Electron screening effects in nuclear reactions and radioactive decays

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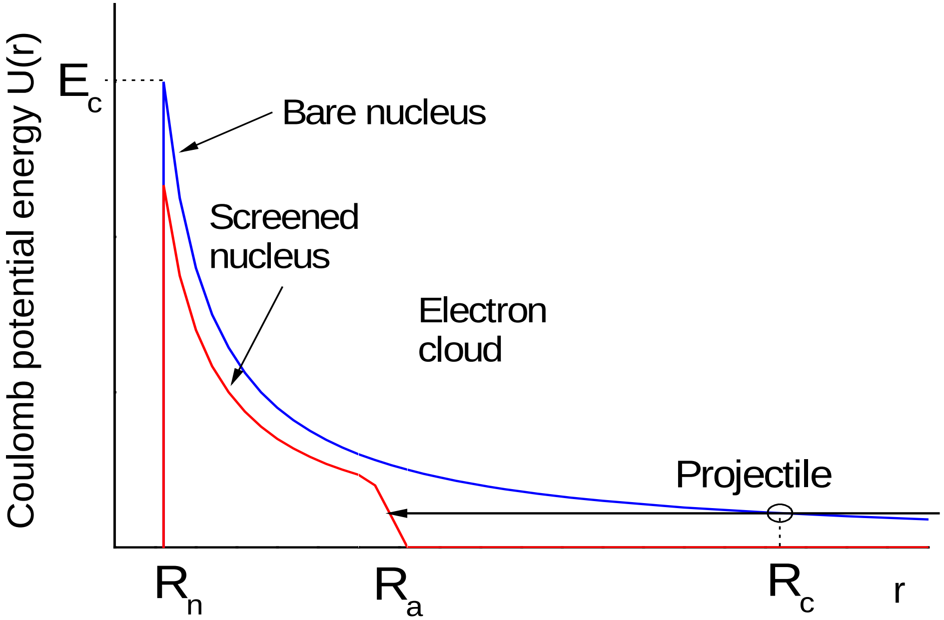
Electron screening

-Nuclear fusion reactions between charged particles

- Sub-Coulomb energies

- Enhancement by the electron clouds surrounding the interacting nuclides



Effective potential energy of Yukawa type, U_{eff}, between two charges Z_1 and Z_2:

$$U_{eff}(r) = \frac{1}{4\pi\varepsilon_0}\frac{Z_1 Z_2 e^2}{r}\exp\left(-\frac{r}{R}\right) \approx \frac{1}{4\pi\varepsilon_0}\frac{Z_1 Z_2 e^2}{r} - \boxed{\frac{1}{4\pi\varepsilon_0}\frac{Z_1 Z_2 e^2}{R}}$$

Electron screening potential energy [U_e]

R being the screening length.

Electron screening – Atomic physics models

The most common models used to study electron screening in interactions between ions (projectile) and atoms/molecules (target):

Dynamic models (atomic physics)
two limiting cases:

sudden limit

$v_p \gg v_e$

projectile orbiting electron(s)

minimum energy transfer
from electronic-
to nuclear-motion

adiabatic limit

$v_p \ll v_e$

projectile orbiting electron(s)

maximum energy transfer from electronic-
to nuclear-motion, U_A

Experimental data for U_e - Examples

Reactions	U_e (eV)		References
	Adiabatic	Experimental	
d(d,p)t	14	25 5	Greife et al. (1995)
^{3}He(d,p)^{4}He	120	186 12	Prati et al. (1994)
d(^{3}He,p)^{4}He	65	123 9	Prati et al. (1994)
^{7}Li(p,α)^{4}He	186	300 160	Engstler et al. (1992)
^{11}B(p,α)^{8}Be	348	430 80	Angulo et al. (1993)

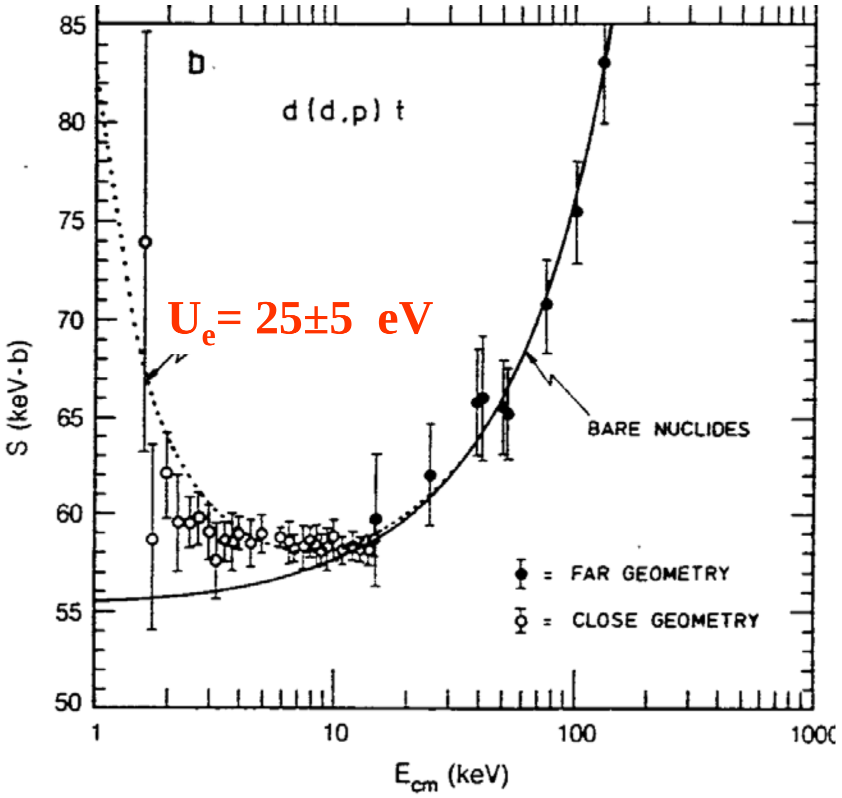
Note: d(d,p)t $\leftrightarrow$ d+d $\rightarrow$ p + t

