Electron Screening

Electron Screening in a Nutshell

- **phenomenon**: electrons in stellar plasma or atomic environment lower the Coulomb barrier between nuclei and enhance fusion cross sections (at low energies)

- **impact**: critical as it alters reaction rates; affects astrophysical models, stellar evolution, nucleosynthesis and lab experiments

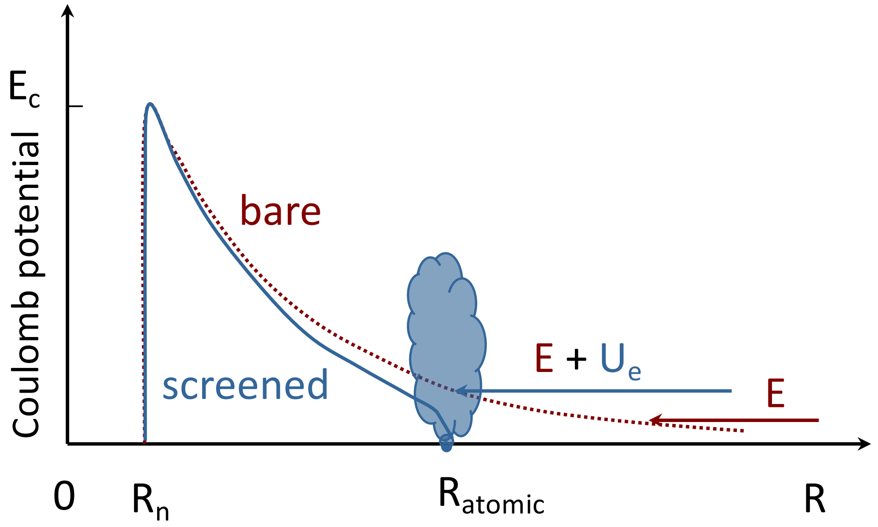
- **status**: despite theoretical developments over past 30 years, discrepancies remain between predicted and experimental screening potentials ("electron screening puzzle")

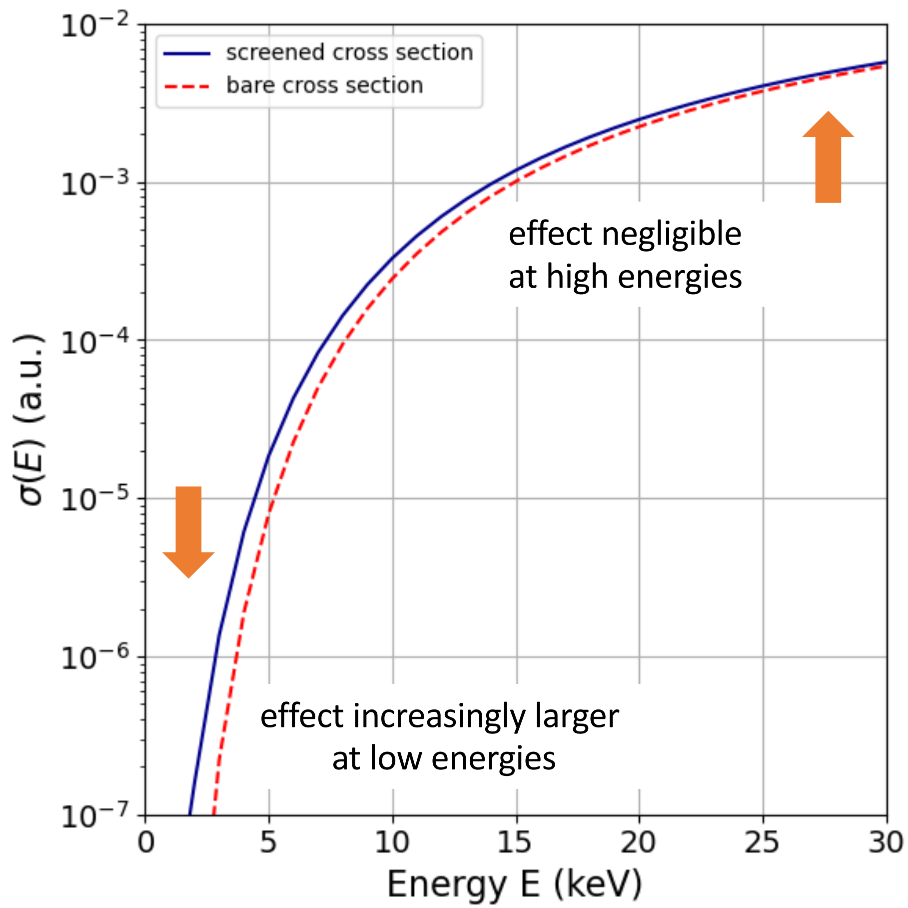
- **note**: laboratory screening different from screening in stars; accurate bare cross section data critical

Nuclear Reactions in Stars (and in the Lab)

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

assumption: $2\pi\eta \sim Z_1 Z_2 (m/E)^{½}$ bare nuclei





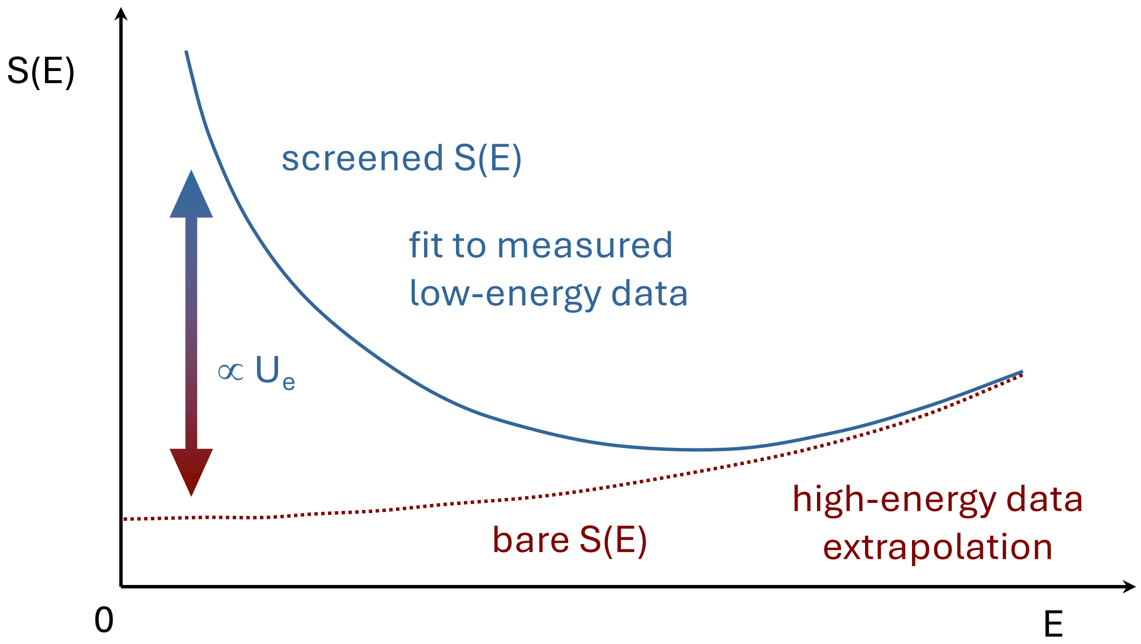
SCREENING POTENTIAL U_e: typically, small amount (~ 10-100 eV)

⇒ corrections typically negligible

⇒ except for ultra-low energies

Enhancement Factor and Screening Potential U_e

$$f_{lab}(E) = \frac{\sigma_s(E)}{\sigma_b(E)} = \frac{S_s(E)}{S_b(E)} \sim \exp\left[\pi\eta \frac{U_e{}^{(lab)}}{E}\right]$$



Remarks:

accurate bare cross section is needed:

- to determine U_e
- to correct for screening effects in plasmas (may be different from lab)

$$\sigma_{pl}(E) = \sigma_b(E)\, f_{pl}(E)$$

experimental U_e values in excess of theoretical limit! → **Electron Screening Puzzle**

How to determine U_e?

