INTERNATIONAL CONFERENCE ON MUON CATALYZED FUSION AND RELATED TOPICS (MUCF-07)

DUBNA, 18-21 JUNE 2007.

Nuclear Fusion in Muonic Molecules and in Deuterated Metals

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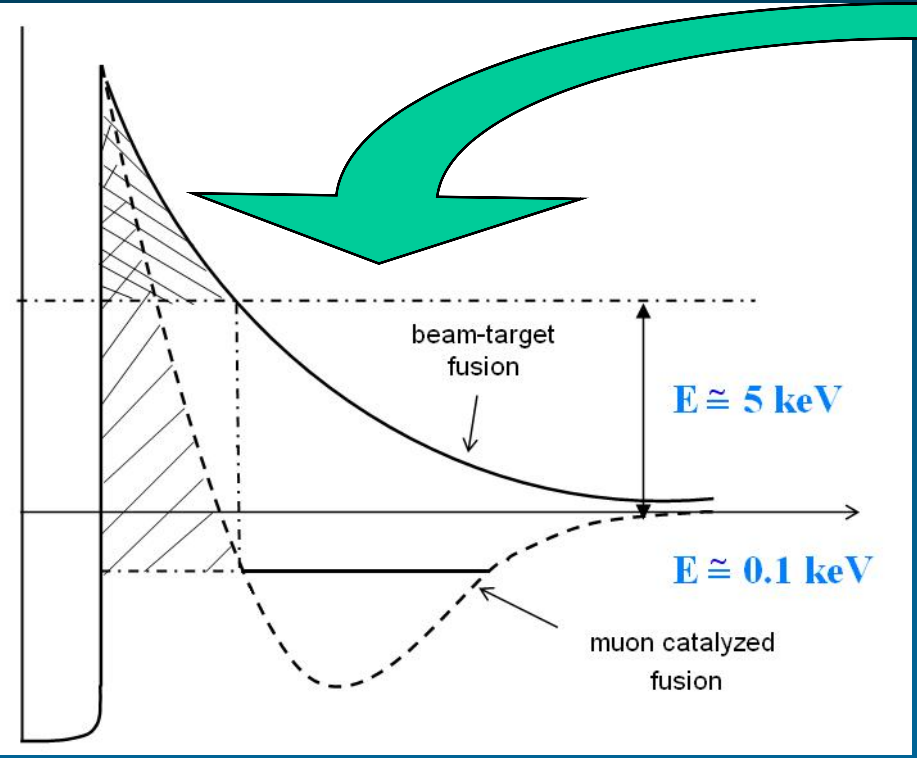
"Trois morceaux en form de poire"
("Three pear-shaped pieces")

- Nuclear data and muonic molecules
- Cold fusion
- Dd fusion in deuterated metals

nobody can say "the talk is shapeless "

Piece 1

In-flight measurements vs μCF results for pd, pt, and dd radiative capture



Data from TUNL (E < 80 keV) and LUNA (available down to E =2.5 keV)

No new results from μCF

Low energy radiative capture data are available for

pd - from PSI and TRIUMF (μCF), TUNL, and LUNA,

pt - from PSI (μCF) and TUNL ,

dd from TUNL and JINR (μCF)*

* in progress -will be reported here

Reaction rates in muonic molecules

$$\lambda_f = K^f \bullet G$$

Deser-Goldberger-Baumann-Thirring formula

Reaction constant for the s-wave

$$K^f = \lim_{v \to 0} (v\sigma^f)\, C_0^{-2}$$

σ^f – reaction cross section for bare nuclei

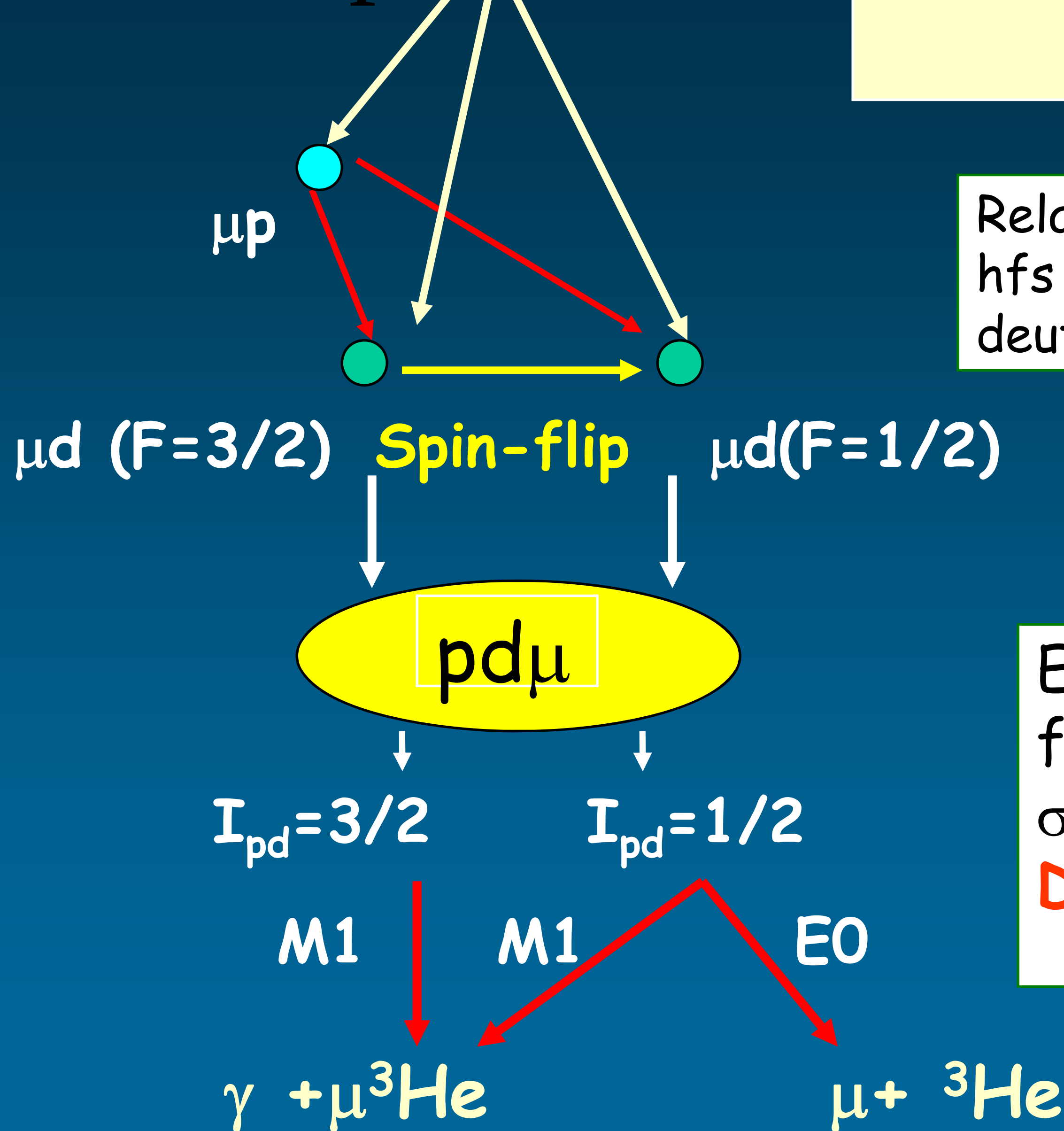
C_0^{-2} – Coulomb penetrability (Gamow) factor,

G- particle density in muonic molecule at nuclear distances (reliably calculated)

+ Definite orbital angular momentum of fusing nuclei (L=0, L=1)

+ Controlled population of nuclear spin states

Kinetics pdμ



Gershtein-Wolfenstein effect

Relative population of μd hfs levels is a function of deuterium concentration C_d

