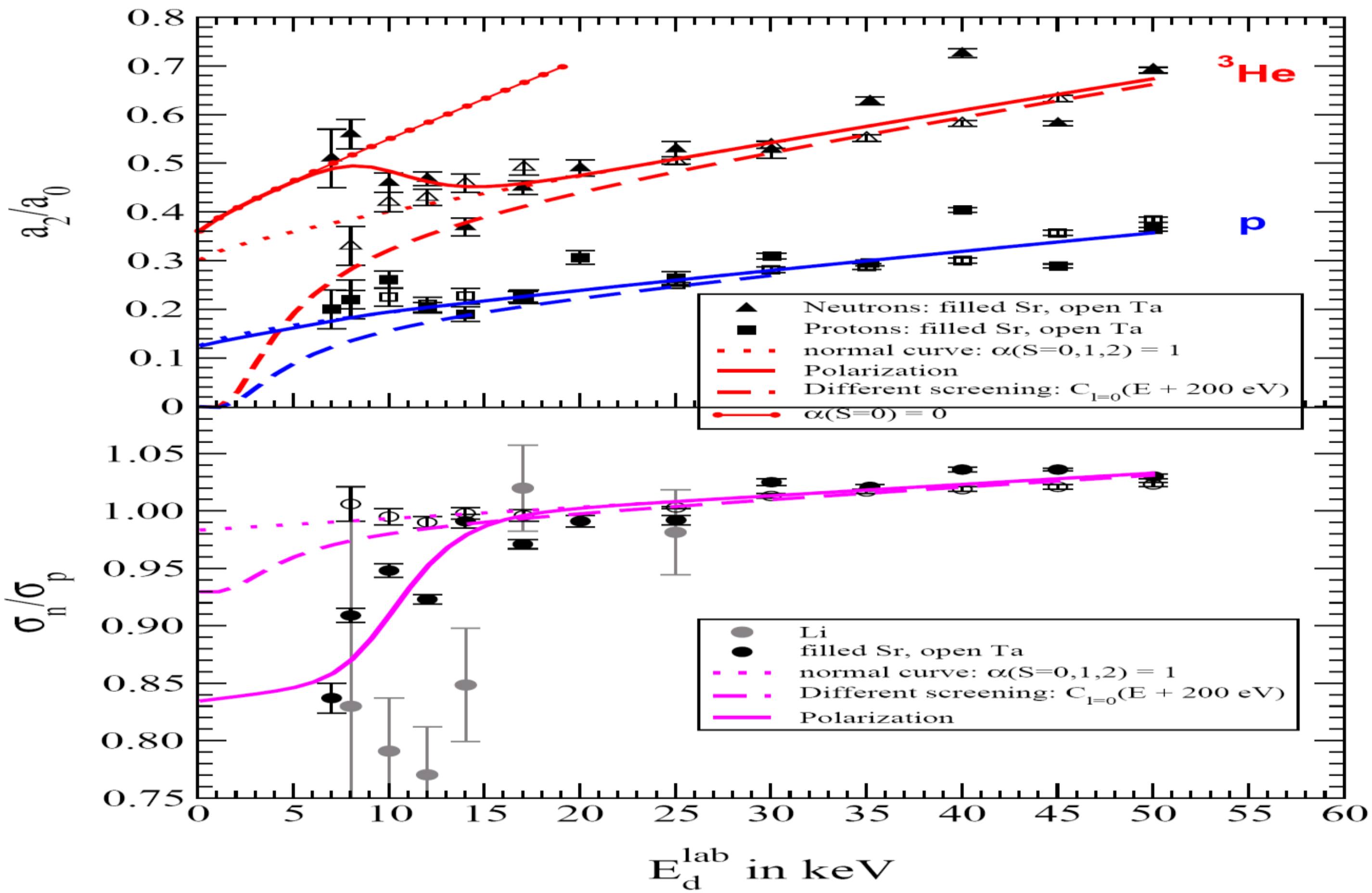
J. Kasagi et al.
LUNA Collaboration

U_e = 25±5 eV
U.Greife et al., Z.Phys. A351 (1995) 107

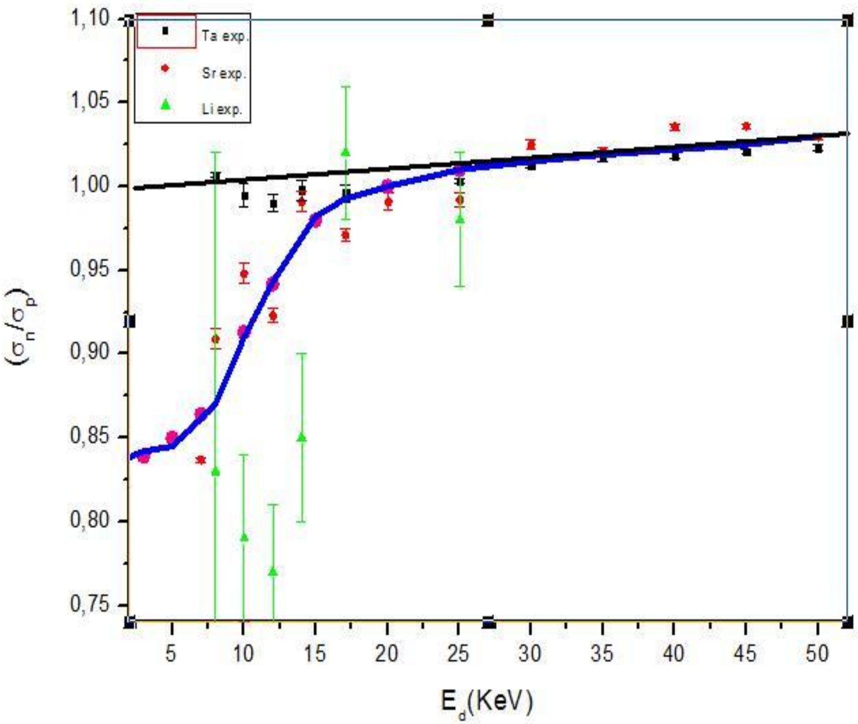
UHV experiments

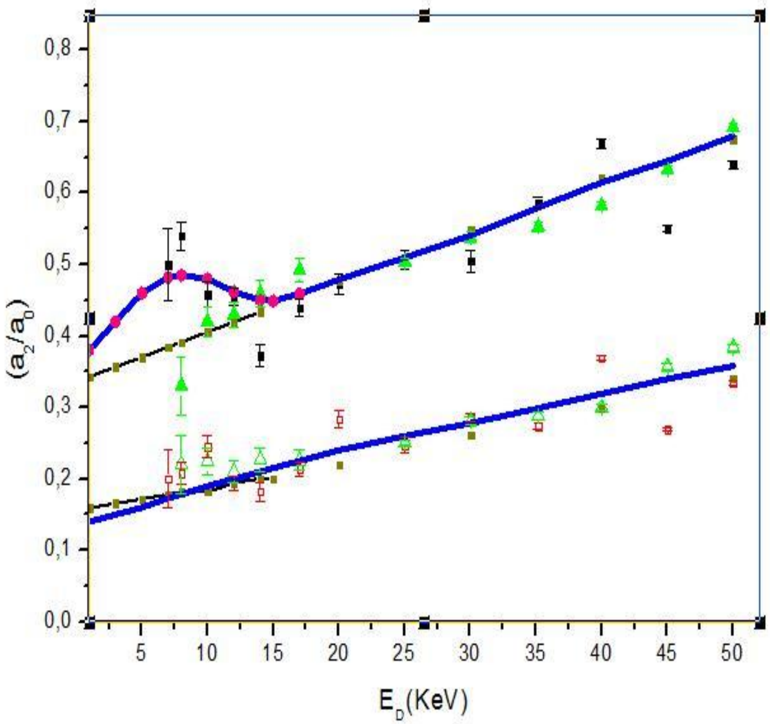
J.Phys. G, 2008

Experimental results of measurements in metals



Theoretical results for unsual branching ratio and angular distrubitions





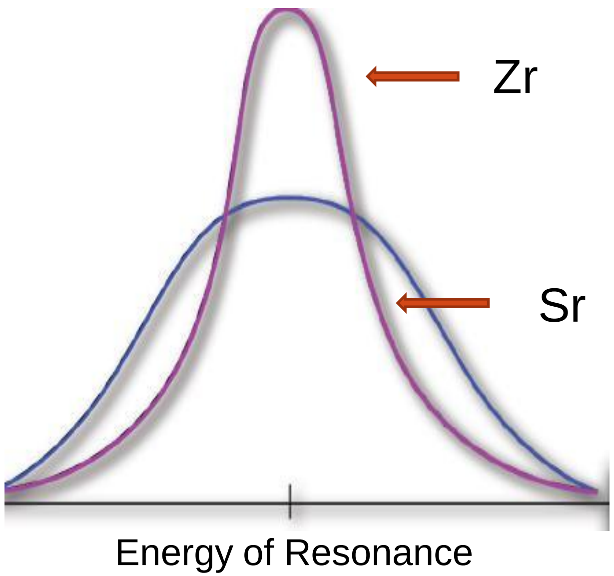
Single particle threshold resonance