Experimentally:

- extrapolation from high-energy cross section data to obtain bare cross section
- measurement of cross sections at lowest accessible energy
- U_e obtained from relative enhancement

Theoretically:

- Adiabatic Limit: assumes effectively static electrons (largest screening estimates)
- Dynamic Models: considers time-dependent interactions

discrepancies between theory and experiments remain

Theoretical Approach: The Adiabatic Limit

Z. Phys. A – Atomic Nuclei 327, 461–468 (1987)

Zeitschrift für Physik A
Atomic Nuclei

Effects of Electron Screening on Low-Energy Fusion Cross Sections

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C. Rolfs
Institut für Kernphysik, Universität Münster, Federal Republic of Germany

Adiabatic Limit:

$U_e = Z_1 Z_2 e^2 / R_{atom}$

$$E_{\text{eff}} = E + U_{\text{e}}$$

$$E_{\text{eff}} = E + E_{\text{el}}(A+B) - E_{\text{el}}(A) - E_{\text{el}}(B)$$

total electron binding energy of combined atom (ejectile)

projectile

target

ATOMIC DATA AND NUCLEAR DATA TABLES **18**, 243–291 (1976)

NEUTRAL-ATOM ELECTRON BINDING ENERGIES FROM RELAXED-ORBITAL RELATIVISTIC HARTREE-FOCK-SLATER CALCULATIONS $2 \leq Z \leq 106$*

KEH-NING HUANG

Z		CONFIGN	E(TOT)
2	HE	1S2	-2.86197
3	LI	2S1	-7.42896
4	BE	2S2	-14.56910
5	B	2P1	-24.52970
6	C	2P2	-37.64532
7	N	2P3	-54.30335
8	O	2P4	-74.80112
9	F	2P5	-99.47060
10	NE	2P6	-128.65249
11	NA	3S1	-162.03769
12	MG	3S2	-199.88575
13	AL	3P1	-242.27341
14	SI	3P2	-289.37845
15	P	3P3	-341.40090
16	S	3P4	-398.49065
17	CL	3P5	-460.81321
18	A	3P6	-528.53143
19	K	4S1	-601.35306

binding energy values are tabulated

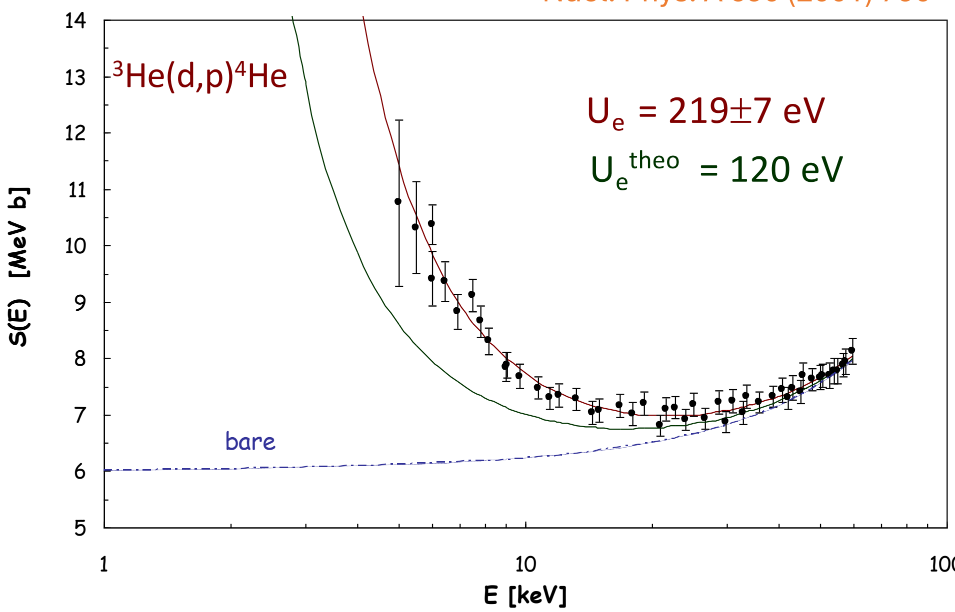
→ U_e can be easily calculated

A Key Example: The $^3He(d,p)^4He$ Reaction

Electron screening effect in the reactions
$^3He(d,p)^4He$ and $d(^3He,p)^4He$ ☆

M. Aliotta[a,1], F. Raiola[a], G. Gyürky[b], A. Formicola[a], R. Bonetti[c], C. Broggini[d], L. Campajola[e], P. Corvisiero[f], H. Costantini[f], A. D'Onofrio[g], Z. Fülöp[b], G. Gervino[h], L. Gialanella[e], A. Guglielmetti[c], C. Gustavino[i], G. Imbriani[e,j], M. Junker[i], P.G. Moroni[f], A. Ordine[e], P. Prati[f], V. Roca[e], D. Rogalla[a], C. Rolfs[a], M. Romano[e], F. Schümann[a], E. Somorjai[b], O. Straniero[k], F. Strieder[a], F. Terrasi[g], H.P. Trautvetter[a], S. Zavatarelli[f]