experimental U_e > adiabatic U_e

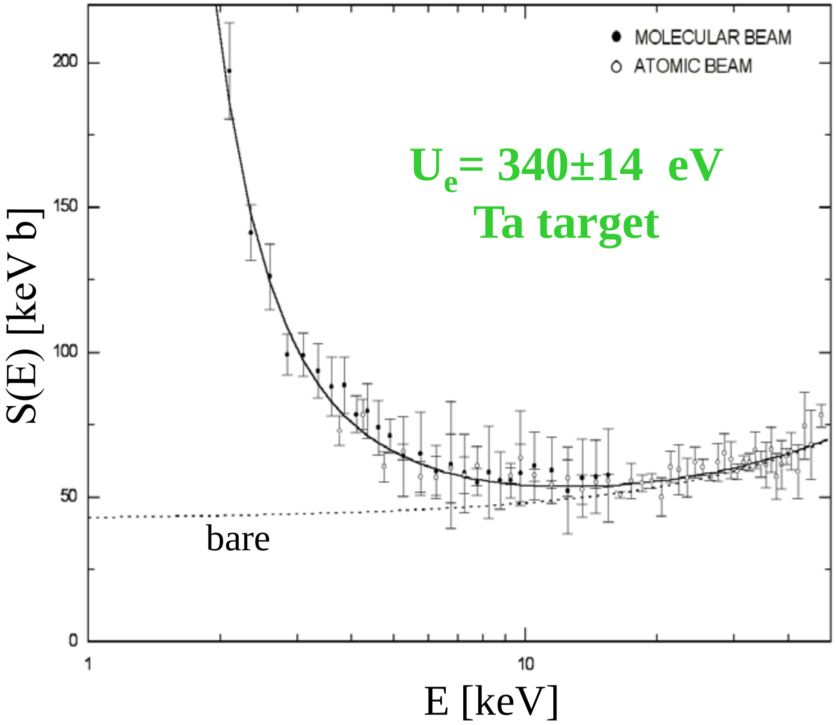
d(d,p)t reaction – U_e value depends on target ?

Gas target

Deuterated solid target



U_e= 25±5 eV



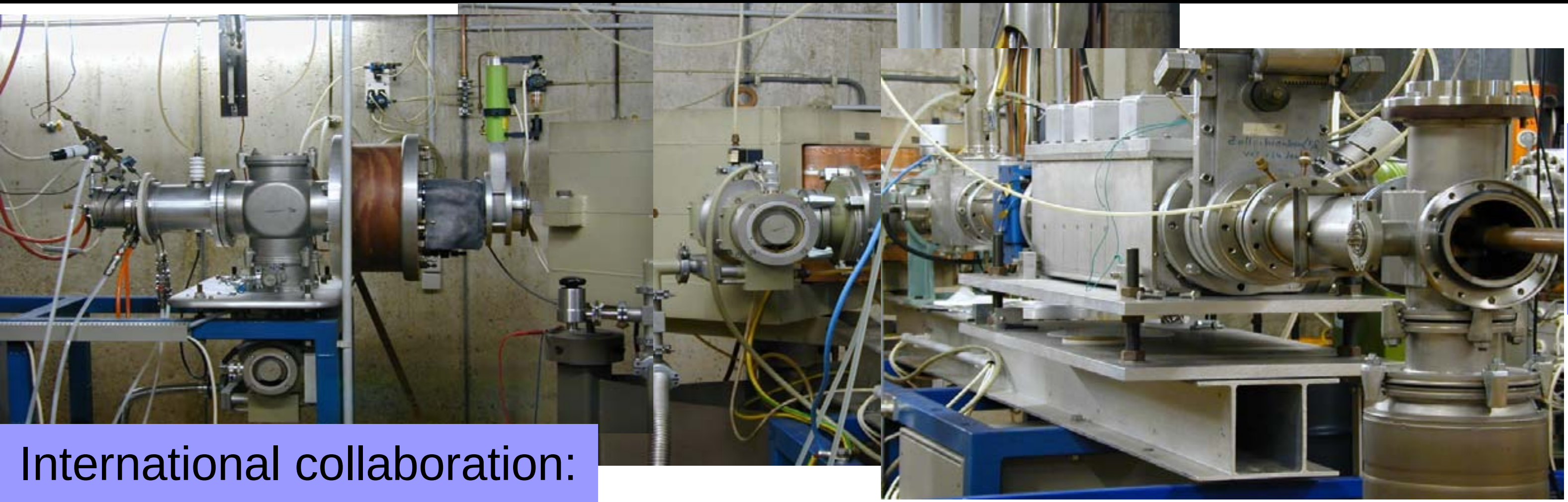
U_e= 340±14 eV

Ta target

F.Raiola et al., Eur. Phys. J. A13(2002)377

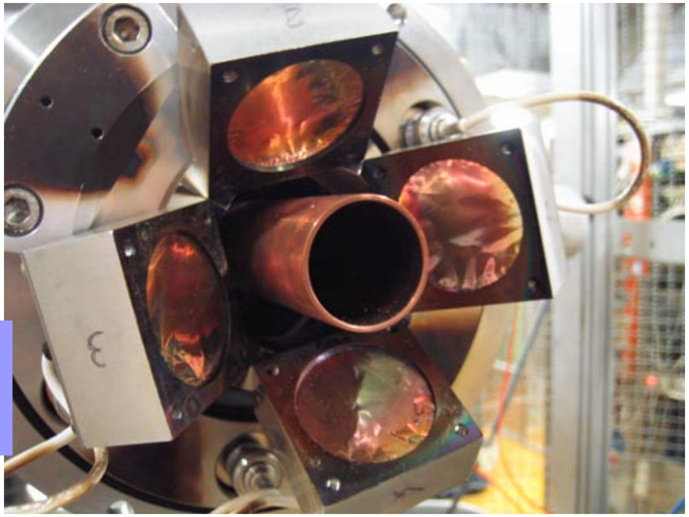
Not predicted by theory !