Enhancement of the fusion yield with C_d
σ(1/2)>> σ(3/2)
Doublet dominance

PSI experiment of 1990

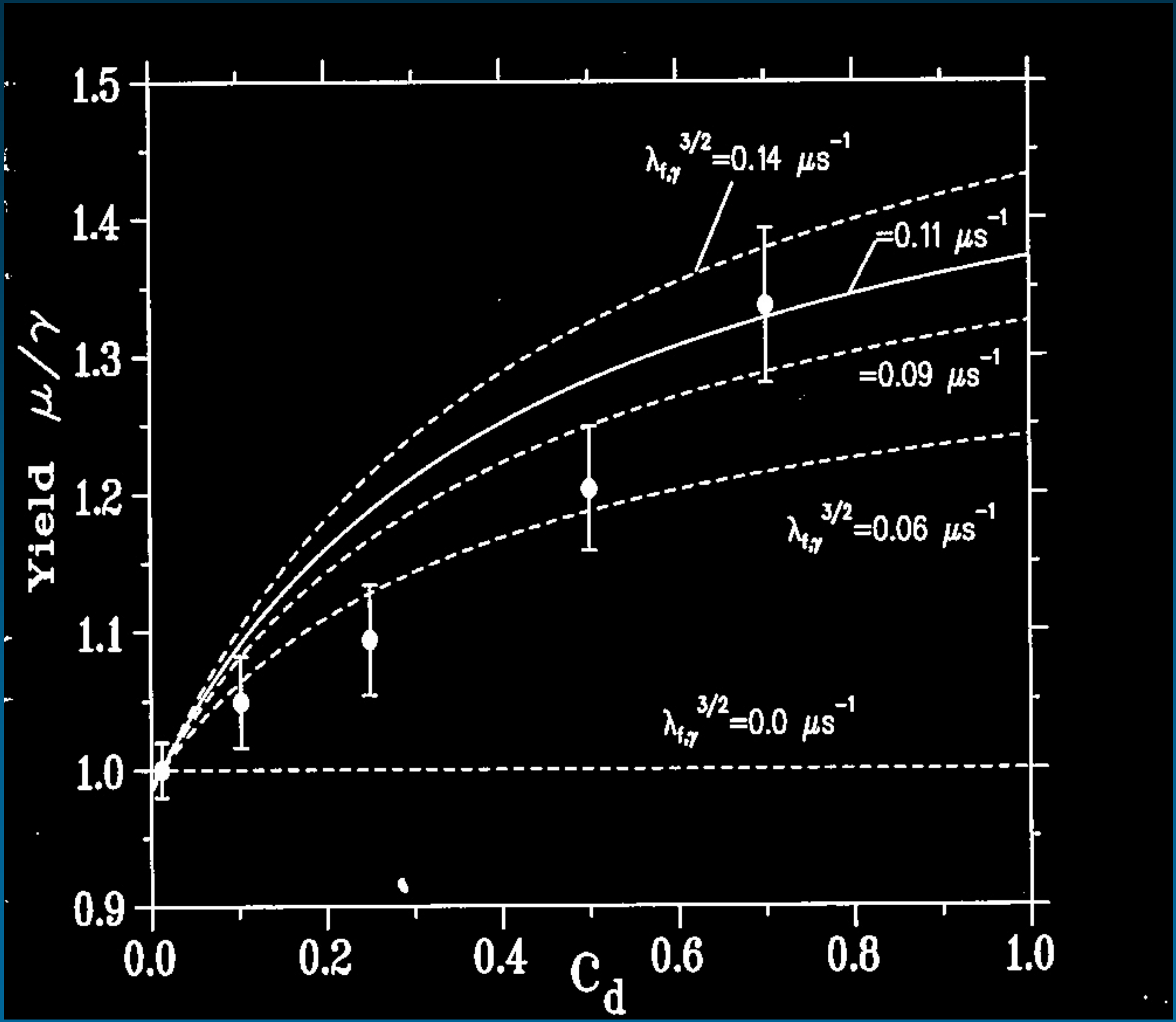
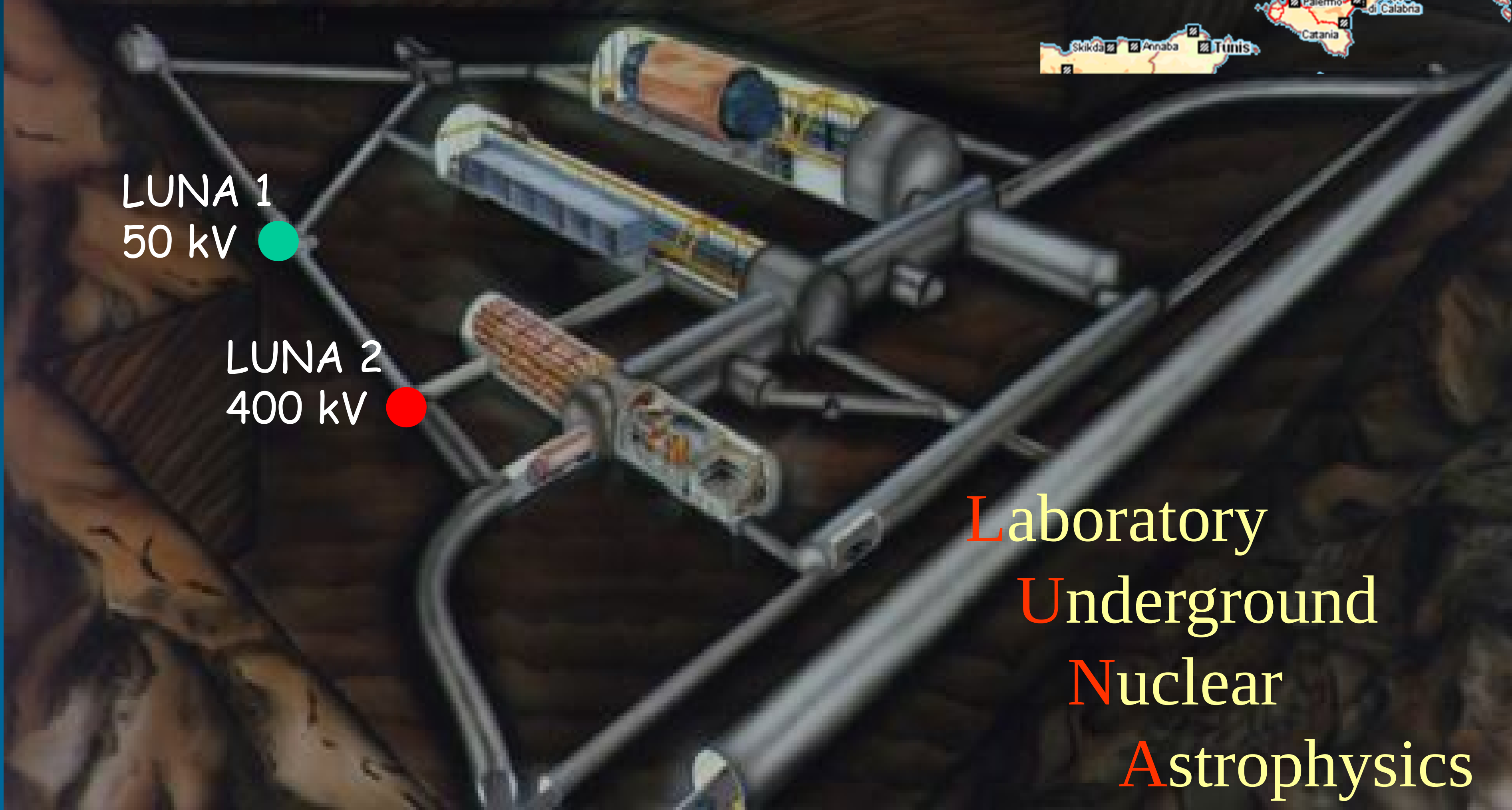


Table of pdμ fusion rates (Petitjean@Shimoda)

$p\mu d$ fusion rate	Exp. results	Refs.	Theories [11,
$\lambda_{f,\gamma}^{1/2}$	0.35 ± 0.02	[4]	0.39
	0.426 ± 0.014	[13]	
$\lambda_{f,\gamma}^{3/2}$	0.11 ± 0.01	[4]	0.11
	0.14 ± 0.02	[13]	
$\lambda_{f,\mu}^{1/2}$	0.056 ± 0.006	[12]	0.062 ± 0.00
	0.050 ± 0.005	[13]	

Wolfenstein–Gershtein effect	Enhancement	Refs.	Theory calculati
$Y_\gamma(c_d = 25\%)/Y_\gamma(c_d = 0.72\%)$	$(17 \pm 1)\%$	[9]	18%
$Y_\gamma(c_d = 21\%)/Y_\gamma(c_d = 0.63\%)$	$(17.2 \pm 0.047)\%$	[3]	18%
$Y_\gamma(c_d = 18\%)/Y_\gamma(c_d = 1.6\%)$	$(12.5 \pm 1.0)\%$	[4]	13.5%