Nucl. Phys. A 690 (2001) 790

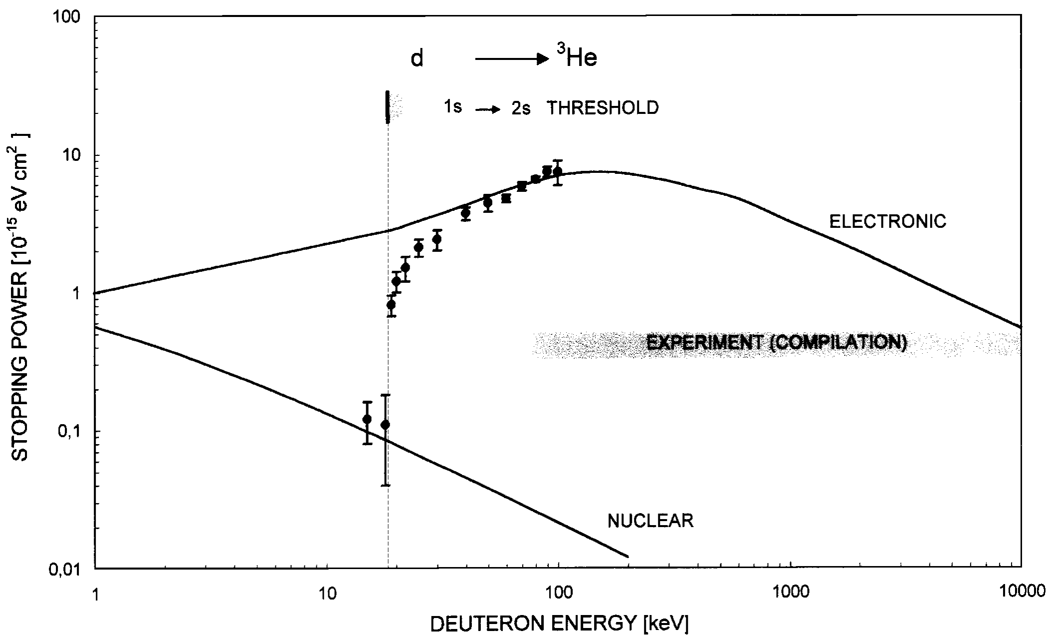


Short note

Energy loss of deuterons in ^3He gas: a threshold effect

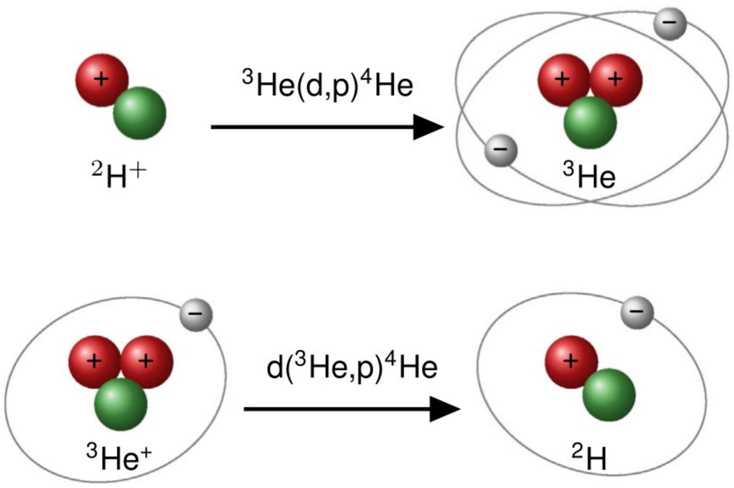
A. Formicola[1], M. Aliotta[1,a], G. Gyürky[2], F. Raiola[1], R. Bonetti[3], C. Broggini[4], L. Campajola[5], P. Corvisiero[6], H. Costantini[6], A. D'Onofrio[7], Z. Fülöp[2], G. Gervino[8], L. Gialanella[5], A. Guglielmetti[3], C. Gustavino[9], G. Imbriani[5,10], M. Junker[9], A. Ordine[5], P. Prati[6], V. Roca[5], D. Rogalla[1], C. Rolfs[1,b], M. Romano[5], F. Schümann[1], E. Somorjai[2], O. Straniero[11], F. Strieder[1], F. Terrasi[7], H.P. Trautvetter[1], and S. Zavatarelli[6]

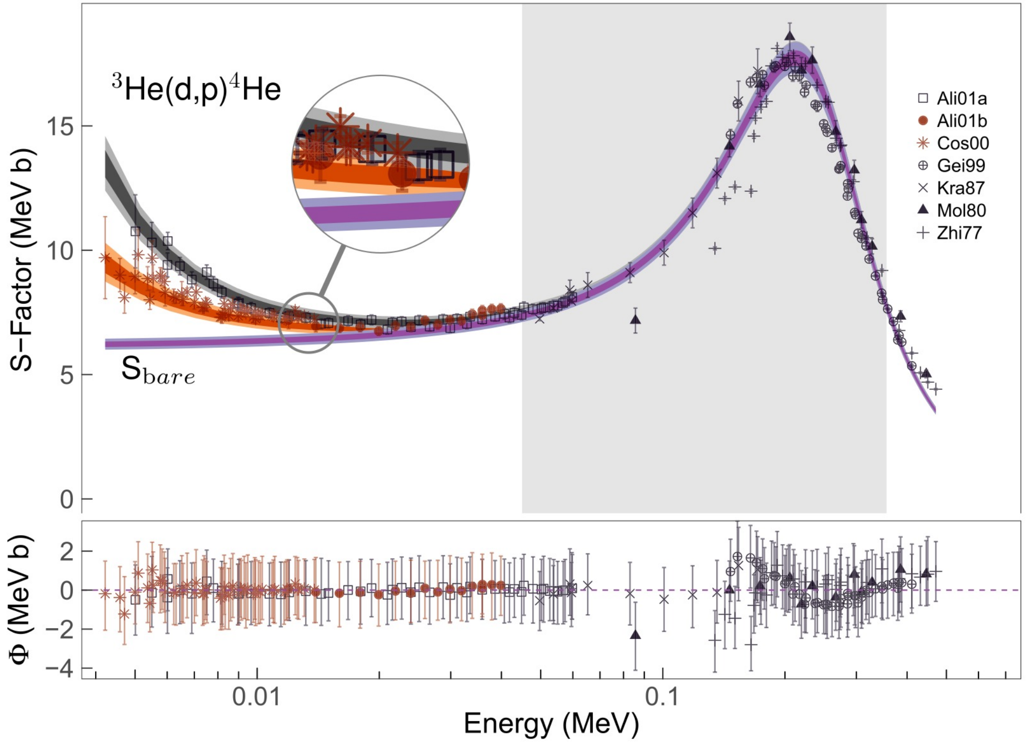
Eur. Phys. J. A 8 (2000) 443



Remarks

inverting role of target and projectile typically leads to different screening effects



