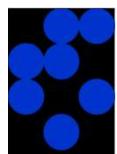


# Nuclear reactions in normal versus inverse kinematics

Matej Lipoglavšek

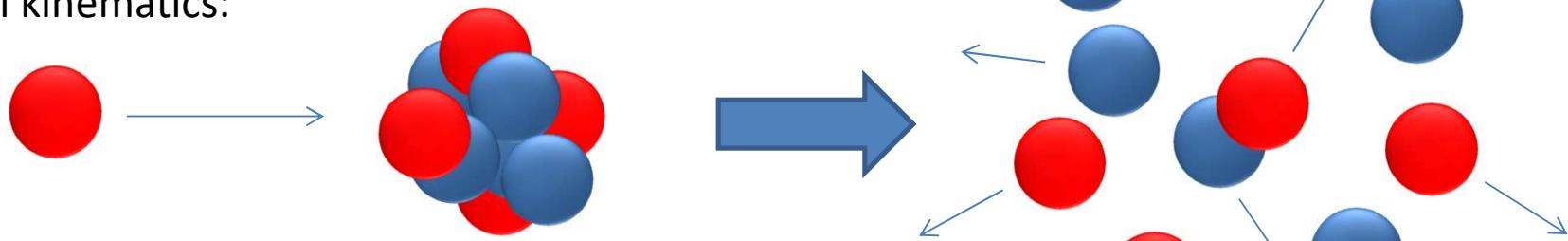
*Jožef Stefan Institute, Ljubljana,  
Slovenia*