The 100 kV accelerator at Bochum, Ruhr-Universität Bochum



$E_{lab} < 100$ keV
$I_{target} \approx 30\ \mu A$
$P < 10^{-8}$ mbar

International collaboration:
Lisboa, Portugal
Bochum, Germany
Debrecen, Hungary
Naples, Italy
Beijing, China



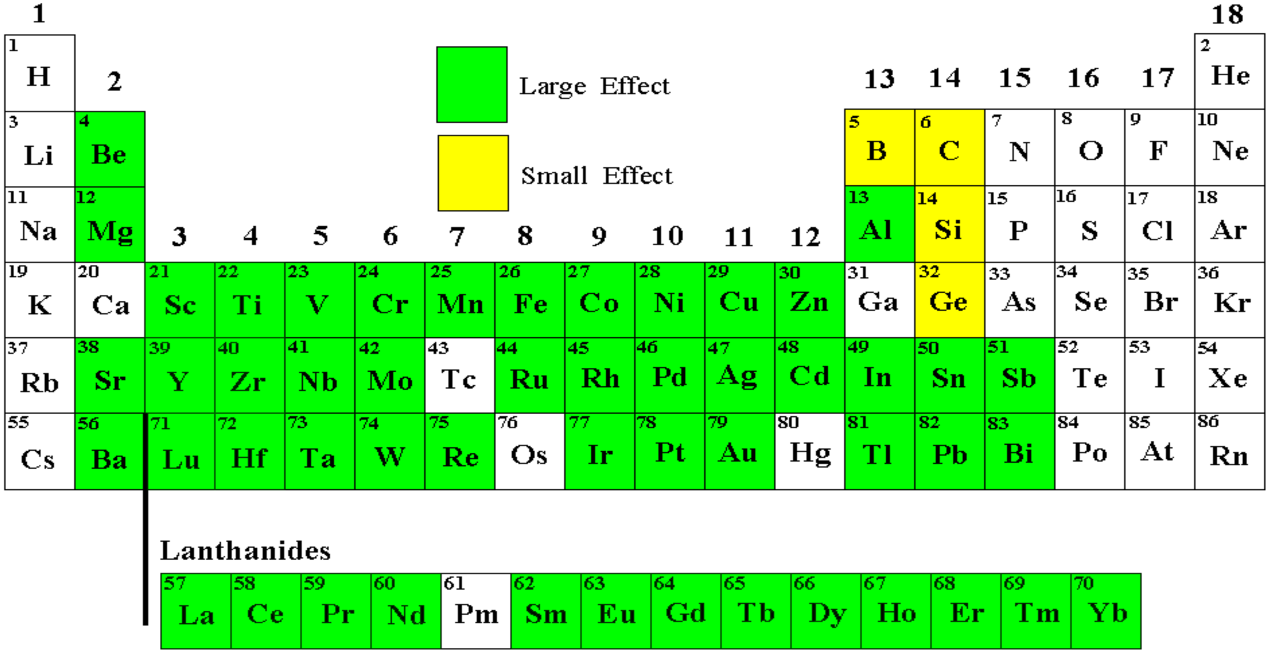
Solid targets preparation: substrates implanted with D^+ until saturation.

Results overview for d(d,p)t reaction

55 samples
in total

FEATURES:

- Insulator and semiconductors show small U_e values ($\approx$ 30 eV)
- Metals show large U_e values ($\approx$ 300 eV)



🟩 Large Effect

🟨 Small Effect

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H																	2 He
3 Li	4 Be 🟩											5 B 🟨	6 C 🟨	7 N	8 O	9 F	10 Ne
11 Na	12 Mg 🟩											13 Al 🟩	14 Si 🟨	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc 🟩	22 Ti 🟩	23 V 🟩	24 Cr 🟩	25 Mn 🟩	26 Fe 🟩	27 Co 🟩	28 Ni 🟩	29 Cu 🟩	30 Zn 🟩	31 Ga	32 Ge 🟨	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr 🟩	39 Y 🟩	40 Zr 🟩	41 Nb 🟩	42 Mo 🟩	43 Tc	44 Ru 🟩	45 Rh 🟩	46 Pd 🟩	47 Ag 🟩	48 Cd 🟩	49 In 🟩	50 Sn 🟩	51 Sb 🟩	52 Te	53 I	54 Xe
55 Cs	56 Ba 🟩	71 Lu 🟩	72 Hf 🟩	73 Ta 🟩	74 W 🟩	75 Re 🟩	76 Os	77 Ir 🟩	78 Pt 🟩	79 Au 🟩	80 Hg	81 Tl 🟩	82 Pb 🟩	83 Bi 🟩	84 Po	85 At	86 Rn

Lanthanides

57 La 🟩	58 Ce 🟩	59 Pr 🟩	60 Nd 🟩	61 Pm	62 Sm 🟩	63 Eu 🟩	64 Gd 🟩	65 Tb 🟩	66 Dy 🟩	67 Ho 🟩	68 Er 🟩	69 Tm 🟩	70 Yb 🟩

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

Much stronger effect for metals than for gaseous or insulator targets:
Enhancement clearly linked to properties of the metallic environment

Consider a “migration” of quasi-free conduction electrons from host metal to the implanted deuterium.

$$\boxed{U_e = U_{\mathrm{metal}} + U_A^{\mathrm{d+d}} \Rightarrow U_e \approx U_{\mathrm{metal}} + 25\ (\mathrm{eV})}$$

A possible classical explanation?