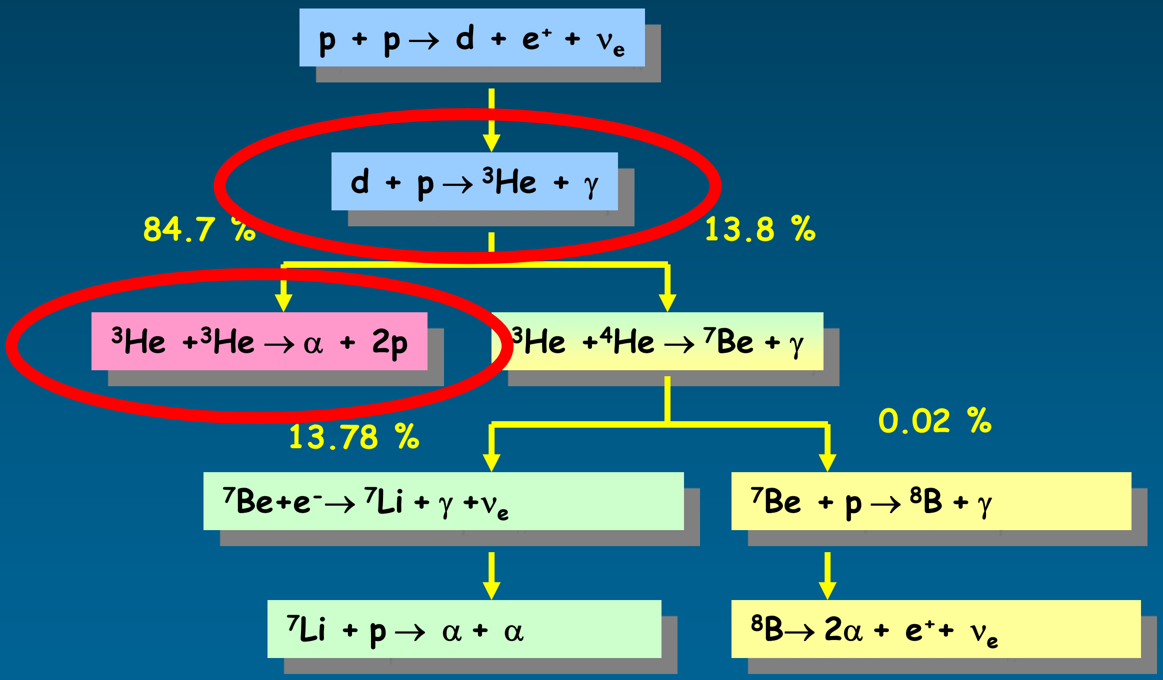
LUNA underground Laboratories



Laboratory
Underground
Nuclear
Astrophysics

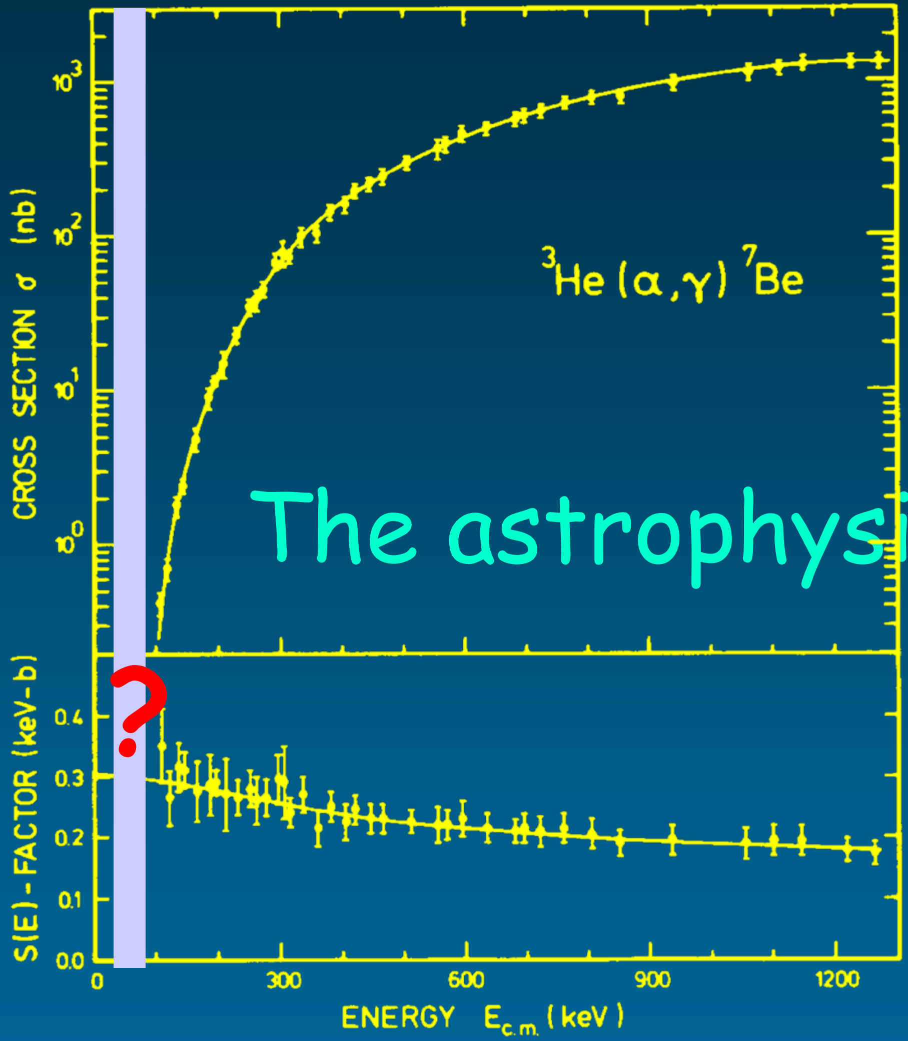
pp chain LUNA results

pp chain



S-factor

The astrophysical S-factor…



$$\sigma(E) = S(E) \cdot \exp(-2\pi\eta) / E$$

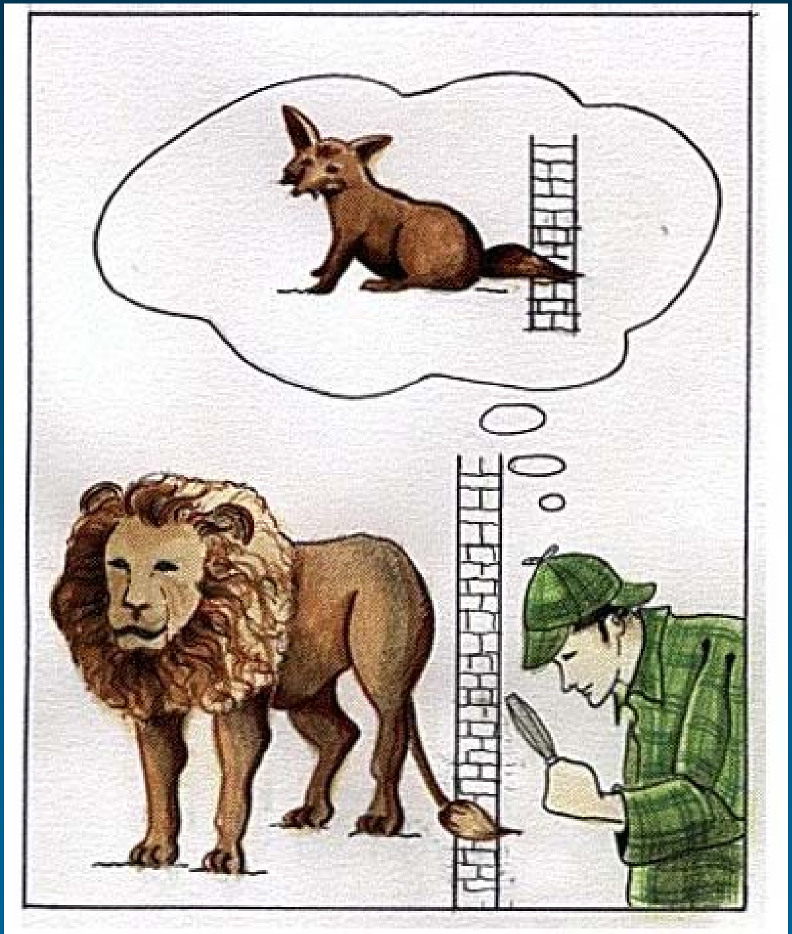
$$S(E) = E \cdot \sigma(E) \cdot \exp(2\pi\eta)$$

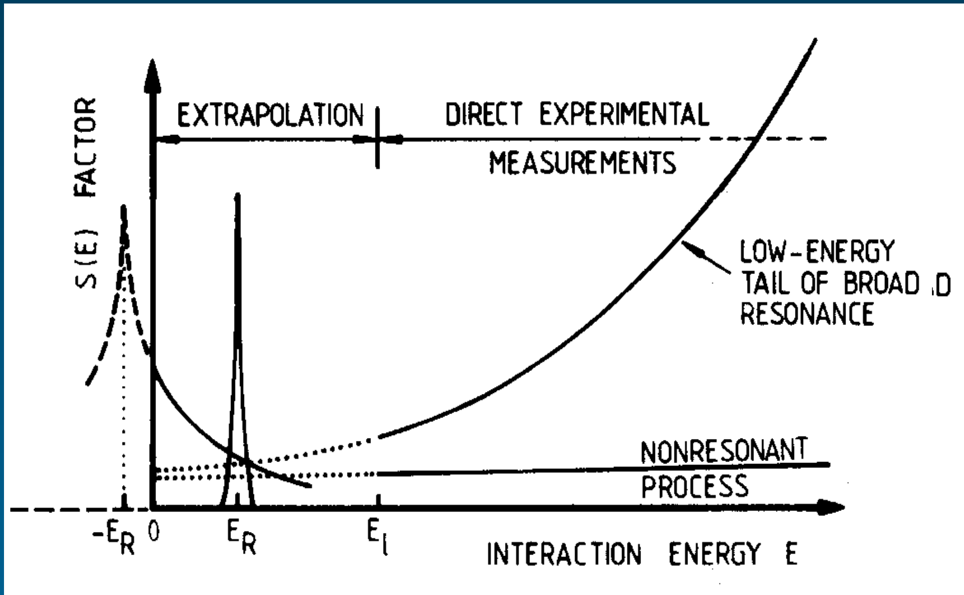
$$2\pi\eta = 31.29 \, Z_1 Z_2 \, (\mu/E)^{0.5}$$

extrapolation is needed….

extrapolation

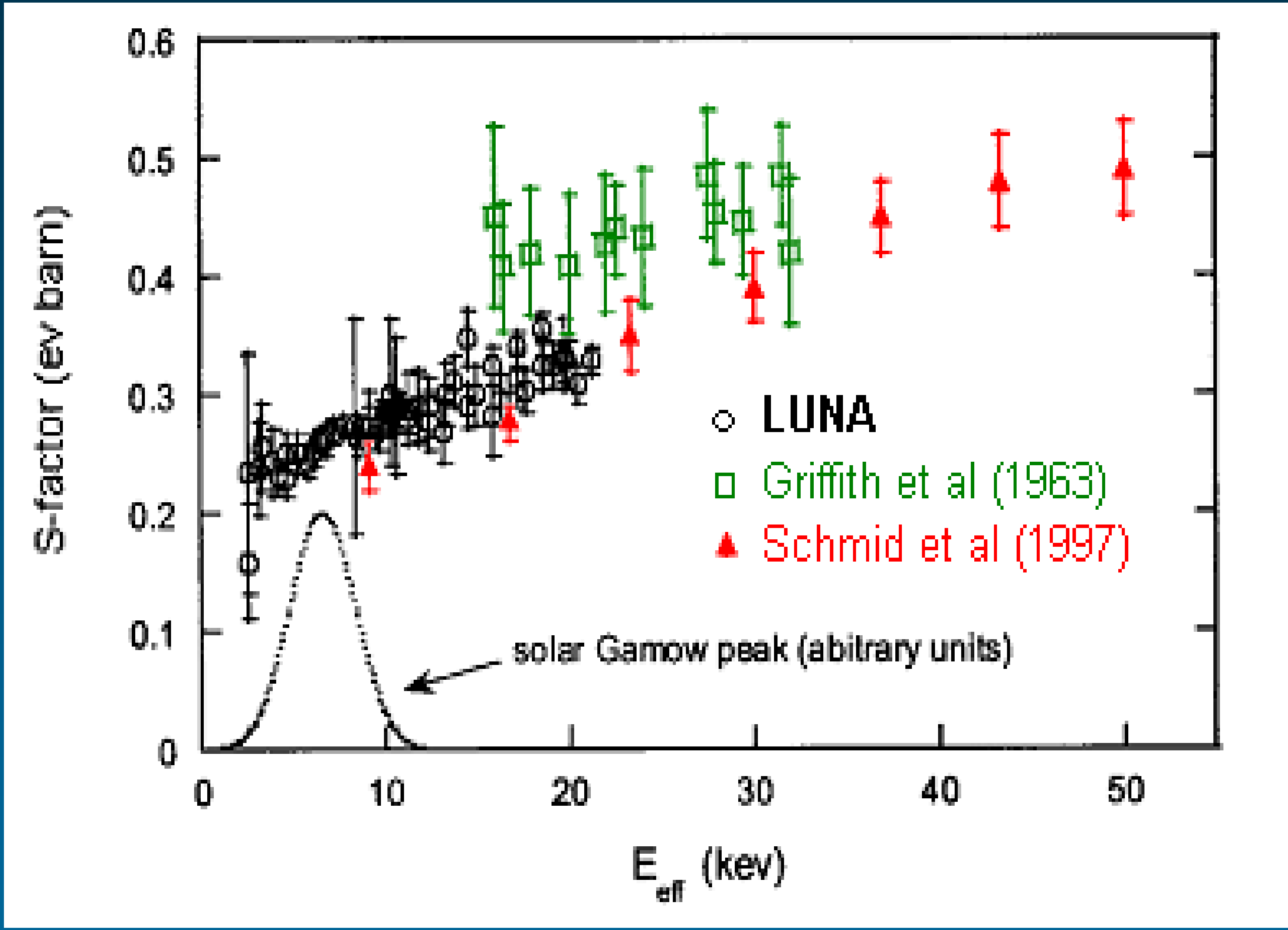
but...





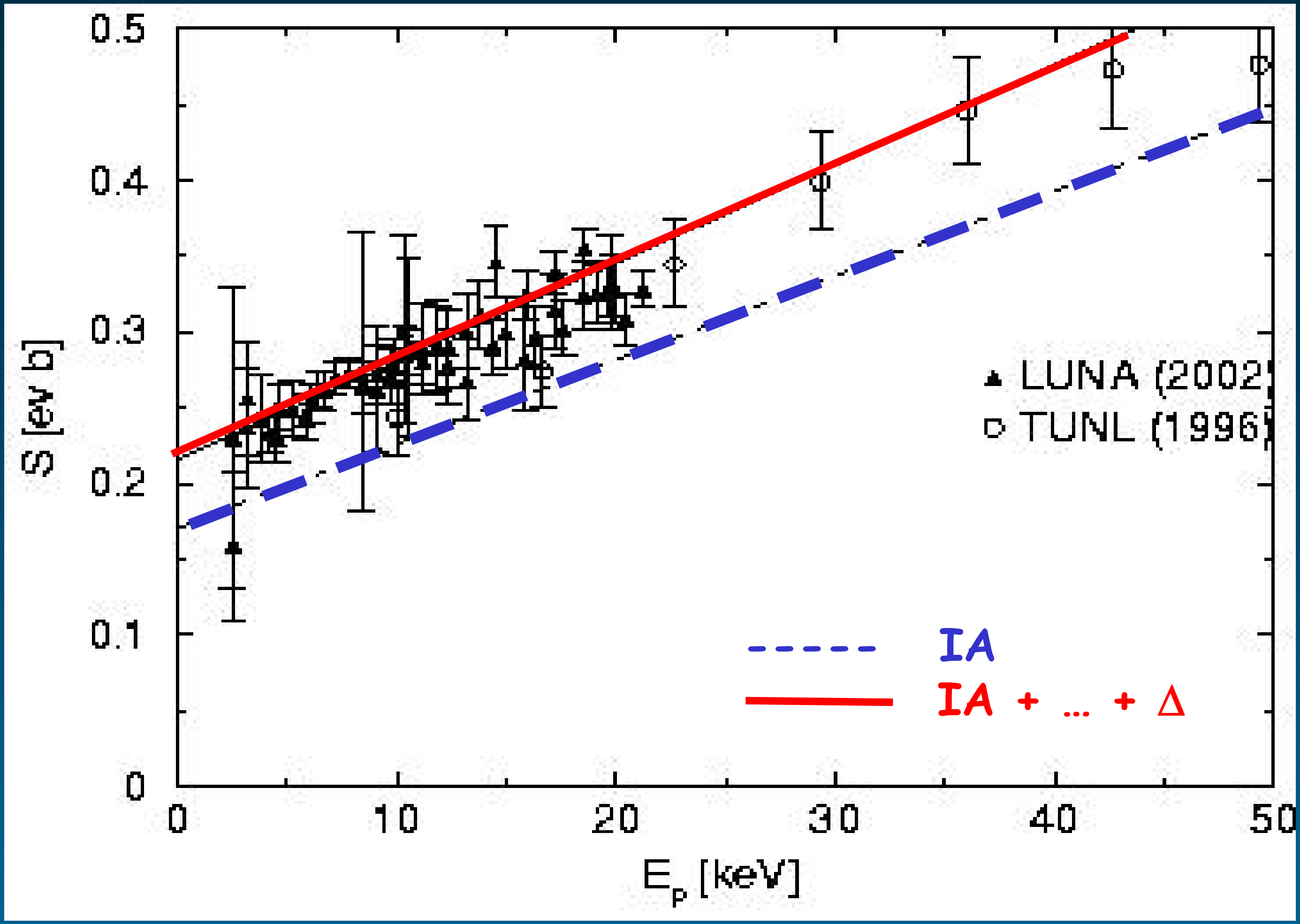
sometimes extrapolation fails !!