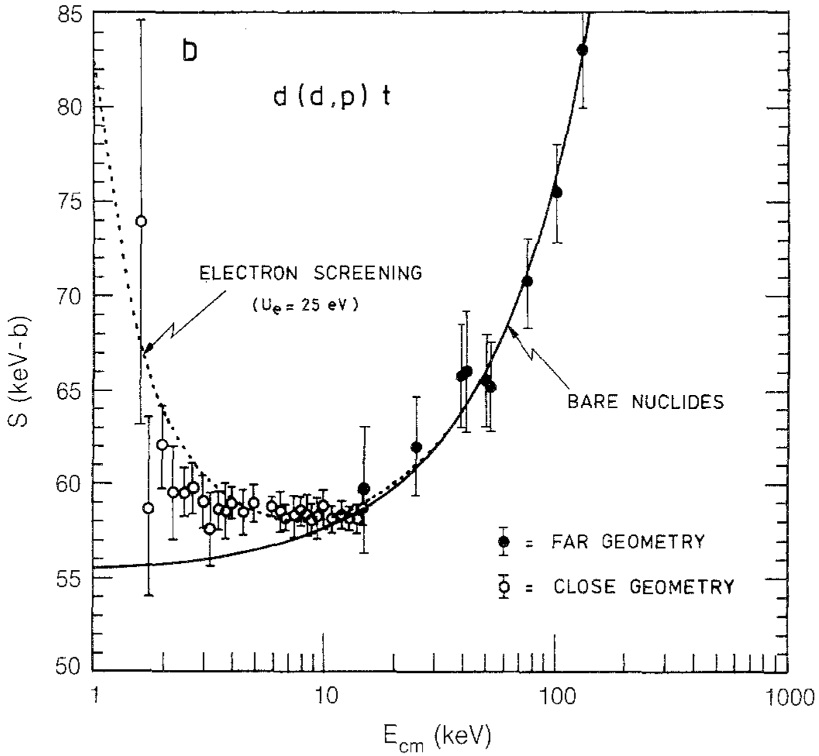


deSouza, Iliadis, Coc, ApJ 872 (2019) 75

The D(d,p)t Reaction

in D_2 gas

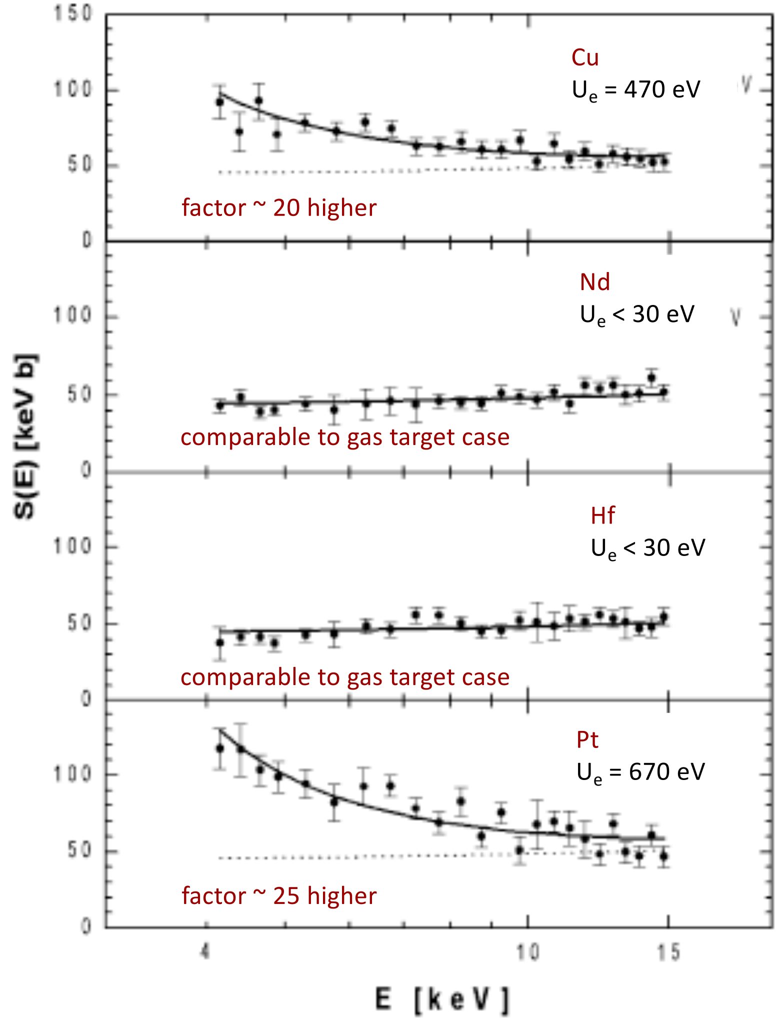
U_e = 15 ± 5 eV in fair agreement with adiabatic limit (U_e = 20-30 eV)



Greife et al. ZPhys. A351 (1995) 107

in metallic hosts

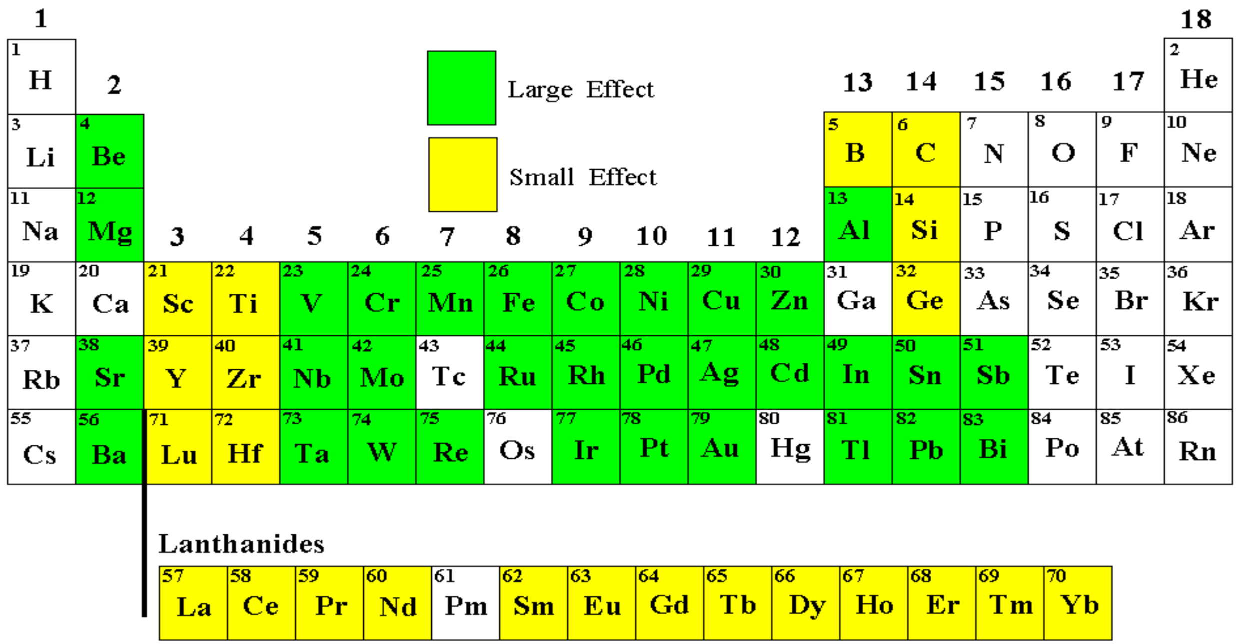
different values in different hosts; some U_e >> 100 eV



Raiola et a. EPJA 19 (2004) 283

D(d,p)t Reaction in Metals, Insulators, and Semiconductors

55 samples
in total



F. Raiola et al.: Eur. Phys. J A19 (2004) 283

Key Results:

- elements in same group show similar U_e values
  - large effect ~ 300 eV (ca. 10x higher than in D_2 gas)
  - small effect ~ 30 eV (as in D_2 gas)
- exceptions: group 13 (B = metalloid) and group 14 (C, Si, Ge = semiconductors)

possible explanation based on Debye model applied to electrons in metals

Debye Model for Quasi-Free Electrons in Metals

using Debye's plasma theory (as for electron screening in stars):

quasi-free electrons in metals cluster around deuterons at a distance R_D (Debye radius):

$$R_D = \sqrt{\frac{\varepsilon_0 kT}{e^2 n_{eff} \rho_a}} = 69\sqrt{\frac{T}{n_{eff}\rho_a}} \quad [m]$$

n_{eff} = number of quasi-free electrons/atom (typically 1 for most metals)