A SIMPLE MODEL: assume a “gas” of classical conduction electrons in metals (Drude model).

In this approximation (Debye screening model), we get that the quasi-free electrons cluster around deuterons at radius (screening length):

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

n_{eff} = number of conduction electrons/atom (typically 1)
ρ_a = atomic density (typically $6\mathrm{x}10^{28}$ m^{-3})

for $\boxed{T \approx 300\ \mathrm{K} \;\Rightarrow\; R_D \approx 5\times10^{-12}\ \mathrm{m}}$

$$U_D = \frac{1}{4\pi\varepsilon_0}\frac{Z_1 Z_2 e^2}{R_D}$$

$$U_e = U_D + U_A \Rightarrow \boxed{U_e \approx 300\mathrm{eV}}$$

Unexpected SUCCESS !!

CRITICAL TESTS:

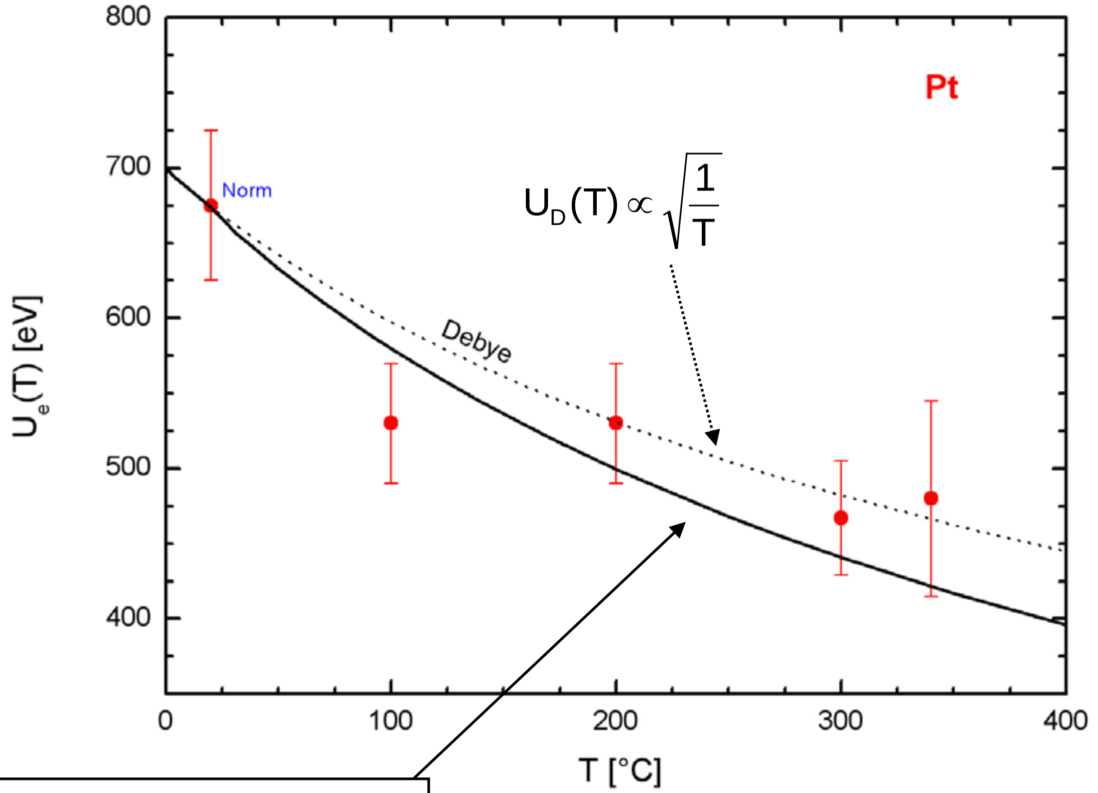
TEMPERATURE DEPENDENCE: $U_D(T) \propto \sqrt{\frac{1}{T}}$

CHARGE DEPENDENCE: $U_D(T) \propto Z$

Temperature dependence of U_e

d(d,p)t reaction in Pt

Temperature range: 20 – 340 ^{o}C



Includes Hall coefficient temperature dependence, i.e., $n_{eff} = n_{eff}(T)$.

Results for target-charge dependence of U_e

^{7}Li : $Z_{target} = 3$

Experimental values:

Li_2WO_4 → **$U_e = 237^{+133}_{-77}$ eV**

Li → **$U_e = 1184 \pm 59$ eV**

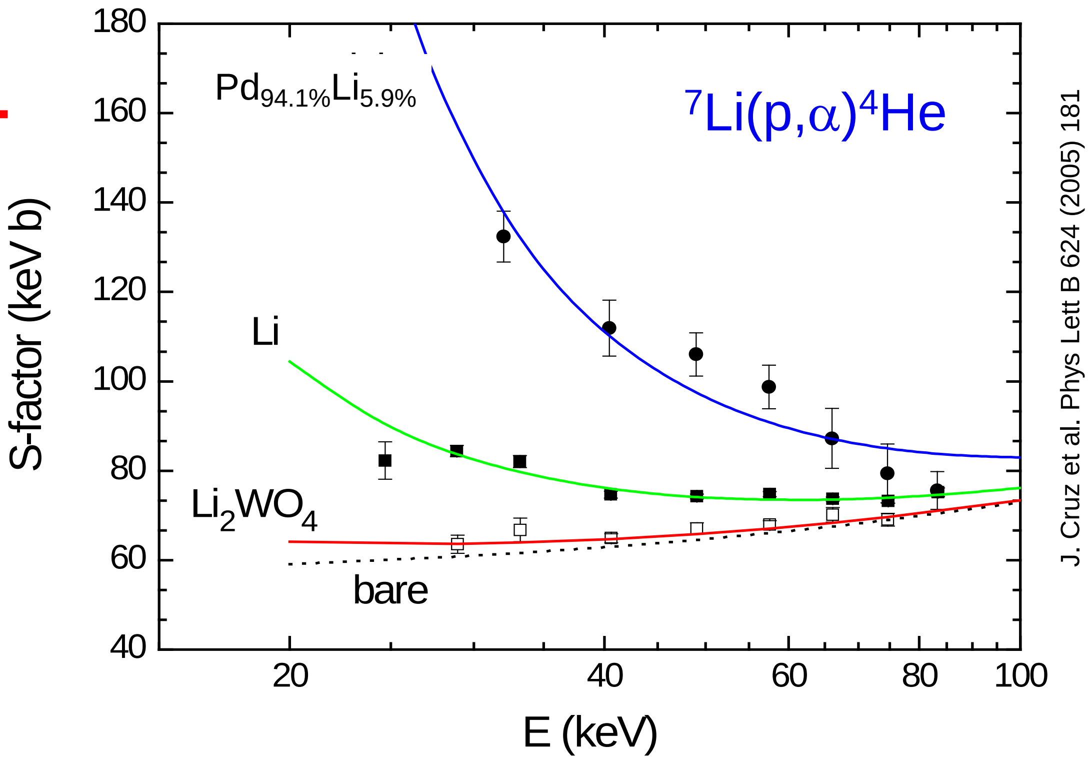
$Pd_{94.1\%}Li_{5.9\%}$ → **$U_e = 3683 \pm 329$ eV**

Debye model predictions:

Li_2WO_4 → $U_e = 300 \pm 160$ eV

Li → $U_e = 1120 \pm 260$ eV

$Pd_{94.1\%}Li_{5.9\%}$ → $U_e = 3100 \pm 440$ eV



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

Similar agreement observed for

$^6Li(p,\alpha)^3He$ ($Z_t = 3$) J. Cruz et al. Phys Lett B 624 (2005) 181

$^9Be(p,\alpha)^6Li$ and $^9Be(p,d)^8Be$ ($Z_t = 4$) D. Zahnow et al. Z. Phys. A359 (1997) 211

$^{50}V(p,n)^{50}Cr$ ($Z_t = 23$) K.U. Kettner, et al. J. Phys. G32 (2006) 489

$^{176}Lu(p,n)^{176}Hf$ ($Z_t=71$) K.U. Kettner, et al. J. Phys. G32 (2006) 489

Radioactive decays – Dramatic consequences ?

Regardless of the origin of the high screening values in metals it is justified to assume that also the decay rate and therefore the $t_{1/2}$ of radioactive nuclei should change when they are implanted in metals. The charged α and β particles also have to penetrate the Coulomb barrier modified by the electrons in the same manner as they do for nuclear reactions.

Speed up of α decay of transuranic nuclear waste material by embedding it in metals at low temperature.

This would have a huge impact on waste disposal management and “re-open” the door to nuclear energy for civil purposes.

Debye model in α decay

Recalling: for radionuclides embedded in metals

- Coulomb barrier height change: $\mathbf{U_e = Z_{alpha}\, Z_{daughter}\, U_e(d+d)\, (T/300)^{-1/2}}$
- $\mathbf{U_e(d+d) \approx 300\ eV}$ at 300 K
- $\mathbf{Z_{alpha} = 2 \quad Z_{daughter} = 80 \Rightarrow U_e} \approx 48$ keV
- Cooling to 4 K $\Rightarrow$ **Ue** $\approx$ 415 keV

- Effectively increases alpha energies by 415 keV

For a radionuclide embeded in a metal lattice and cooled to temperatures of a few Kelvin, we would expect, according to the Debye model:

$^{210}\mathrm{Po} \rightarrow \alpha + {}^{206}\mathrm{Pb}$ $\quad t_{1/2} = 138$ days $\longrightarrow$ 0.5 days

$^{226}\mathrm{Ra} \rightarrow \alpha + {}^{222}\mathrm{Rn}$ $\quad t_{1/2} = 1600$ years $\longrightarrow$ 1.3 years

EUREKA!!

α decay – Experimental Results

- **F.Raiola et al., Eur. J. Phys. A32 2007**
  ^{210}Po decay : half-life shorter by 6.3% at 12K than at room temperature.

- **H.B. Jeppesen et al., Eur. J. Phys. A32 2007**
  ^{221}Fr decay : at room temperature, half-life shorter by < 0.5 % observed in metals than in insulators.