$d(p,\gamma)^3He$



S-factor (ev barn)
0.6
0.5
0.4
0.3
0.2
0.1
0
0
10
20
30
40
50
E_eff (kev)
LUNA
Griffith et al (1963)
Schmid et al (1997)
solar Gamow peak (abitrary units)

calculation
s



sizeable effect of non nucleonic degrees of freedom

Viviani et al.: PRC61 (2000) 064001

S-factor for $d(p,\gamma)^3He$

(muon catalyzed fusion, PSI):

$S_s(0)=0.105\pm0.01$ eV b (1990)

(collisional experiment, TUNL):

$S(0)=0.166 \pm 0.014$ eV b (1997)

$S_s(0)=0.109 \pm 0.01$ eV b (1997)

(collisional experiment, LUNA):

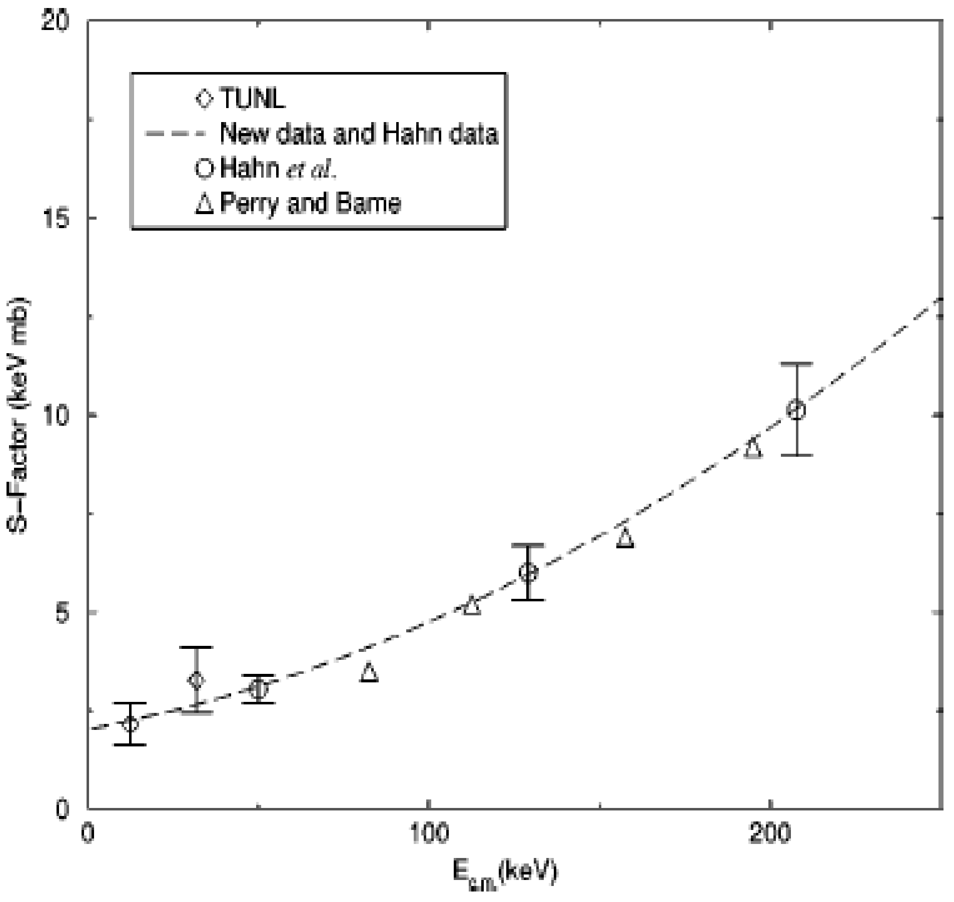
$S(0)=0.216 \pm 0.010$ eV b (2002)

S_s –not available

(collisional experiment, Griffiths et al):

$S(0)=0.25 \pm 0.04$ eV b (1963)

S-factor for $^3H(p,\gamma)^4He$ TUNL data (2002)



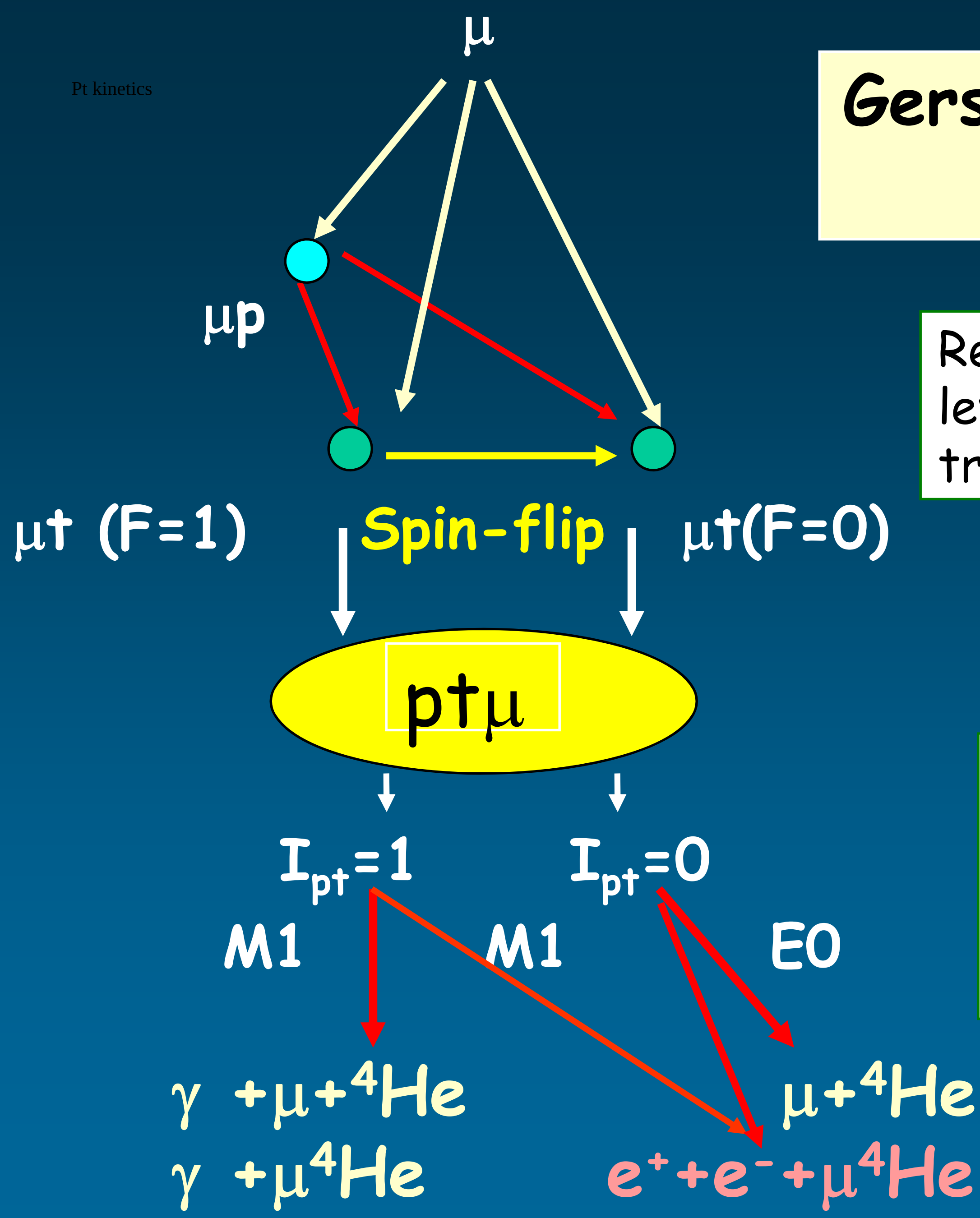
S

S_s=0.008±0.003 keV mb

In muonic molecule

λ_f (I_{pt}=1)= 4/3K•G

Pt kinetics



Gershtein-Wolfenstein effect

Relative population of μt hfs levels is a function of tritium concentration C_t

Relative population of pμt hfs levels is a function of C_t

PSI experiment (1993)