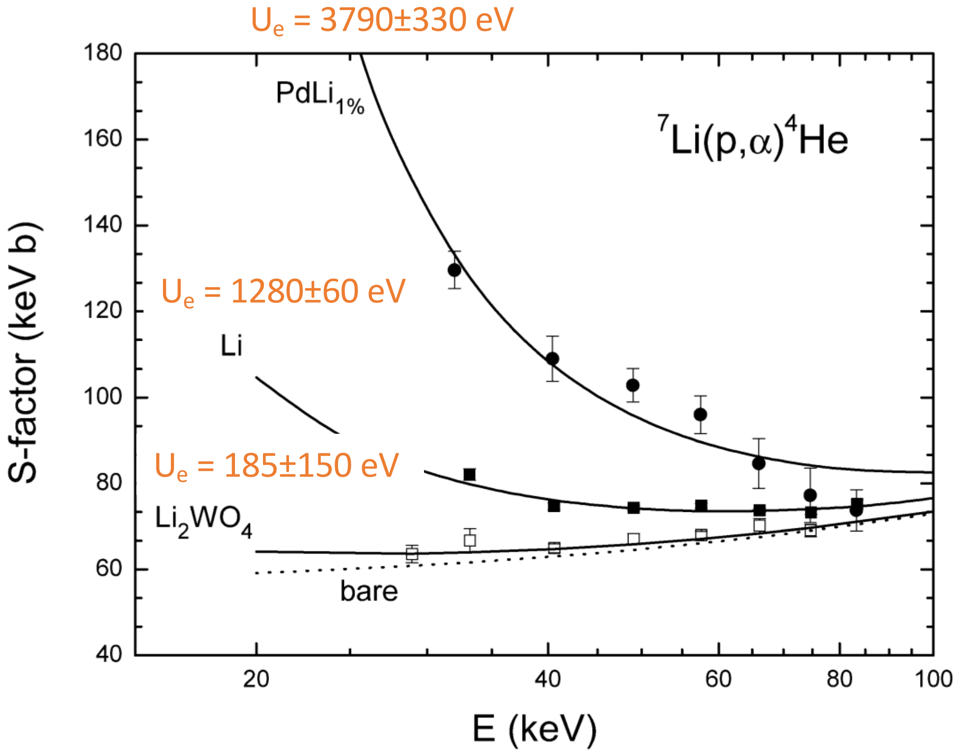
ρ_a = atomic density (typically 6×10^{28} m^{-3})

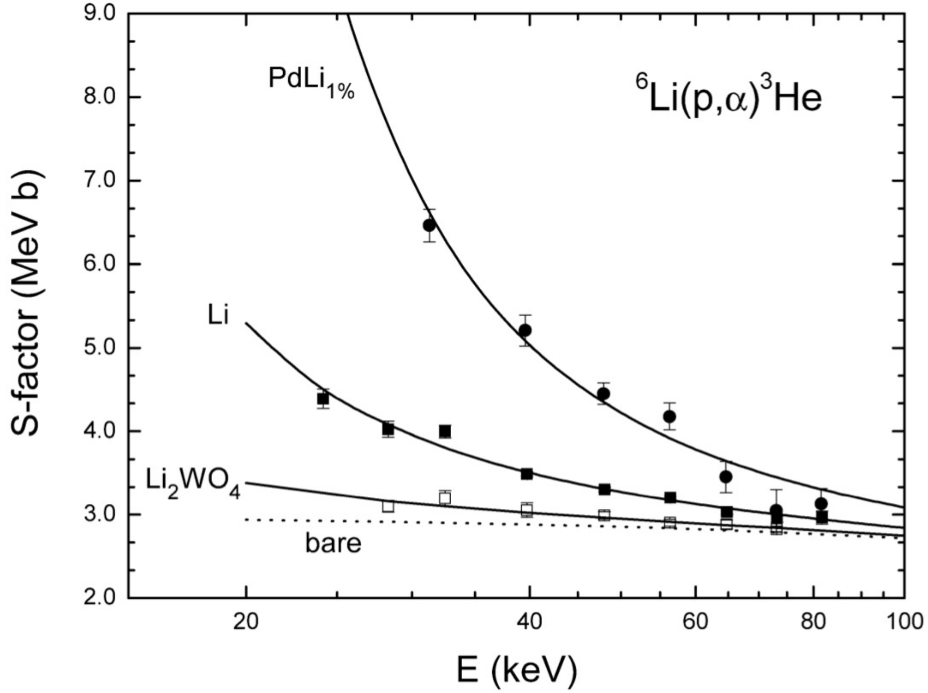
at room temperature (T ~ 300 K): $R_D \sim 0.1\ R_a$ → extra increase of U_e (Debye enhancement)

$R_D \sim 1/10\ R_a \quad \Rightarrow \quad U_{e,D} \cong Z_1 Z_2 e^2/R_D$ ($U_{e,D}$ ~ 300 eV for d+d in metals)

see: Bonomo et al NPA 719 (2003) 37c and Cruz et al. Phys Lett B 624 (2005) 181 for more details

Experimental Verification for $^{6,7}Li(p,\alpha)^{3,4}He$





Cruz et al. Phys Lett B 624 (2005) 181

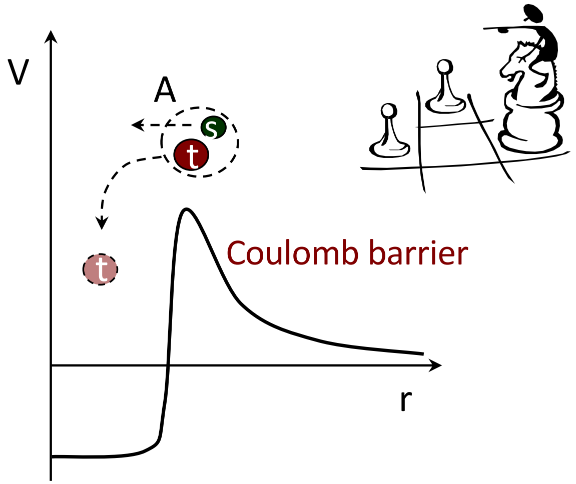
additional (Debye) enhancement observed in Li metal and Li alloy (PdLi)

isotopic independence of electron screening also verified

Other Experimental Efforts

Trojan Horse Method (indirect method)

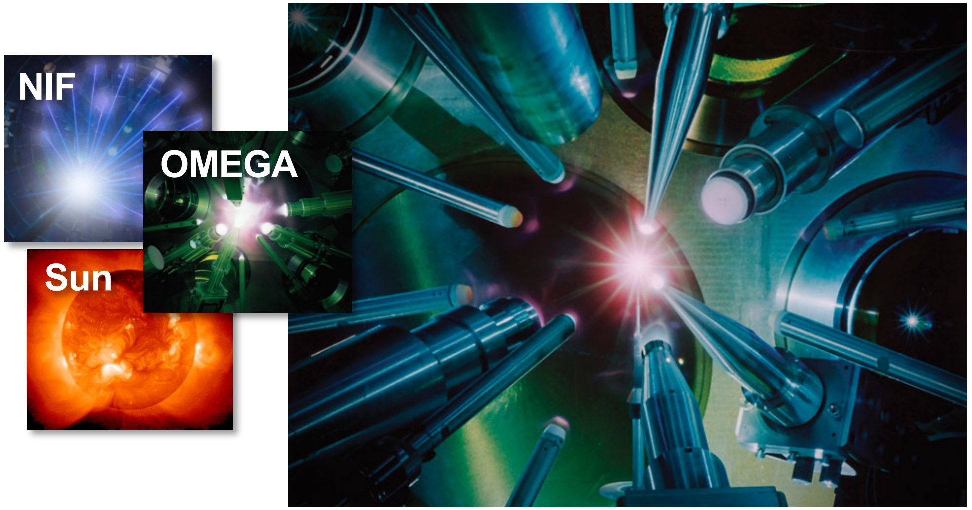
suitable 3-body reaction as a proxy for
2-body reaction of astrophysical interest



reaction occurring in nuclear field of target nucleus
→ free from electron screening effect
→ bare cross section