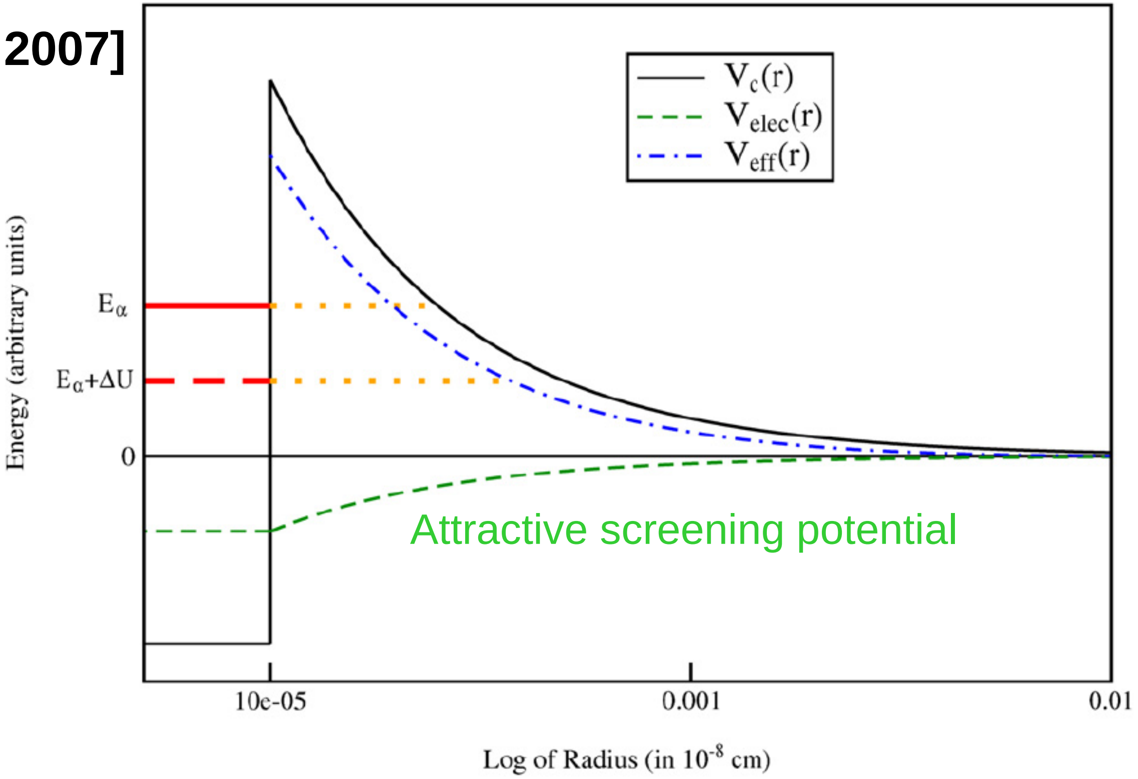
- **N. Severijns et al., Phys. Rev. C 024304 2007**
  ^{253}Es decay : measured half-life between 4K and 50 mK: results within 2% of literature value.

Even though there is a change in the “right sense”, all results are clearly smaller than the ones predicted by the Debye model.

α decay — Theoretical Comment

[N.T. Zinner Nucl. Phys. A781, 81, 2007]

Rather than reducing the alpha barrier height, screening reduces BOTH the alpha energy AND the barrier peak. The screened barrier will be longer than through the unscreened barrier ⇒ slightly longer half-lifes expected.



It explains why large differences in screening energies for various host materials does not lead to significant changes of half-lives, but expected trend contrary to experimental results.

Beta decay

Enhanced electron screening in metals would:

1. Slow down electrons, thus reduce beta decay phase space and increase half-lives.
2. Accelerate positrons, thus increase positron phase space and decrease half-lives.

Effects predicted at ~ 10% level, less spectacular than alpha.

Experimental data:

- B. Limata et al., Eur. J. Phys. A28 251, 2006

^{22}Na beta+ decay half-life shorter by 1.2(2)% at 12 K. Predicted 6%.

- B. Wang et al., Eur. J. Phys A28 375, 2006

^{7}Be e-capture half-life bigger by 0.8% 'consistent with Debye model'

J.R. Goodwin et al., Eur. J. Phys. A34 2007

^{198}Au beta- decay half-life unchanged between 19K and room temperature.

Conclusions

- nuclear reactions enhanced electron screening in metals well parametrized using Debye model. However, need for improved theory.

- half-lives in alpha and beta decays: the results are consistent in the sign of half-life change with the prediction of the Debye model, but the observed effects are significant smaller than expected by this model.

Thank you for your interest and attention.

Debye screening model in metals

Assume the quasi-free conduction electrons follow a MB distribution:

$$n_e = n_{e0}\exp\left(-\frac{q_e\phi}{k_B T_e}\right) \approx n_{e0}\left(1-\frac{q_e\phi}{k_B T_e}\right) \qquad (1)$$

Poisson's equation must also be satisfied:

$$-\varepsilon_0 \nabla^2\phi = q_e(n_e - n_{e0}) \qquad (2)$$

Replacing (2) in (1) we get:

$$\nabla^2\phi - \phi / R_D = 0 \qquad (3)$$

$$R_D = \sqrt{\frac{\varepsilon_0 k_B T_e}{n_{e0} q_e^2}} = 69\sqrt{\frac{T_e}{\rho_a n_{eff}}} \quad \text{(m)}$$

The solution of (3) with boundary condition that ϕ vanishes at infinity is:

$$\phi(r) = \frac{1}{4\pi\varepsilon_0}\frac{Z_1 e}{r}\exp\left(-\frac{r}{R_D}\right) \Rightarrow V(r) = \frac{1}{4\pi\varepsilon_0}\frac{Z_1 Z_2 e^2}{r}\exp\left(-\frac{r}{R_D}\right) \approx \frac{1}{4\pi\varepsilon_0}\frac{Z_1 Z_2 e^2}{r} - \boxed{\frac{1}{4\pi\varepsilon_0}\frac{Z_1 Z_2 e^2}{R_D}} \longleftarrow \mathbf{U_D}$$

Considering also the bound electrons contribution:

$$V(r) \approx \frac{1}{4\pi\varepsilon_0}\frac{Z_1 Z_2 e^2}{r} - U_D - U_e^{bound}$$

Nuclear Astrophysics

GOAL: study the nuclear reactions that in the earliest stages of the universe and in stars are responsible for the formation of the chemical elements and their isotopes, and control the associated energy generation, neutrino luminosity and evolution of stars.