$\lambda_{pt}^{f}\ (S_{pt}=1) = 0.07 \pm 0.01\ \mu s^{-1}$,

while TUNL result would give

$$\lambda_{pt}^{f}\ (S_{pt}=1) = 0.01 \pm 0.003\ \mu s^{-1}$$

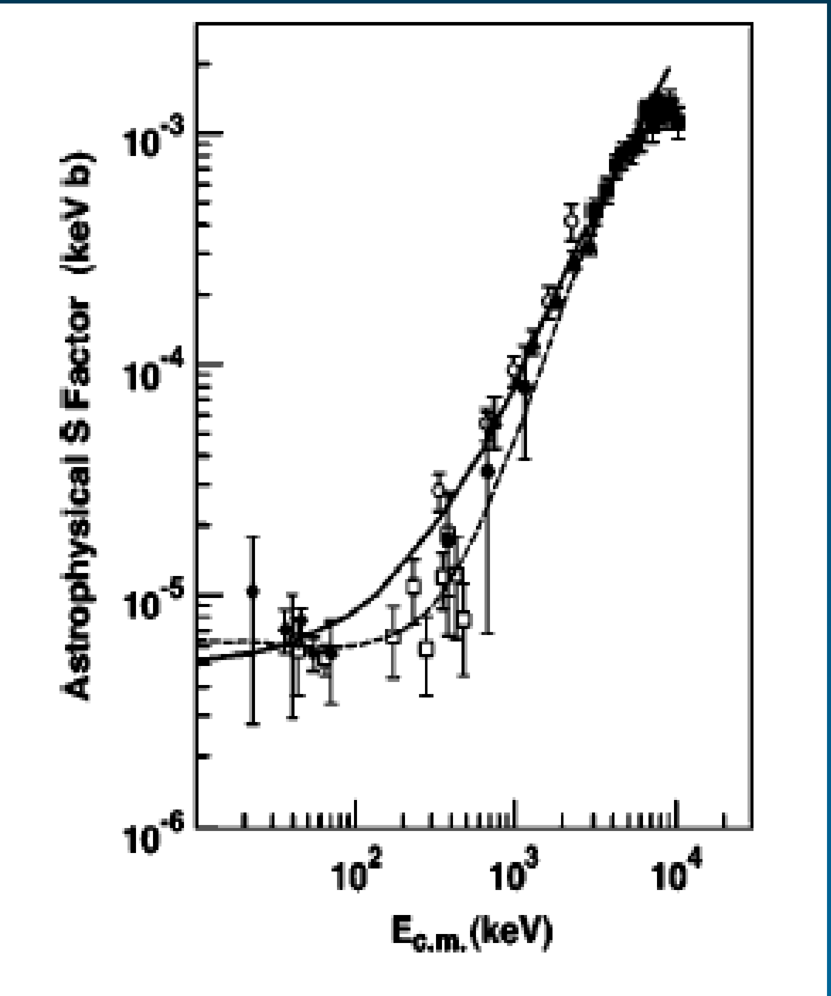
Estimate from the data on mirror reaction of thermal neutron capture $^{3}He(n,\gamma)^{4}He$:

$$\lambda_{pt}^{f}\ (I=1) = 0.008 \pm 0.0005\ \mu s^{-1}$$

Muon conversion rate $\lambda_{pt}^{\mu}(S_{pt}=0)=0.15\pm0.04\ \mu s^{-1}$ >> theory, while $e^{+}e^{-}$ pairs were not observed

Completely contradictory results

Radiative capture d+d $\rightarrow$ ^{4}He + γ



Indications to a p-wave transition were obtained from in-flight measurements with polarized deuterons (TUNL, 1993-2004).

Earlier such a transition was considered as forbidden by isotopic invariance of nuclear forces (Radicati 1952, Trainor 1952, Gell-Mann&Telegdi, 1953) .

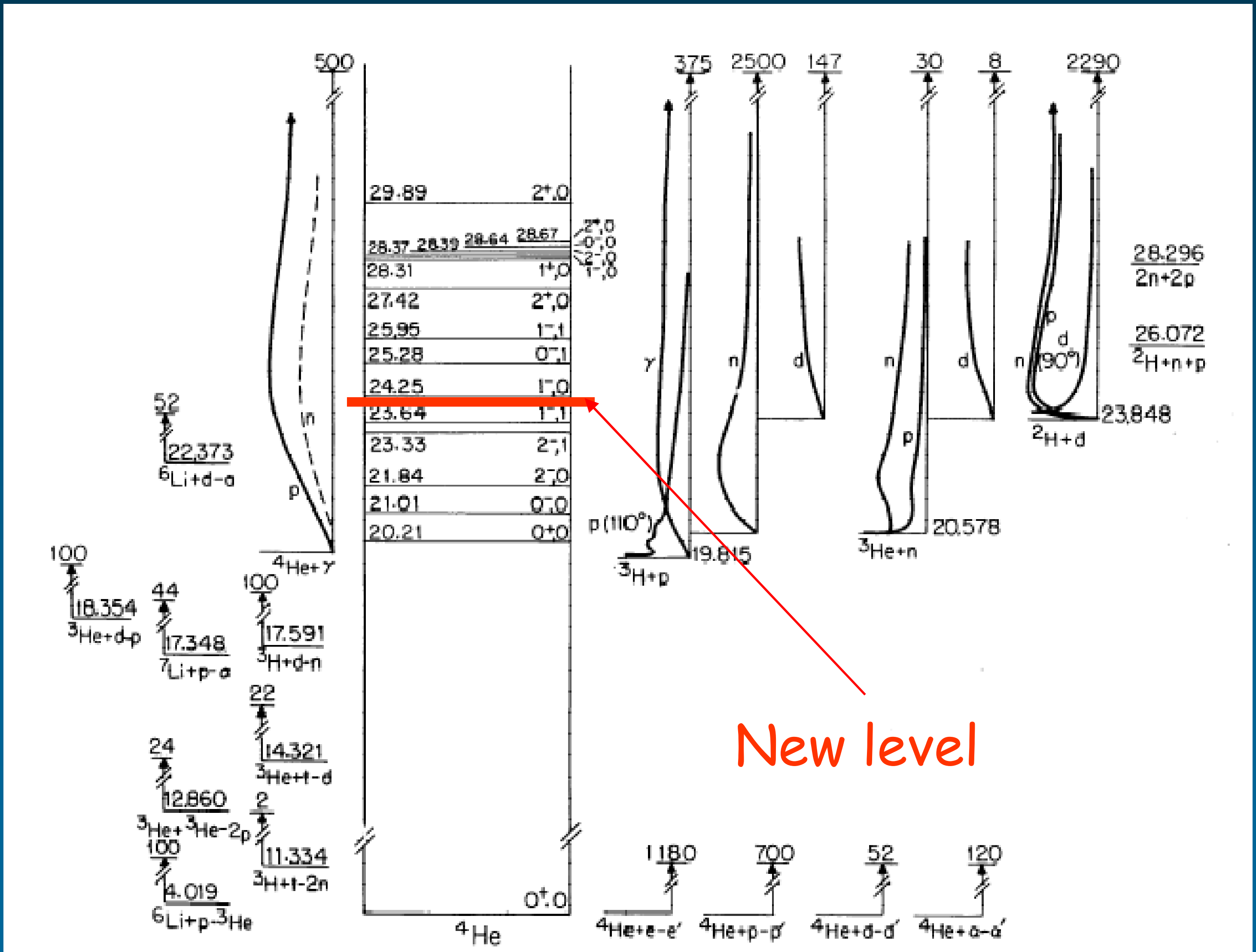
Its presence changes the cross section extrapolations to sub-Coulomb energies.

The reaction proceeds by 55% *E*2, 29% *E*1, and 16% *M*2 radiation.

TME	Multipolarity $p\mathcal{L}$	TME Fit Strength (%)	Phase (deg)
$^5s_2$	$E2$	55±8	0.0
$^3p_1$	$E1$	29±6	77±3
$^3p_2$	$M2$	16±3	44±8

A new level

"…a new 1-, T = 0 level at Ex = 24:25 MeV that has important eects on the d+d reactions at low energies. Isospin mixing between this state and the $^3P_1$, T = 1 level at E_x = 23:64 MeV causes signicant dierences in the p-wave part of the d+d reactions, as have been observed in muon-catalyzed and polarized d+d fusion experiments."



Cold Fusion

(in the manner of the beginning)

Dd fusion in deuterated metals

(continuation of the previous)

Motivation. In a crystal lattice there may be additional effect: e.g., the diffusivity of deuterium and its mobility e.g., in Pd metal are very high, and they are accompanied by a quantum interaction between the deuterons and conduction electrons that could create additional conditions for screening as compared to other metals with high deuterium concentration but low diffusivity (Fukai&Sugtimoto, 1985)

Anomalous enhancement of *DD* reaction in Pd and Au/Pd/PdO heterostructure targets under low-energy deuteron bombardment

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(Submitted 5 November 1998)
Pis'ma Zh. Éksp. Teor. Fiz. **68**, No. 11, 785–790 (10 December 1998)

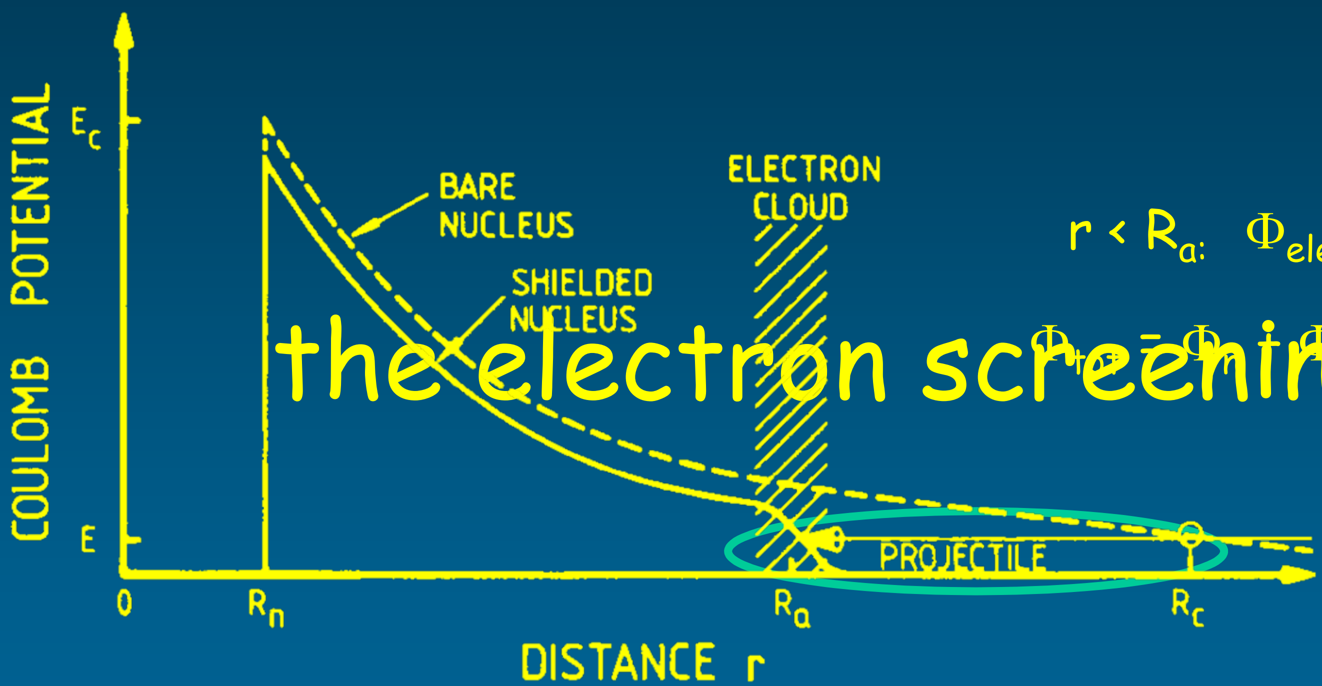
Yields of protons emitted in the $D+D$ reaction in Pd, Au/Pd/PdO, Ti, and Au foils are measured by a $dE-E$ counter telescope for bombarding energies between 2.5 and 10 keV. The experimental yields are compared with those predicted from a parametrization of the cross section and stopping power at higher energies. It is found that for Ti and Au target the enhancement of the $D(d,p)T$ reaction is similar to that observed with a deuterium gas target (several tens of eV). The dependence of the yields on the bombarding energy corresponds well to the screening potential parameters $U_s=250\pm 15$ eV for Pd and 601 ± 23 eV for Au/Pd/PdO. Possible models of the enhancement obtained

Screening effect of atomic electrons

interaction not between "bare" nuclei

in the lab: atoms and/or ions interact

in the stars: plasma electrons



$r < R_a$: $\Phi_{electr} = cost \approx -Z_1e/R_a$

$\Phi_{tot} = \Phi_n + \Phi_{electr} = Z_1e/r - Z_1e/R_a$

the electron screening....