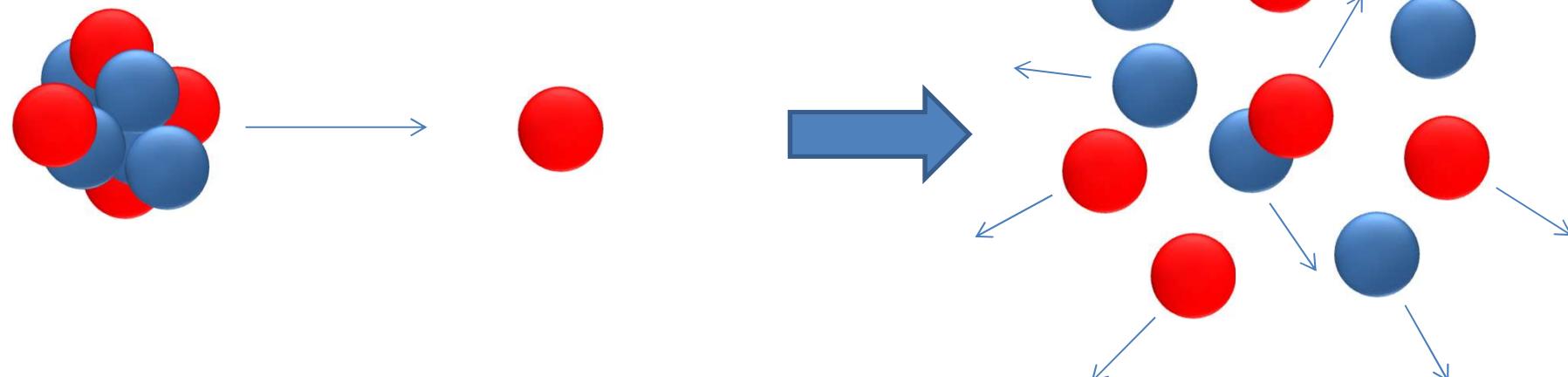
Russbach, March 2022

# Kinematics

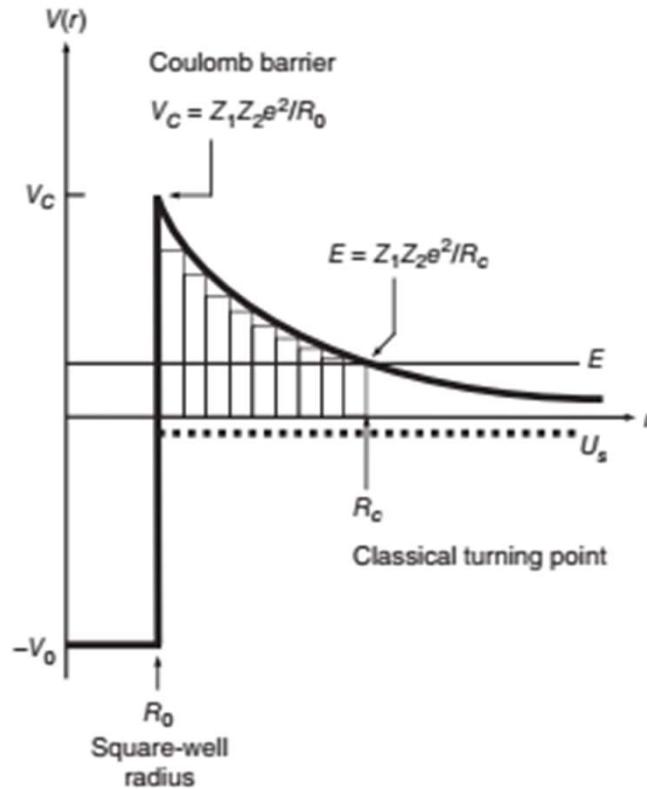
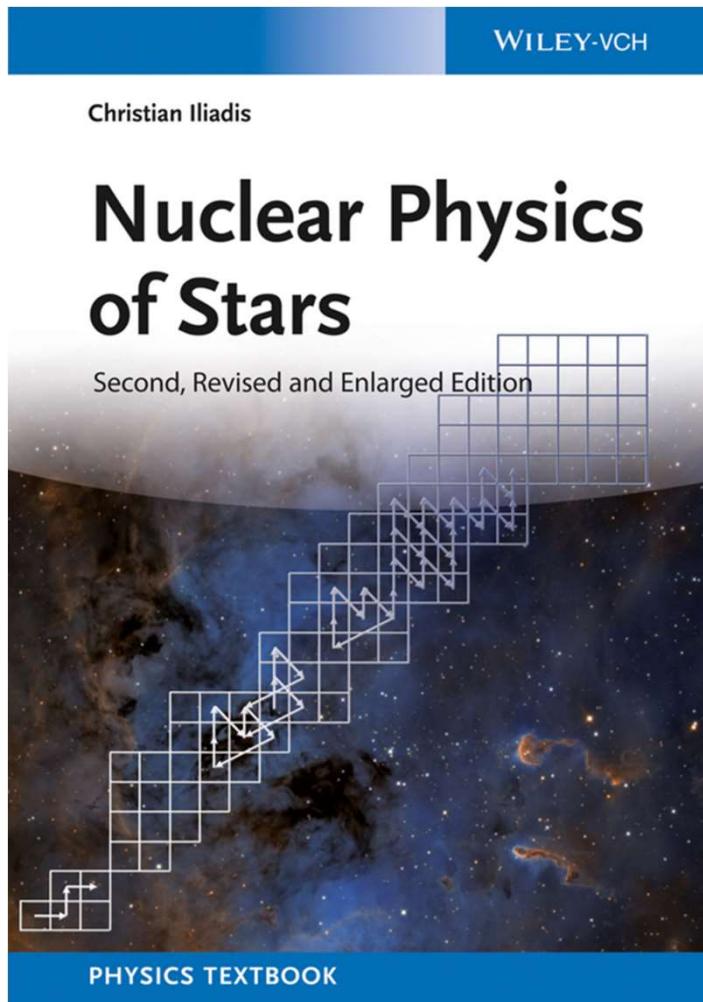
Normal kinematics:



Inverse kinematics:



# Tunneling



Coulomb barrier transmission probability

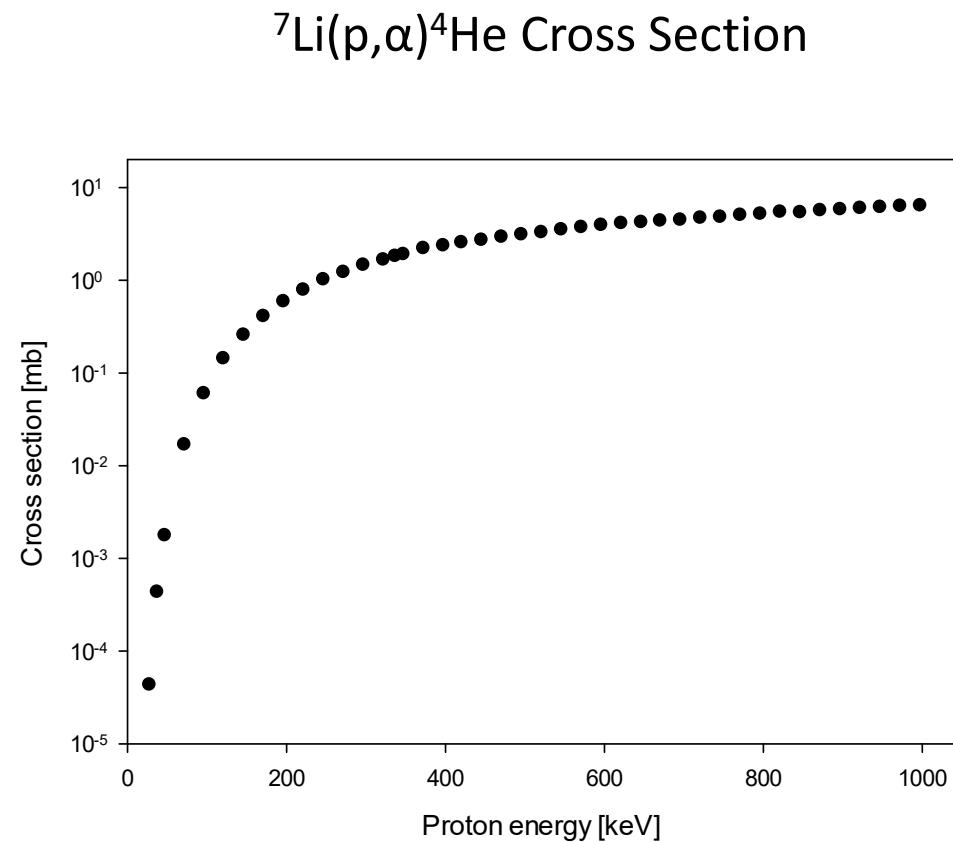
$T = e^{-2\pi\eta}$ , Gamow factor, where

Sommerfeld parameter:  $\eta = \frac{Z_1 Z_2 e^2}{4\pi\epsilon_0 hc} \cdot \sqrt{\frac{\mu c^2}{2E}}$

# Astrophysical S-factor

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

$\sigma$  - cross section,  
 $S(E)$  – S factor,  
 $E$  – geometrical factor,  
 $e^{-2\pi\eta}$  - Gamow factor.



C. Rolfs and R.W.Kavanagh, Nucl. Phys. **A455** (1986) 179.

# Catalysis of nuclear reactions by muons

LETTERS TO THE EDITOR

1127

Rubin, U. S. Geological Survey Radiocarbon Laboratory, kindly communicated to the writer. (See references 9 and 10.)

<sup>9</sup> H. Craig, Tellus (to be published).

<sup>10</sup> H. Craig, reference 5.

<sup>11</sup> Benton, Estoque, and Dominitz, Science Report No. 1, Civil Engineering Department, Johns Hopkins University, 1953 (unpublished).

<sup>12</sup> W. F. Libby, Science 123, 656 (1956); Proc. Nat. Acad. Sci. 42, 365 (1956).