Inertial Confined Fusion (National Ignition Facility)

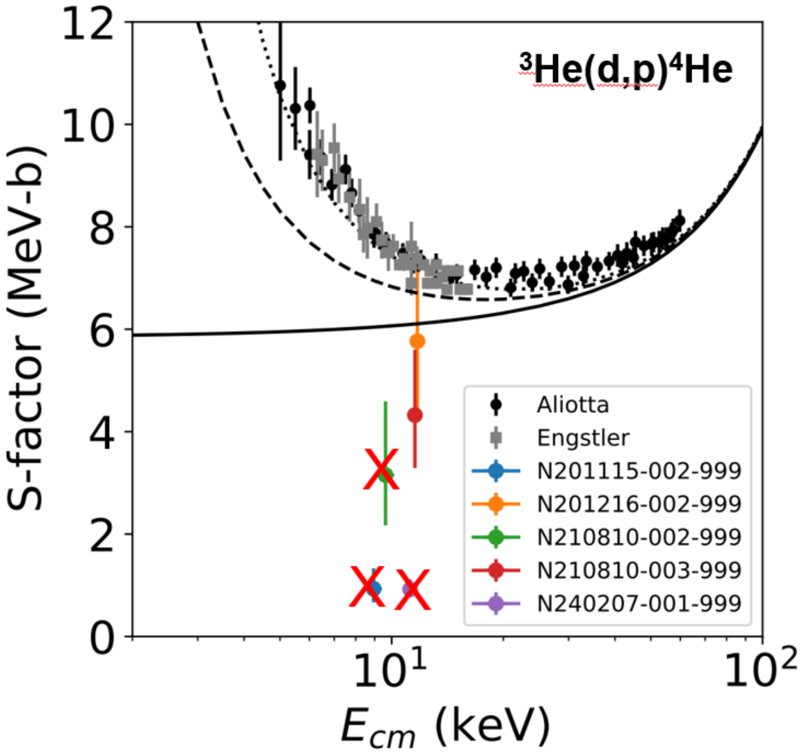
attempt at measuring plasma screening
in nuclear reactions at NIF and OMEGA



temperature and density conditions achieved,
but screening effect still too weak to be measured
huge technical challenges remain

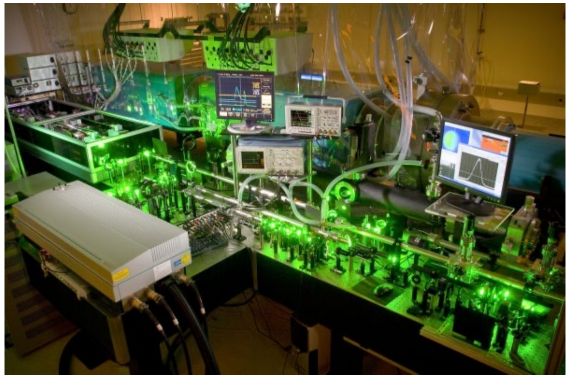
Other Experimental Efforts (Results)

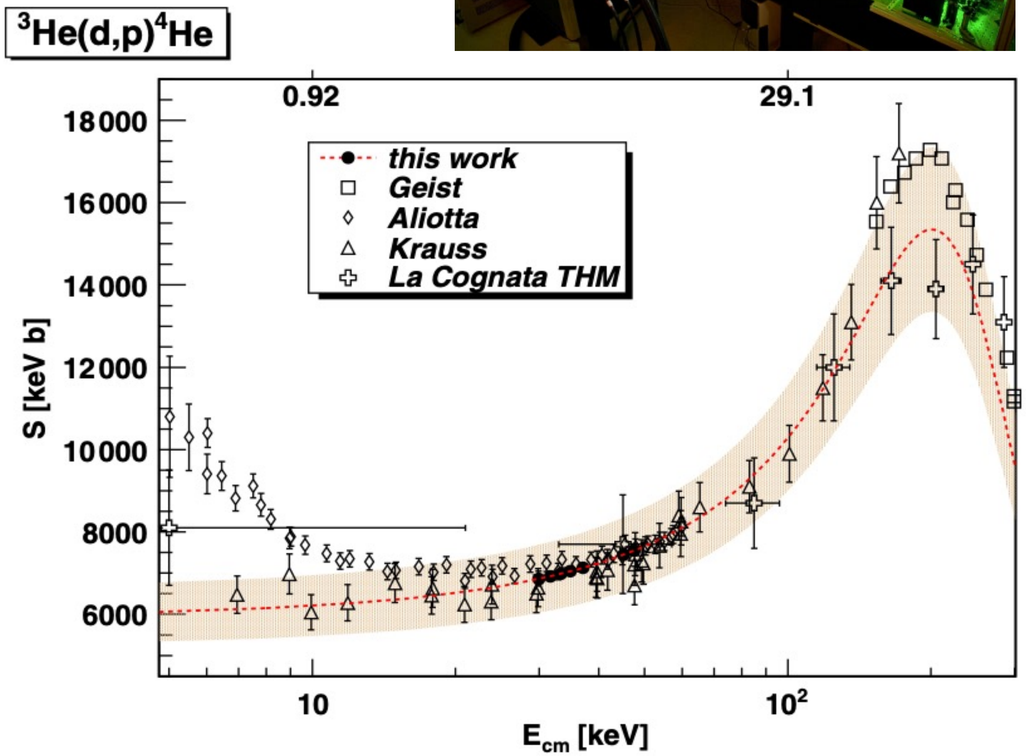
NIF shots



Gatu Johnson (private comm.)

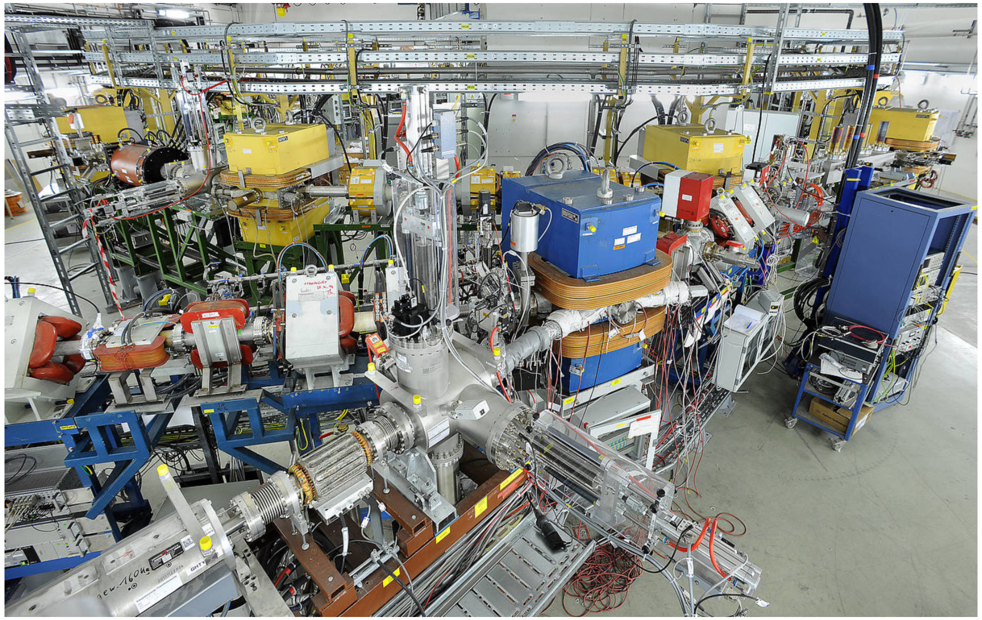
Centre for High-Energy
Density Science
University of Texas