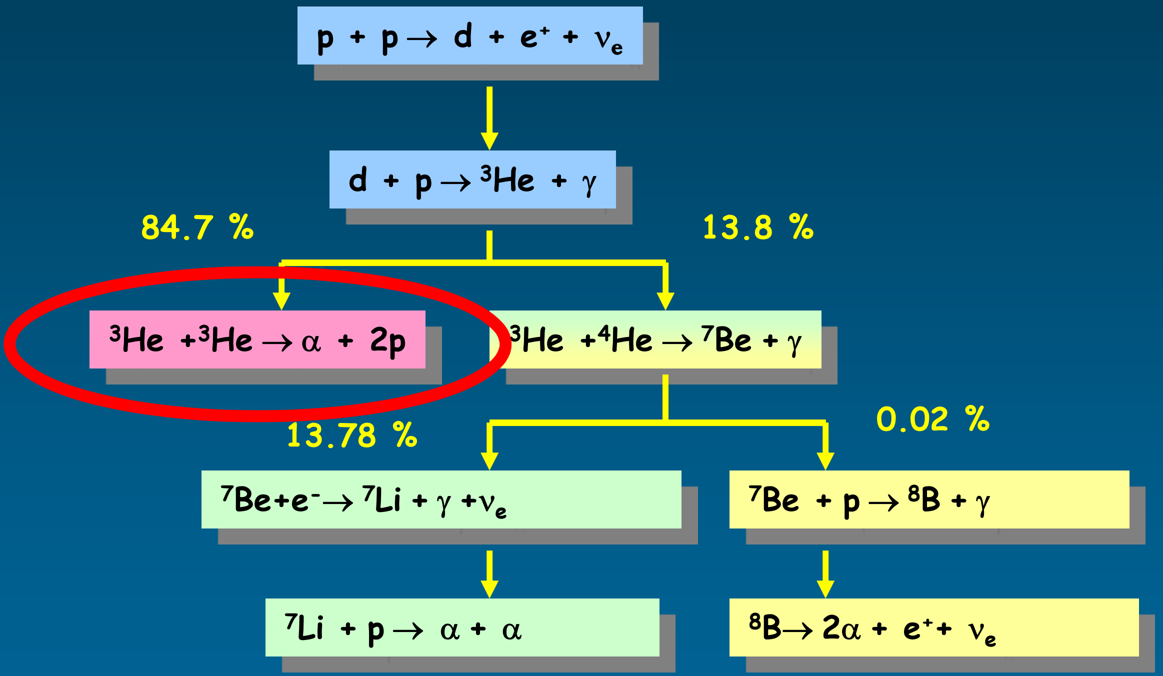
for $r > R_a$: $F_{repuls} = 0$

$E_{eff} = Z_1Z_2e^2/R_n - Z_1Z_2e^2/R_a$ $R_n/R_a \approx 10^{-5}$: negligible correction

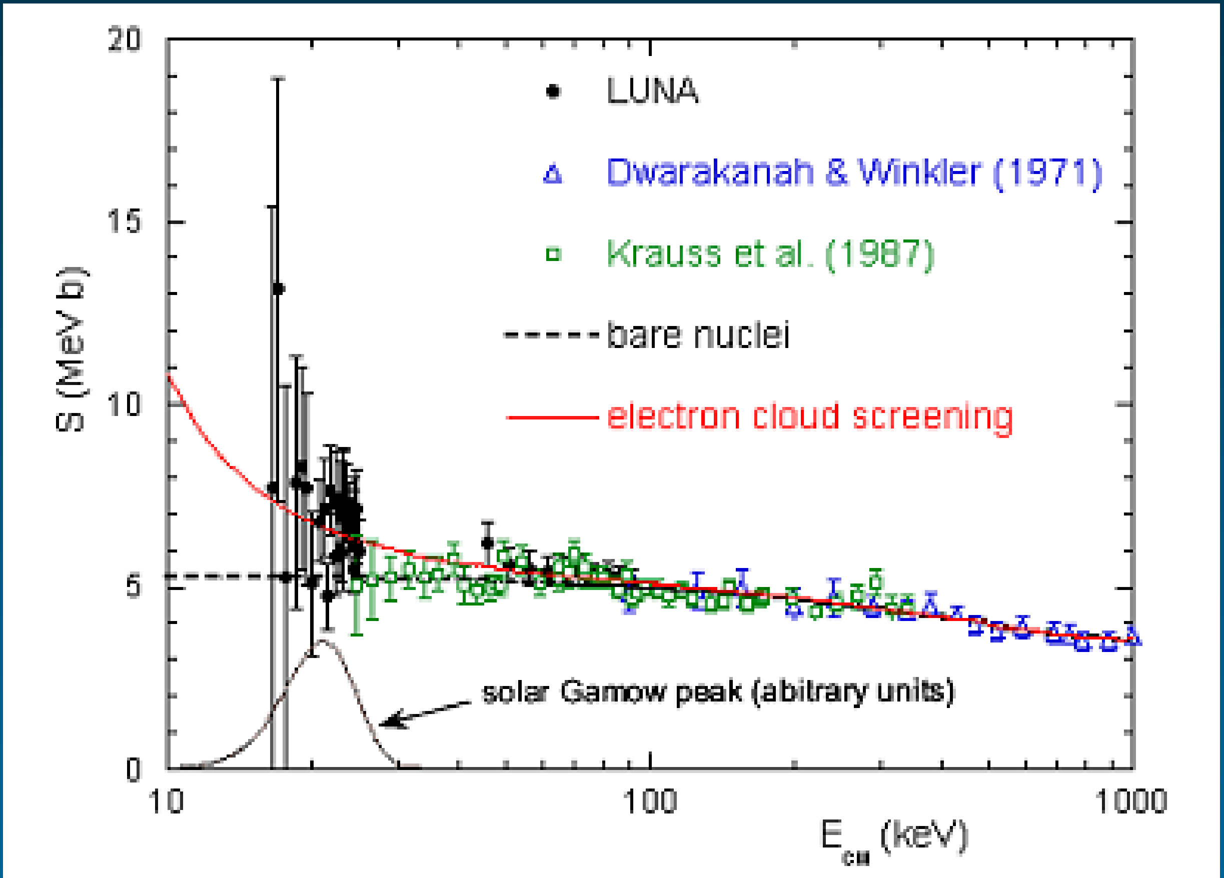
but if: $R_c > R_a$ barrier thickness dramatically changes.