<sup>13</sup> P. Morrison and J. Pine, Ann. N. Y. Acad. Sci. 62, 69 (1955).

<sup>14</sup> K. Mayne, Geochim. et Cosmochim. Acta 9, 174 (1956).

<sup>15</sup> Fowler, Burbidge, and Burbidge, Astrophys. J. Suppl. 2, 167 (1955).

<sup>16</sup> M. Koshiba and M. Schein, Phys. Rev. 103, 1820 (1956).

<sup>17</sup> Note added in proof.—The results of these calculations were discussed with F. Begemann and W. F. Libby during the summer of 1956; they now find that their recent data on the tritium balance in the Mississippi Valley, taking into account outward vapor transport of tritium as discussed above, indicate a production rate over that area equal to the value calculated above for North America. Recently J. Arnold has also concluded from consideration of the present calculations that tritium is probably being accreted from the sun.

## Catalysis of Nuclear Reactions by $\mu$ Mesons\*

L. W. ALVAREZ, H. BRADNER, F. S. CRAWFORD, JR., J. A. CRAWFORD,<sup>†</sup> P. FALK-VAIRANT, M. L. GOOD, J. D. GOW,  
A. H. ROSENFIELD, F. SOLMITZ, M. L. STEVENSON,  
H. K. TICHO, AND R. D. TRIPP

Radiation Laboratory, University of California, Berkeley, California  
(Received December 17, 1956)

IN the course of a recent experiment involving the stopping of negative  $K$  mesons in a 10-inch liquid hydrogen bubble chamber,<sup>1</sup> an interesting new reaction was observed to take place. The chamber is traversed by many more negative  $\mu$  mesons than  $K$  mesons, so that in the last 75 000 photographs, approximately 2500  $\mu^-$  decays at rest have been observed. In the same pictures,



FIG. 1. Example of H-D reaction catalyzed by  $\mu^-$  meson. The incident meson comes to rest, drifts as a neutral mesonic atom, is ejected with 5.4 Mev by the H-D reaction, comes to rest again after 1.7 cm, and decays.

between the last bubble of the primary track and the first bubble of the secondary track. This gap is a real effect, and not merely a statistical fluctuation in the spacing of the bubbles, since in some cases the tracks form a letter X (see Fig. 1), and in another case the secondary track is parallel to the primary, but displaced transversely by about 1 mm at the end of the primary. These real gaps appear also (although perhaps less frequently) between some otherwise normal-looking  $\mu^-$  endings and the subsequent decay electron; they are thought to be the distance traveled by the small neutral mesonic atom.<sup>3</sup>

One may quickly dispose of the most obvious suggestion that the events are  $\pi^- - \mu^- - e^-$  decays. If, by some unknown process, negative  $\pi$  mesons could decay

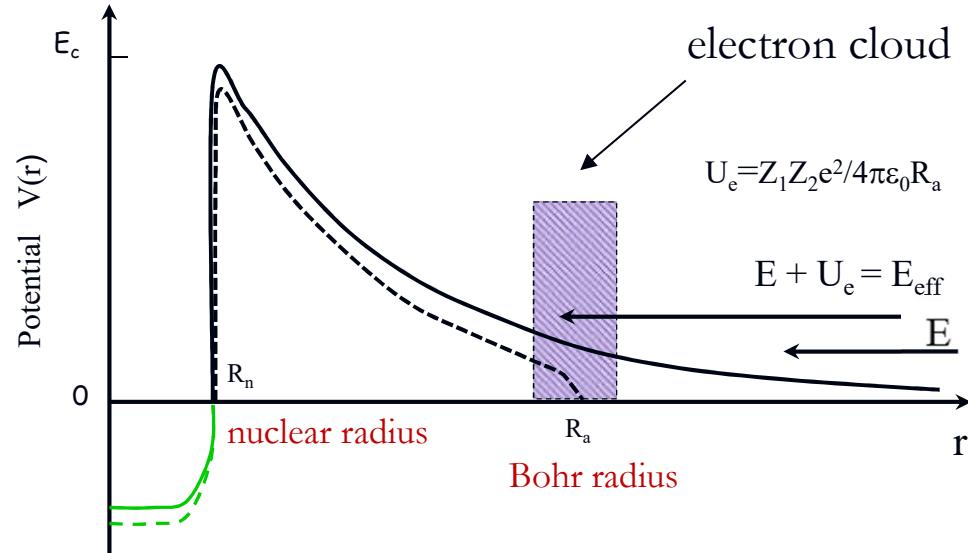
Instead of  
 $D(p,\gamma)^3\text{He}$   
Alvarez measured  
 $D(p,\mu)^3\text{He}$