Barbui et al PRL 111 (2013) 082502

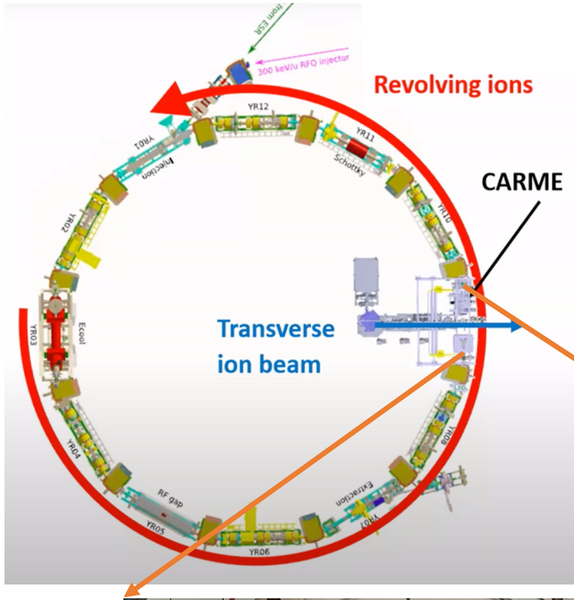
Other Experimental Efforts

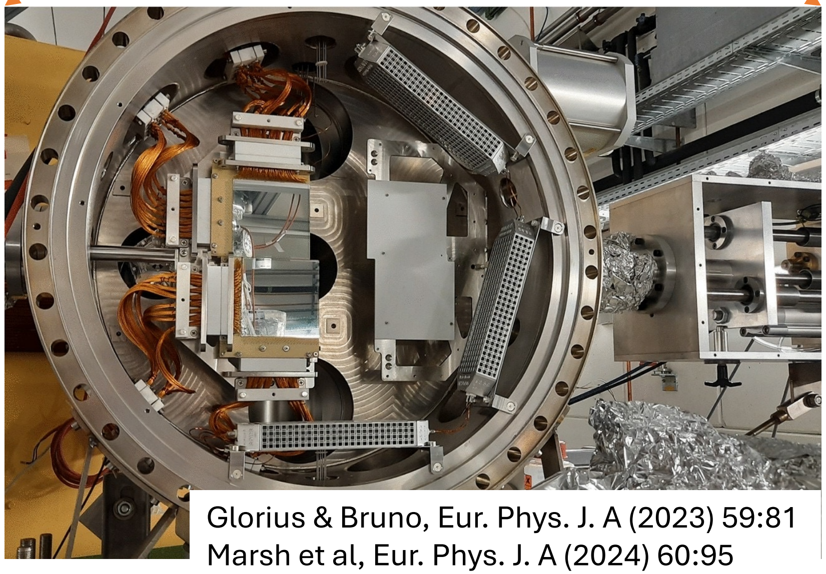


CRYRING facility at GSI

experiments with

- crossed beams for bare cross sections at stellar energies
- jet target for screened cross sections measurements



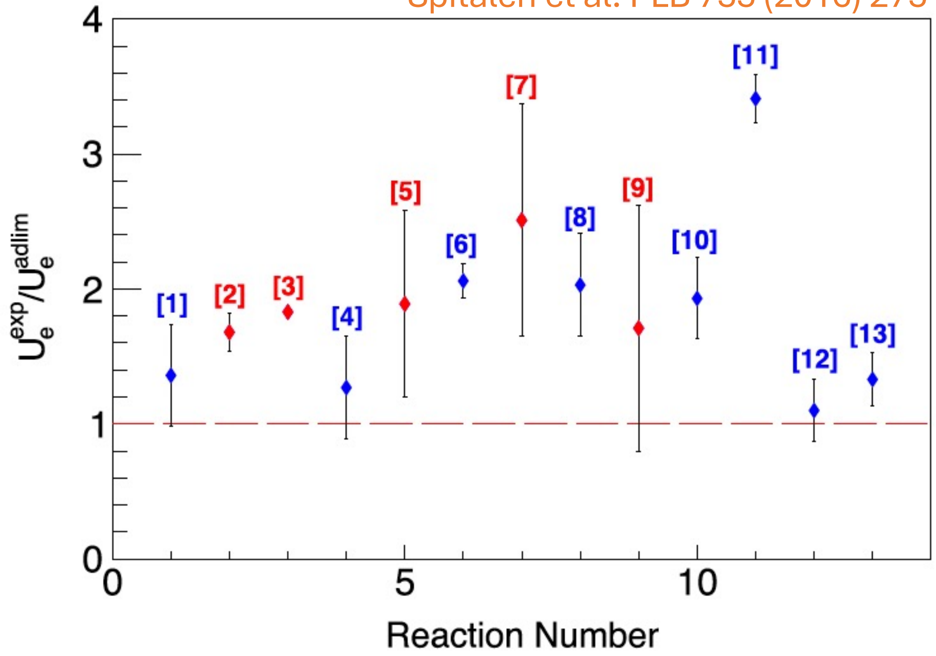


Glorius & Bruno, Eur. Phys. J. A (2023) 59:81
Marsh et al, Eur. Phys. J. A (2024) 60:95

Electron Screening Puzzle

For many reactions, experimental U_e values are exceed theoretical (adiabatic) limits

Spitaleri et al. PLB 755 (2016) 275



	Reaction	U_e^{adlim} (eV)	U_e^{exp} (eV)	Note	Ref.
[1]	$^2H(d,t)^1H$	14	19.1±3.4		[16,17]
[2]	$^3He(d,p)^4He$	65	109±9	D_2 gas target	[18]
[3]	$^3He(d,p)^4He$	120	219±7		[18]
[4]	$^3He(^3He,2p)^4He$	240	305±90	compilation	[2]
[5]	$^6Li(d,\alpha)^4He$	175	330±120	H gas target	[19]
[6]	$^6Li(d,\alpha)^4He$	175	330±49		[19,20]
[7]	$^6Li(p,\alpha)^3He$	175	440±150	H gas target	[19]
[8]	$^6Li(p,\alpha)^3He$	175	355±67		[19,21,22]
[9]	$^7Li(p,\alpha)^4He$	175	300±160	H gas target	[19]
[10]	$^7Li(p,\alpha)^4He$	175	363±52		[19,21,23]
[11]	$^9Be(p,\alpha_0)^6Li$	240	788±70		[24,25]
[12]	$^{10}B(p,\alpha_0)^7$	340	376±75		[26,27]
[13]	$^{11}B(p,\alpha_0)^8Be$	340	447±67		[26,28]

see also: Vesić, Particles 7 (2024) 834 for an extensive review

Possible Solutions for Electron Screening Puzzle?

stopping power values

hard to measure at ultra low energies --> extrapolations from high energy data often used; are these reliable?