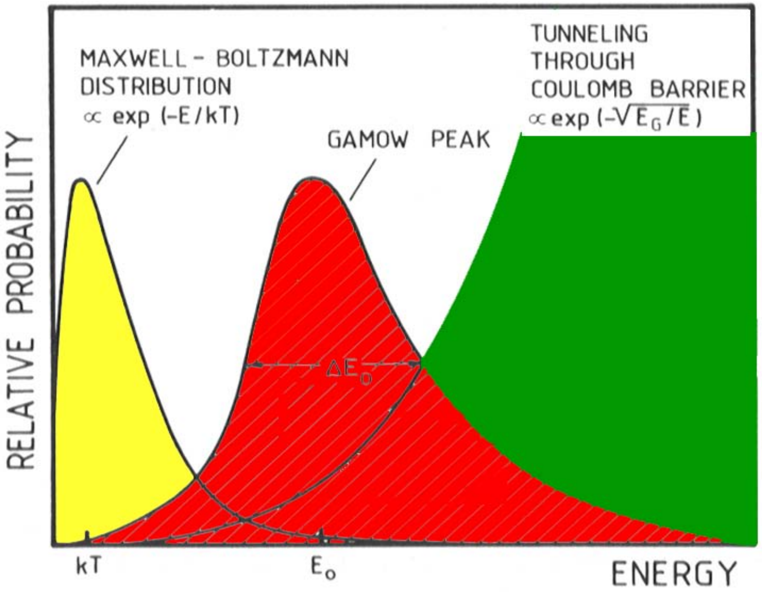
Inside stars, charged-particle-induced fusion reactions, occur far below the Coulomb barrier (**the Gamow peak**).

↓

The cross section drops nearly exponentially with decreasing energy:

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

Astrophysical S-factor
- contains all nuclear effects
- smooth energy function



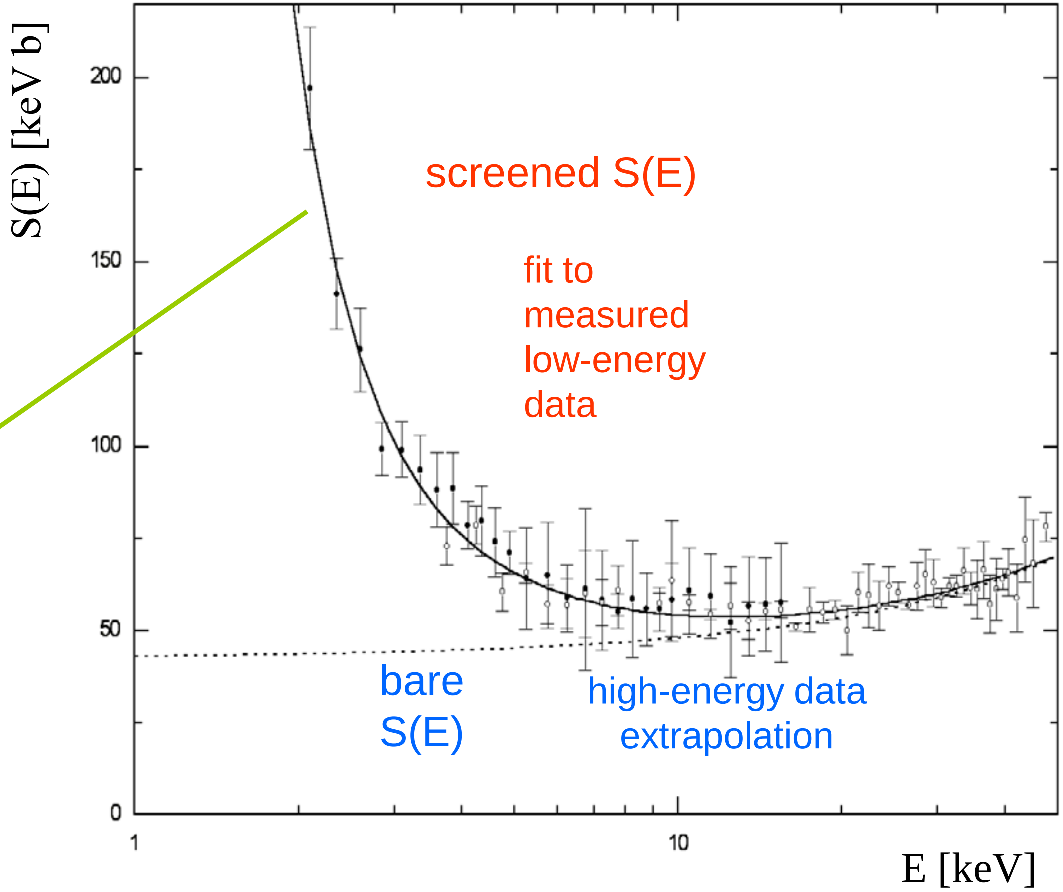
$kT \approx 1.3$ keV
$E_0 \approx 15 - 25$ keV
$E_C \approx 1000$ keV

Electron screening – Experimental approach

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

Astrophysical S-factor
- contains all nuclear effects
- smooth energy function

$\propto$Coulomb barrier penetration probability



Fitting function:

$$S_s(E) = \frac{E}{E+U_e}\exp\left[\pi\eta\frac{U_e}{E}\right]S_b(E)$$

One free parameter: $\mathbf{U_e}$

First approach: Thomas-Fermi model

Considered as giving a good description of electrons in metals, even though it is known that in these materials, electron screening may need more complex models (field of many-body physics).

According to this model, the metal conduction electrons cluster around the implanted deuteron at radius (screening length):

$$R_{TF} = \sqrt{\frac{\varepsilon_0 E_F}{3e^2 \rho_a n_{eff}}}$$

$R_{Hall} = [e\, n_{eff}(Hall)\, \rho_a]^{-1}$

E_F = Fermi energy (around 10 eV for metals)

n_{eff} = number of conduction electrons/atom (typically 1)

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

$$R_{TF} \approx 5.5 \times 10^{-11}\,\mathrm{m} \Rightarrow U_e = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{R_{TF}} + U_A^{d+d} \Rightarrow U_e \approx 50\ \mathrm{eV}$$

TF model can´t explain high U_e values!!