# Electron Screening

Cross section increases at low energies when the interacting nuclei are not bare. Enhancement factor

$$f = \frac{e^{-2\pi\eta(E+U_e)}}{e^{-2\pi\eta(E)}}$$

where  $U_e$  is the screening potential.

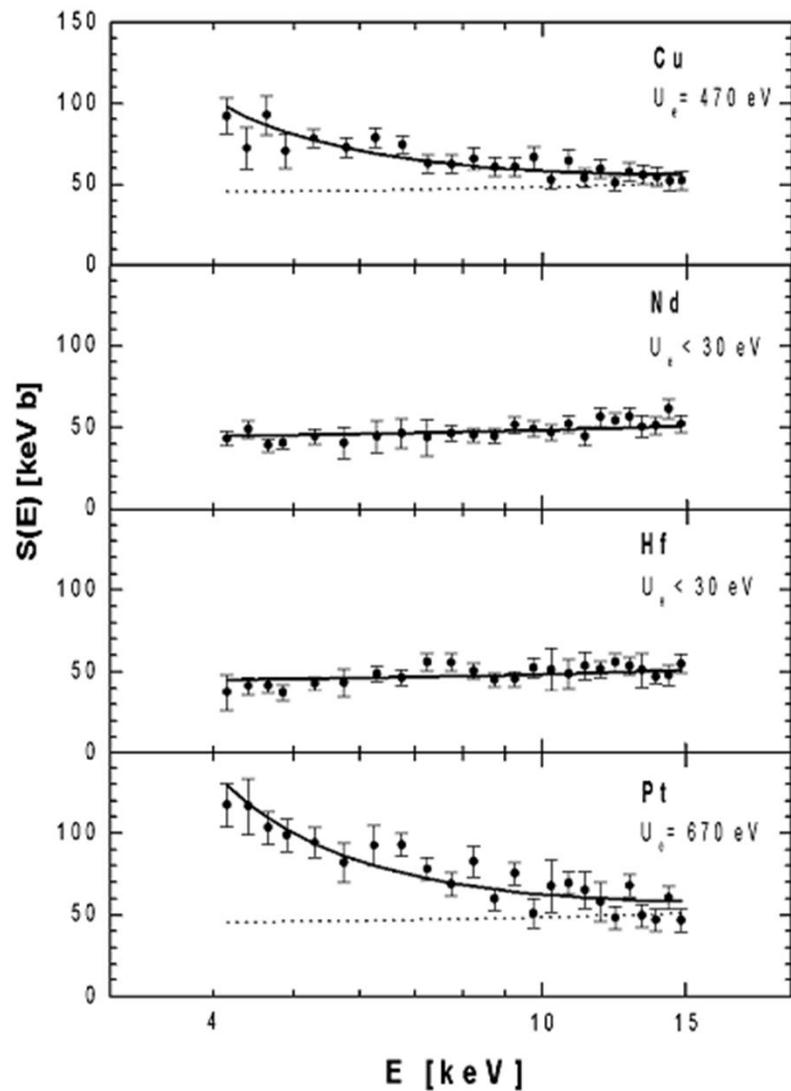


H. J. Assenbaum, K. Langanke and C. Rolfs, Z. Phys. A **327** (1987) 461.  
395 citations (Web of Science, November 2021).