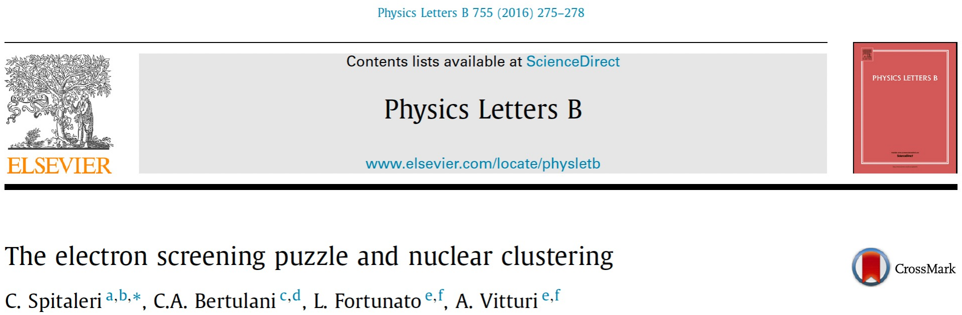
atomic effects in beam-target interactions

'channelling'
target type (solid, gas, atomic, molecular)
atomic physics models

assumed nuclear reaction models

dynamic effects?
nuclear structure?

Can Nuclear Clustering provide Additional ‘Screening’?


Physics Letters B 755 (2016) 275–278

Contents lists available at ScienceDirect

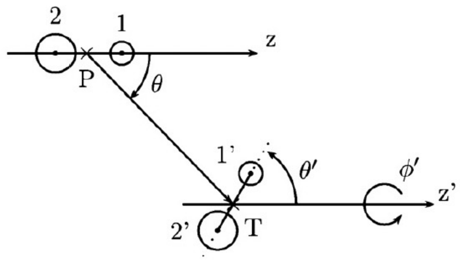
Physics Letters B

www.elsevier.com/locate/physletb

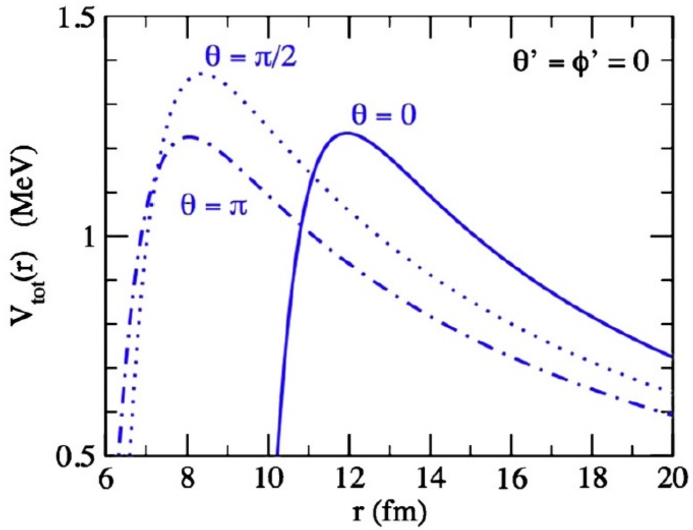
The electron screening puzzle and nuclear clustering

C. Spitaleri [a,b,*], C.A. Bertulani [c,d], L. Fortunato [e,f], A. Vitturi [e,f]

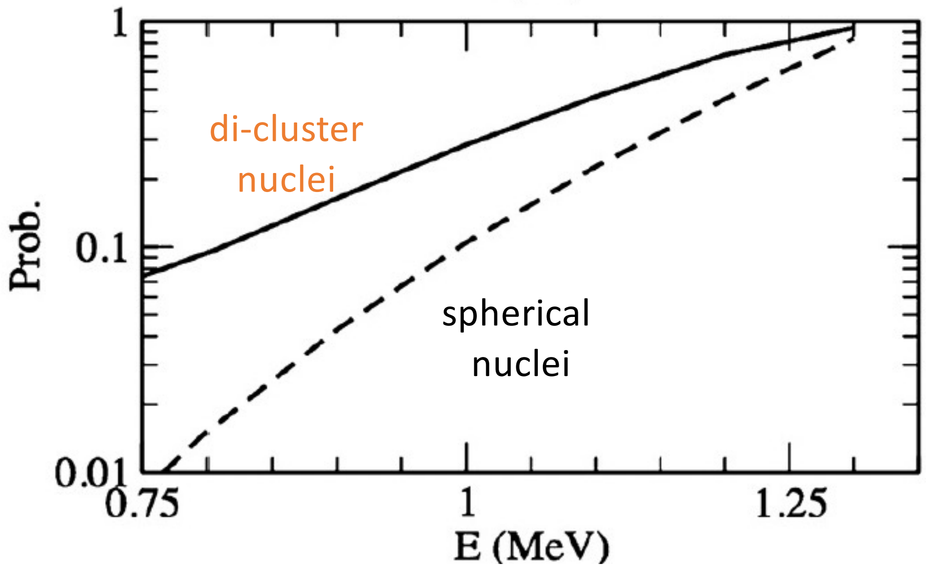
di-cluster orientation



modified Coulomb barrier



enhanced fusion probability



Relevance to this ERC

Idea:
investigate screening in reactions with highly clustered nuclei, but involving different isotopes

Examples:	$^{6}Li + \alpha$	$^{6}Li + d$	$^{10}B + \alpha$	$^{10}B + d$
	$^{7}Li + \alpha$	$^{7}Li + d$	$^{11}B + \alpha$	$^{11}B + d$

if enhancement is purely atomic, no difference should be observed (isotopic independence)

if different enhancements observed → hint for nuclear clustering effects?

low-energy experiments are tough; theoretical developments possible?

Summary

Electron screening effect very important at low energies

screening in stellar plasma different from screening in the lab

major experimental (and theoretical) work but discrepancies remain

nuclear clustering effects still largely unexplored → possible theoretical breakthrough?

			ERC-NUCLEAR Kick-off Event - 15 May 2025	
09:30	09:45		**welcome and introductions**	Marialuisa (MLA)
09:45	10:00		ERC Overview	MLA
10:00	10:40		Scientific Goals	Michael + MLA
10:40	11:00		discussion	
11:00	11:30		coffee break	
			Experimental Programme	
11:30	12:00		10B(a,p) and 10B(a,d)	Jamie
12:00	12:30		10B(a,n)	Rhys
12:30	13:00		6,7Li(a,g)	Alessandro
13:00	14:00		Lunch & Photo	
			Computational Programme	
14:00	14:40		First Stars: Stellar Models and Nucleosynthesis	Marco
			Theoretical Programme	
14:50	15:30		Reactions with clusters	Guillaume
15:30	16:00		Coffee Break	
16:00	16:40		R-matrix developments	James
16:40	17:00		Closing Remarks and Next Steps	
19:30			Dinner at Nok's Kitchen by the Castle	