LUNA results

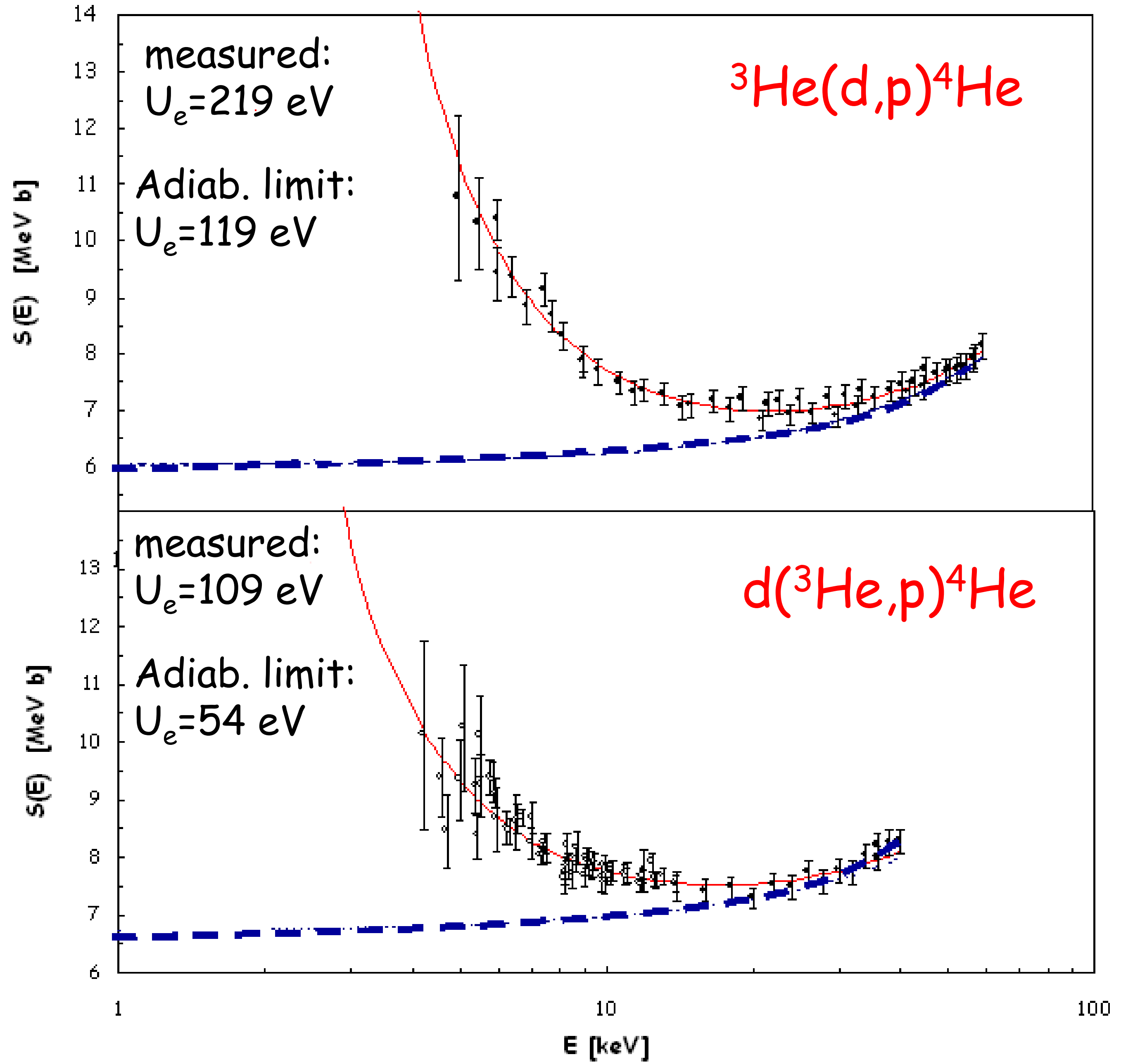
pp chain



$^3He(^3He,2p)^4He$

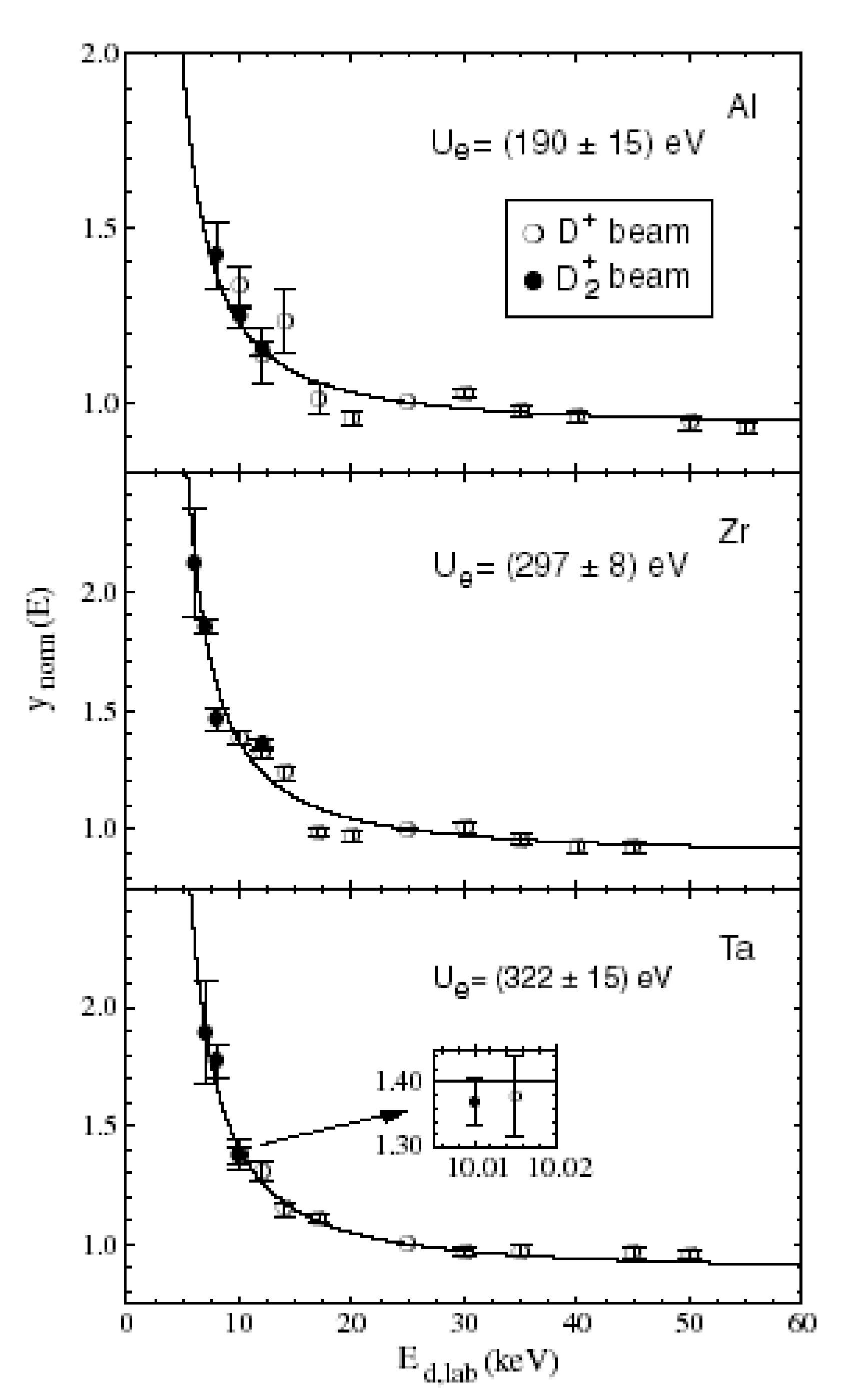


D(^{3}He,p)^{4}He


measured:
U_e=219 eV
Adiab. limit:
U_e=119 eV
^{3}He(d,p)^{4}He
measured:
U_e=109 eV
Adiab. limit:
U_e=54 eV
d(^{3}He,p)^{4}He
S(E) [MeV b]
E [keV]
14
13
12
11
10
9
8
7
6
1
10
100

In 2001, the electron screening effect in d(d,p)t and d(d,n)^{3}He reactions has been studied for the metals Al, Zr, and Ta. The deuterated metals were produced via implantation of low- energy deuterons (Czreski et al.,)

The resulting *Us* values *Us* = 190 ± 15, 297 ± 8, and 322 ± 15 eV for Al, Zr, and Ta, respectively) are about one order of magnitude larger than the value found in a gas-target experiment *Us*=25±5 eV (Greife et al., 1995).



Berlin Data for Ta, 2003

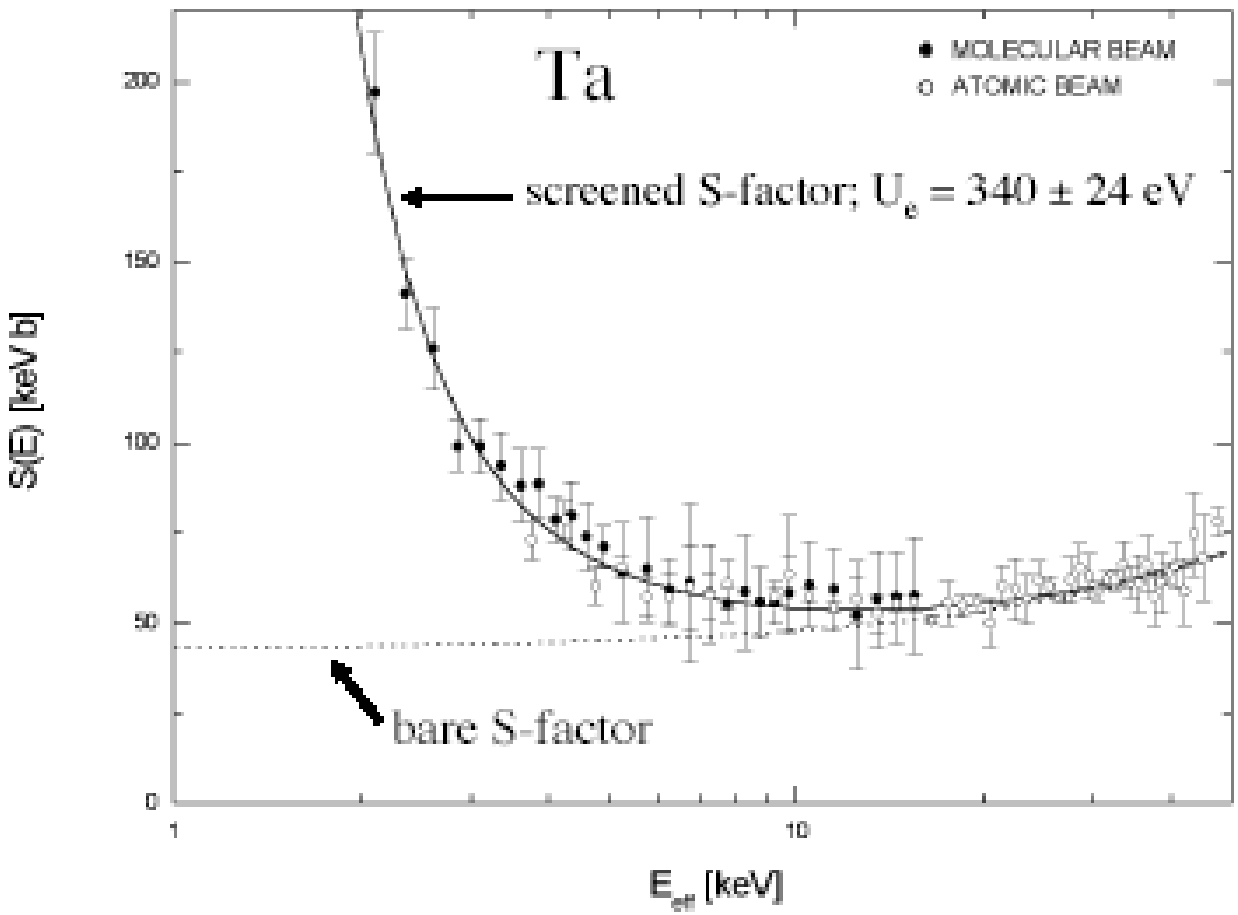


Fig. 1. Measured astrophysical S-factor of the d(d,p)t reaction in deuterated Ta

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Physics Letters B 547 (2002) 193–199
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Electron screening in d(d, p)t for deuterated metals and the periodic table ☆

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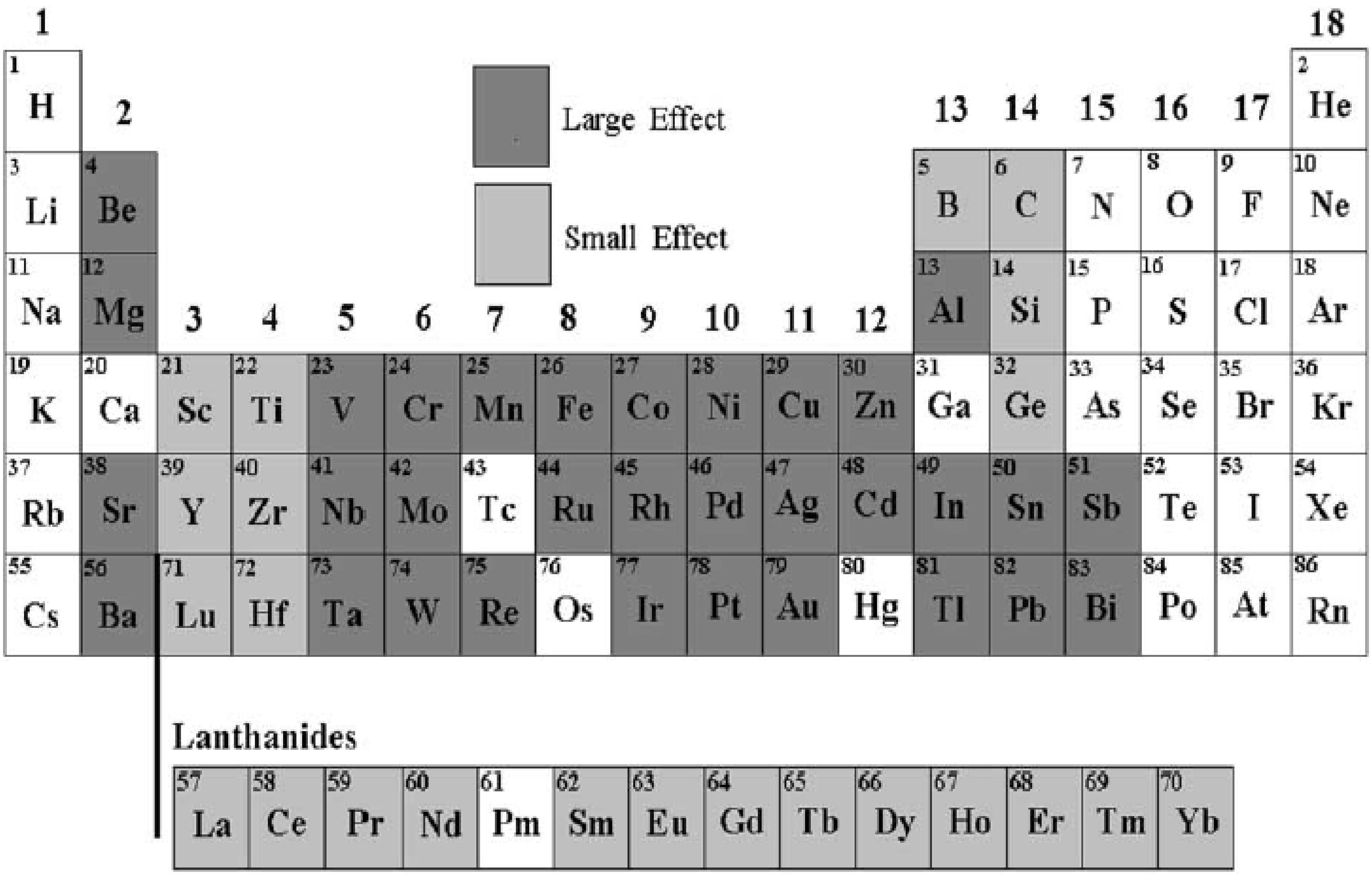
D(D,p)T for deuterated metals and insulators (58 samples through the Periodic table)



- Large screening in all metals

  $U_s \sim 300$ eV vs $U_{adiabatic} \sim 27$ eV

- Small screening for the insulators

What electronic properties of the metals lead to the observed correlation with the periodic table

and what is the acceleration mechanism leading to the high observed Us values?