$$\frac{R_n}{R_a} \approx 10^{-5} \Rightarrow U_e = \frac{e^2}{4\pi\epsilon_0 R_a} = 27 \text{ eV for d+d reaction}$$

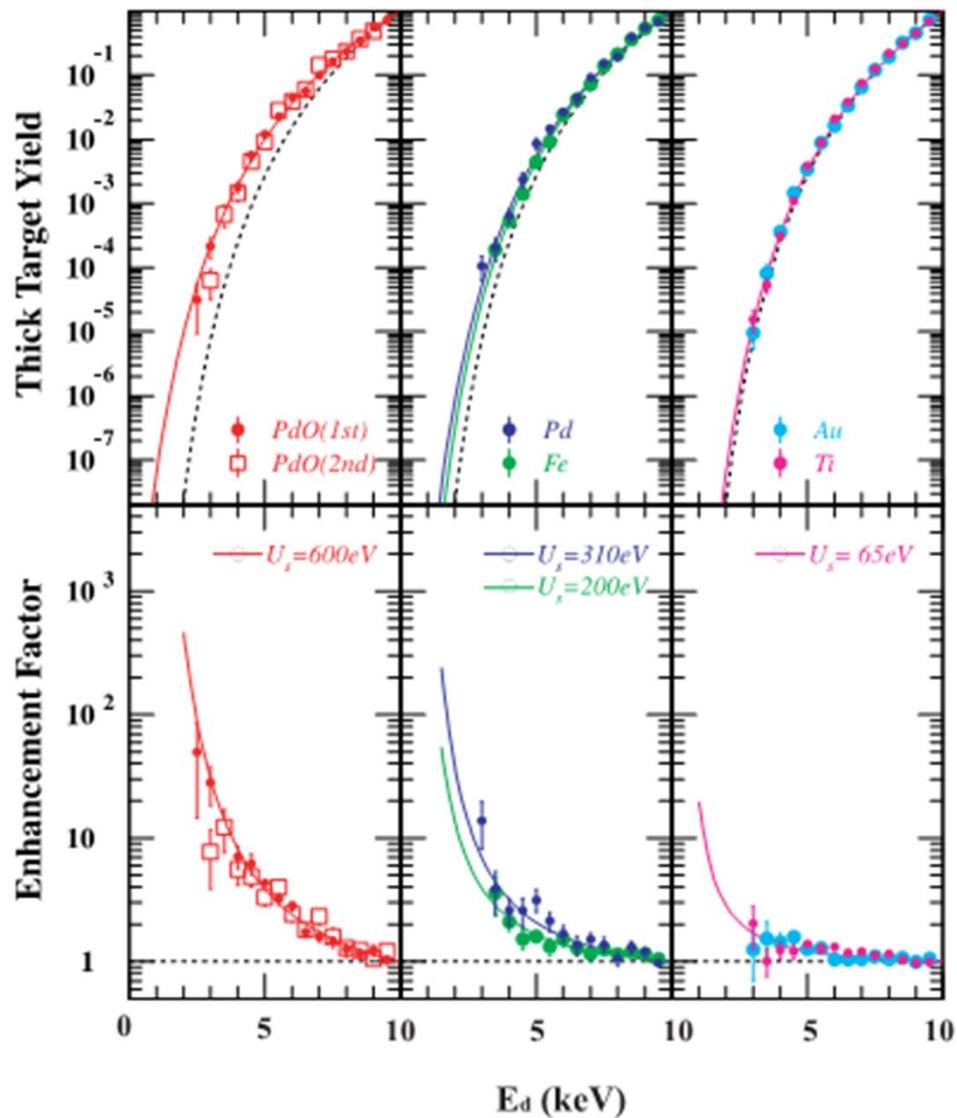
# Previous Results 1

for d(d,p)t reaction from F. Raiola et al., Eur. Phys. J. A19 (2004) 283.