The collaboration

J. Cruz[1], F.Raiola[2], G.Gyürky[3], Z.Fülöp[3], S.Zeng[4], M.Aliotta[5], H.Luis[1], A.Di Leva[2], M.Fonseca[1], L.Gang[4], L.Gialanella[7], A.P.Jesus[1], K.U.Kettner[8], B.Limata[7], J.P. Ribeiro[1], V.Roca[7], C. Rolfs[2], M.Romano[7], D. Schürmann[2], E.Somorijai[3], F.Strieder[2], F. Terrasi[6]

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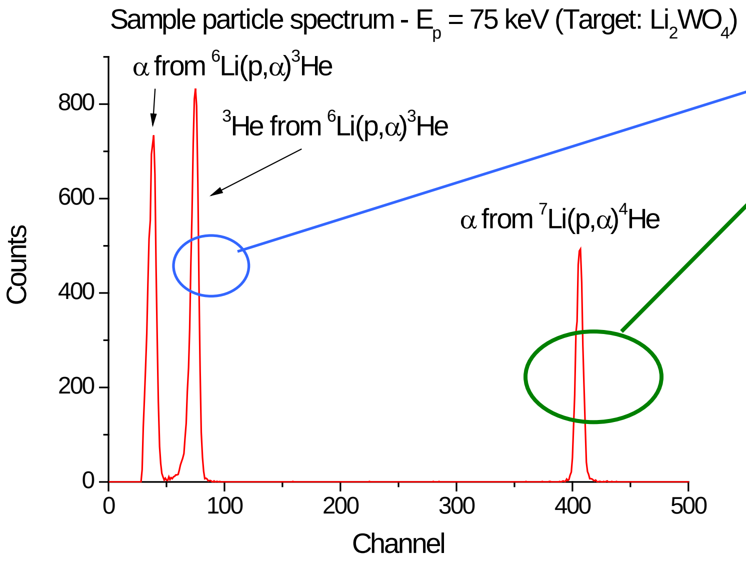
“Low” energy part - Determination of $U_e(E)$ - Formalism



$$\boxed{N(E,\theta)}=N_p\frac{\Omega_{lab}}{4\pi}(1+\delta)\int_{E-\Delta}^{E}K_\Omega(E',\theta)W(E',\theta)\frac{\sigma(E')}{\varepsilon(E')}dE'$$

Thick target yield: $Y^\infty(E,\theta)=N(E,\theta)/N_p$

Thin target yield:

$$Y(E,\theta)=\frac{Y^\infty(E,\theta)-Y^\infty(E-\Delta E,\theta)}{\Delta E}\approx$$

$$\approx\frac{\boxed{\sigma(E_{eff})}\,\Omega K_\Omega(E_{eff},\theta)W(E_{eff},\theta)}{4\pi\,\varepsilon(E_{eff})}$$

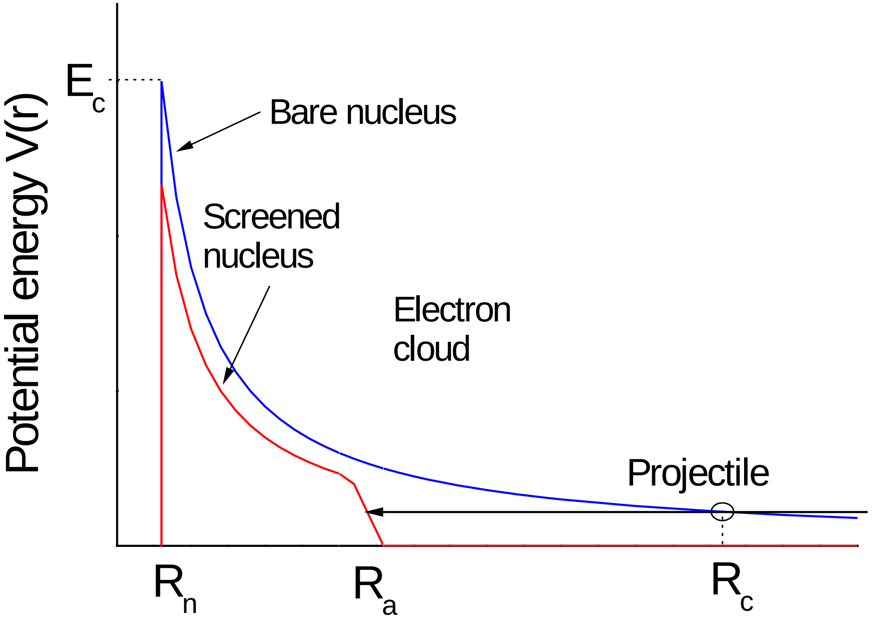
$$S(E_{eff})=\sigma(E_{eff})E_{eff}\exp(2\pi\eta)$$

Electron screening - Definition

The cross section of a charged-particle-induced nuclear reaction is enhanced at sub-Coulomb energies by the electron clouds surrounding the interacting nuclides:

$$f(E) = \frac{\sigma_s(E)}{\sigma_b(E)} = \frac{\sigma_b(E+U_e)}{\sigma_b(E)} \approx$$

$$\approx \frac{E}{E+U_e} \exp\left[\frac{31.29}{2} Z_1 Z_2 \sqrt{\mu} \frac{U_e}{\sqrt{E^3}}\right]$$



U_e : electron screening potential energy (corresponds to the energy transfer from the electronic cloud to the incoming projectile).