There was no explanation to this enhanced electron screening. Several possible reasons have been considered (including the thermal motion of target atoms, channeling, diffusion, conductivity, Fermi-shuttle mechanism, crystal structure, etc.)

None of them could explain the results.

Eur. Phys. J. A 19, 283–287 (2004)
DOI 10.1140/epja/i2003-10125-0

THE EUROPEAN PHYSICAL JOURNAL A

Debye

If n_{eff} is the number of valence electrons per metallic atom which can be effectively treated as classical and quasi-free, one may apply the classical plasma theory of Debye leading to an electron sphere of radius [9]

$$R_{\mathrm{D}} = (\varepsilon_0 kT/e^2 n_{\mathrm{eff}} \rho_{\mathrm{a}})^{1/2} = 69(T/n_{\mathrm{eff}} \rho_{\mathrm{a}})^{1/2} \quad (\mathrm{m}) \qquad (4)$$

around positive singly charged ions (here: deuterons in the lattice) with the temperature of the free electrons T in units of K and the atomic density ρ_{a} in units of m^{-3}. For $T = 293$ K, $\rho_{\mathrm{a}} = 6 \times 10^{28}\ \mathrm{m}^{-3}$, and $n_{\mathrm{eff}} = 1$, one obtains a radius R_{D}, which is about a factor 10 smaller than the Bohr radius of a hydrogen atom. With the Coulomb energy between two deuterons at R_{D} set equal to U_e, one obtains $U_e = (4\pi\varepsilon_0)^{-1} e^2/R_{\mathrm{D}} = 300$ eV, the order of magnitude of the observed U_e values. A comparison of the

Critical test

- A critical test of the Debye model – a temperature dependence $U_s \sim T^{-1/2}$

Experimentally verified

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

J. Phys. G: Nucl. Part. Phys. 31 (2005) 1141–1149 doi:10.1088/0954-3899/31/11/002

Electron screening in d(d, p)t for deuterated metals: temperature effects

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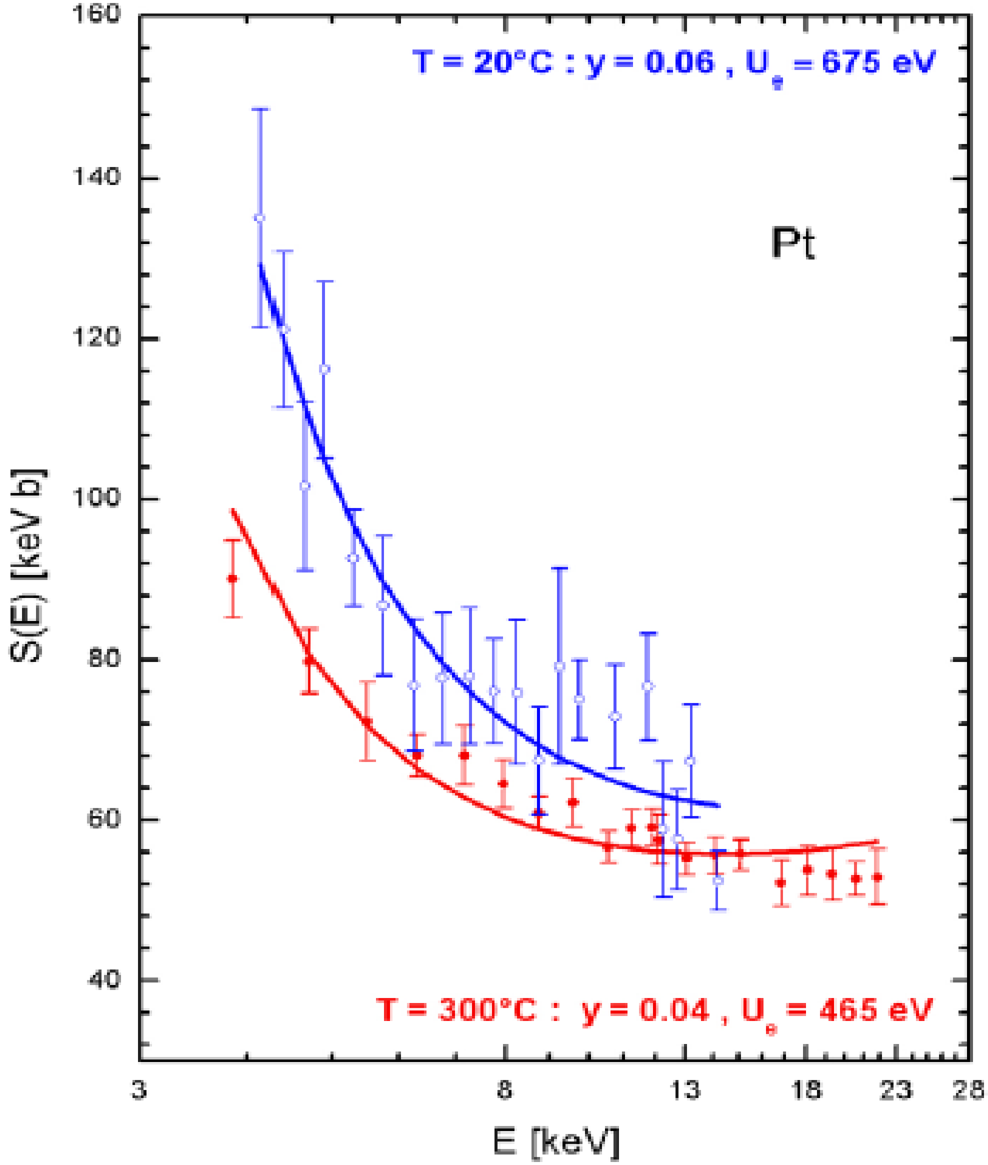
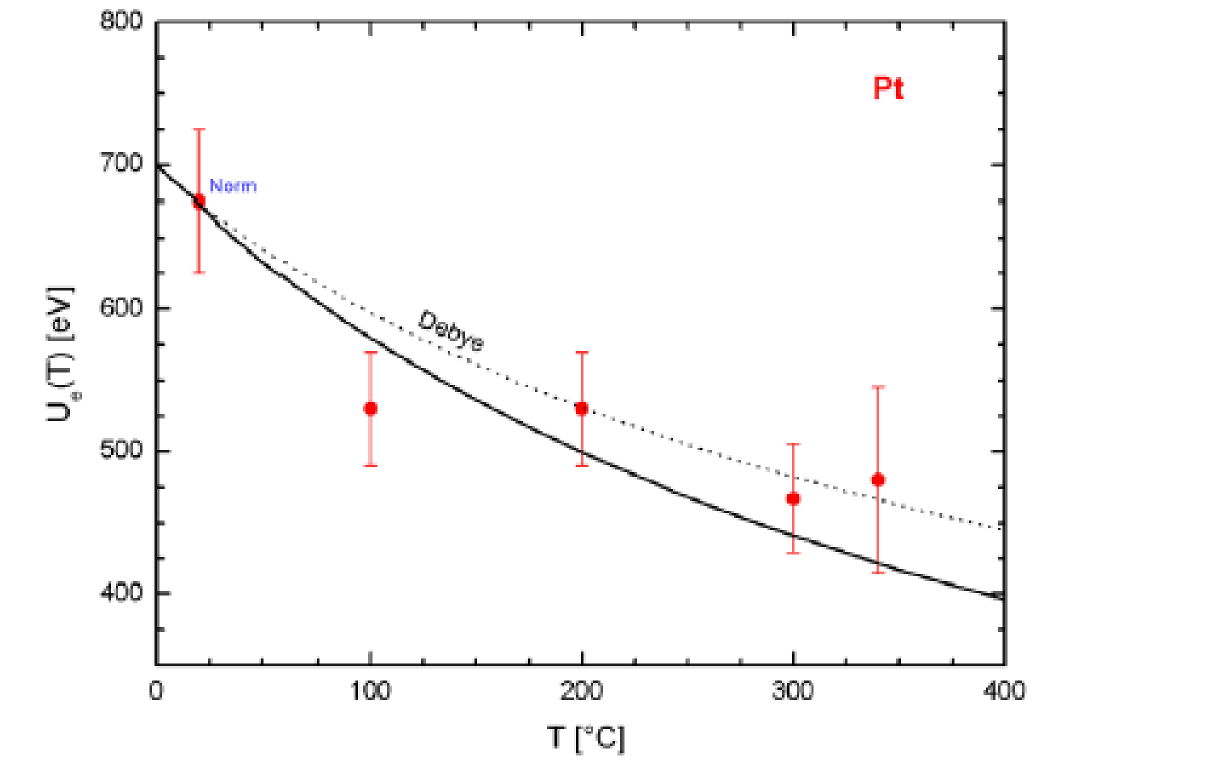
Critical test2



The *S*(*E*) factor of d(d, p)t for Pt at *T* = 20 *C* and 300 *C*, with the deduced solubilities *y*.

The curves through the data points include the bare *S*(*E*) factor and the electron screening with the given *Us* values.



The observed values $Ue(T)$ for Pt are shown as a function of sample temperature T.

The dotted curve represents the prediction of the Debye model and the solid curve includes the observed T-dependence of the Hall coefficient, i.e. $n_{eff}(T)$.

- Debye energy U_D *scales* with the nuclear charge Z of the target atoms Critical test4

  Verified for Z=3 (Li), 4 (Be), 23 (V), 71 (Lu) for pure metals.

- $U_D \sim Z_i$ (Debye energy scales with the nuclear charge of the ion)

  Also verified with D(^{3}He, p) ^{4}He reaction.

- Electron screening is an effect *in the entrance channel* (confirmed in reactions with neutrons in the exit channel)

Why the simple Debye model appears to work so well?

Electron screening in metallic environments: a plasma of the poor man

C. Rolfs

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Abstract. Fusion reactions play a key role in stars for the understanding of their energy production, evolution and neutrino emission. An important aspect is hereby the effects of electron screening, which increase the fusion cross sections. The fusion reaction D(D,p)T was recently studied in deuterated metals and insulators, i.e. for 58 samples across the periodic table, where a dramatic increase was observed for all the metals. An explanation of the data is presented as well as important future applications are discussed.

Key words. Nuclear Astrophysics–Fusion reactions–Radioactive decay