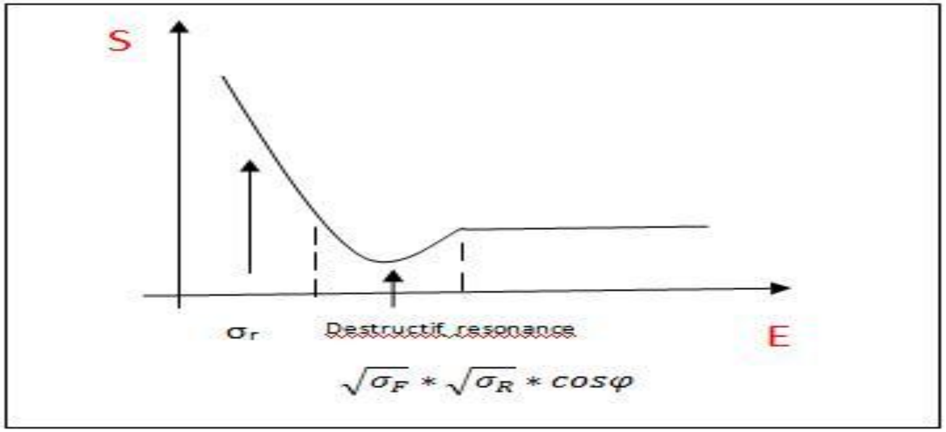
$$\sigma = (\sqrt{\sigma_F} + \sqrt{\sigma_R})^2 = \sigma_F + \sigma_R + 2\sqrt{\sigma_F}\sqrt{\sigma_R}cos\varphi$$

$$\sigma_R \sim \pi\lambda^2\omega\frac{\Gamma_a * \Gamma_b}{(E - E_{R)} + \frac{\Gamma^2}{4}} \qquad Tg\varphi = \frac{\Gamma}{2(E - E_0)}$$

$$\Gamma_D \gg \Gamma_P \approx \Gamma_n \qquad E \gg E_0 \qquad E \gg \Gamma$$

new resonance at He^4 $\qquad \sigma = \sigma_F + c(1 - \frac{a}{E^2})$





Conclusions

- Simple physical theory, interplay between the electron screening and the resonance excitation, based on known effects, to verify in accelerator experiments, can explain the branching ratio and the angular distributions of the D+d reactıons
- The resonance contribution can explain the enhanced electron screening effect observed in metallic environments
- Experiments with atomically clean target are needed