Material	$U_e$ (eV) <sup>(b)</sup>	Solubility $1/x$ <sup>(c)</sup>	$n_{\text{eff}}$ <sup>(b)</sup>	$n_{\text{eff}}$ (Hall) <sup>(d)</sup>
Metals				
Be	$180 \pm 40$	0.08	$0.2 \pm 0.1$	$(0.21 \pm 0.04)$
Mg	$440 \pm 40$	0.11	$3.0 \pm 0.5$	$1.8 \pm 0.4$
Al	$520 \pm 50$	0.26	$3.0 \pm 0.6$	$3.1 \pm 0.6$
V	$480 \pm 60$	0.04	$2.1 \pm 0.5$	$(1.1 \pm 0.2)$
Cr	$320 \pm 70$	0.15	$0.8 \pm 0.4$	$(0.20 \pm 0.04)$
Mn	$390 \pm 50$	0.12	$1.2 \pm 0.3$	$(0.8 \pm 0.2)$
Fe	$460 \pm 60$	0.06	$1.7 \pm 0.4$	$(3.0 \pm 0.6)$
Co	$640 \pm 70$	0.14	$3.1 \pm 0.7$	$(1.7 \pm 0.3)$
Ni	$380 \pm 40$	0.13	$1.1 \pm 0.2$	$1.1 \pm 0.2$
Cu	$470 \pm 50$	0.09	$1.8 \pm 0.4$	$1.5 \pm 0.3$
Zn	$480 \pm 50$	0.13	$2.4 \pm 0.5$	$(1.5 \pm 0.3)$
Sr	$210 \pm 30$	0.27	$1.7 \pm 0.5$	
Nb	$470 \pm 60$	0.13	$2.7 \pm 0.7$	$(1.3 \pm 0.3)$
Mo	$420 \pm 50$	0.12	$1.9 \pm 0.5$	$(0.8 \pm 0.2)$
Ru	$215 \pm 30$	0.18	$0.4 \pm 0.1$	$(0.4 \pm 0.1)$
Rh	$230 \pm 40$	0.09	$0.5 \pm 0.2$	$(1.7 \pm 0.4)$
Pd	$800 \pm 90$	0.03	$6.3 \pm 1.3$	$1.1 \pm 0.2$
Ag	$330 \pm 40$	0.14	$1.3 \pm 0.3$	$1.2 \pm 0.3$
Cd	$360 \pm 40$	0.18	$1.9 \pm 0.4$	$(2.5 \pm 0.5)$
In	$520 \pm 50$	0.02	$4.8 \pm 0.9$	
Sn	$130 \pm 20$	0.08	$0.3 \pm 0.1$	
Sb	$720 \pm 70$	0.13	$11 \pm 2$	
Ba	$490 \pm 70$	0.21	$9.9 \pm 2.9$	
Ta	$270 \pm 30$	0.13	$0.9 \pm 0.2$	$(1.1 \pm 0.2)$
W	$250 \pm 30$	0.29	$0.7 \pm 0.2$	$(0.8 \pm 0.2)$
Re	$230 \pm 30$	0.14	$0.5 \pm 0.1$	$(0.3 \pm 0.1)$
Ir	$200 \pm 40$	0.23	$0.4 \pm 0.2$	$(2.2 \pm 0.5)$
Pt	$670 \pm 50$	0.06	$4.6 \pm 0.7$	$3.9 \pm 0.8$
Au	$280 \pm 50$	0.18	$0.9 \pm 0.3$	$1.5 \pm 0.3$
Tl	$550 \pm 90$	0.01	$5.8 \pm 1.2$	$(7.4 \pm 1.5)$
Pb	$480 \pm 50$	0.04	$4.3 \pm 0.9$	
Bi	$540 \pm 60$	0.12	$6.9 \pm 1.5$	

# Previous Results 2



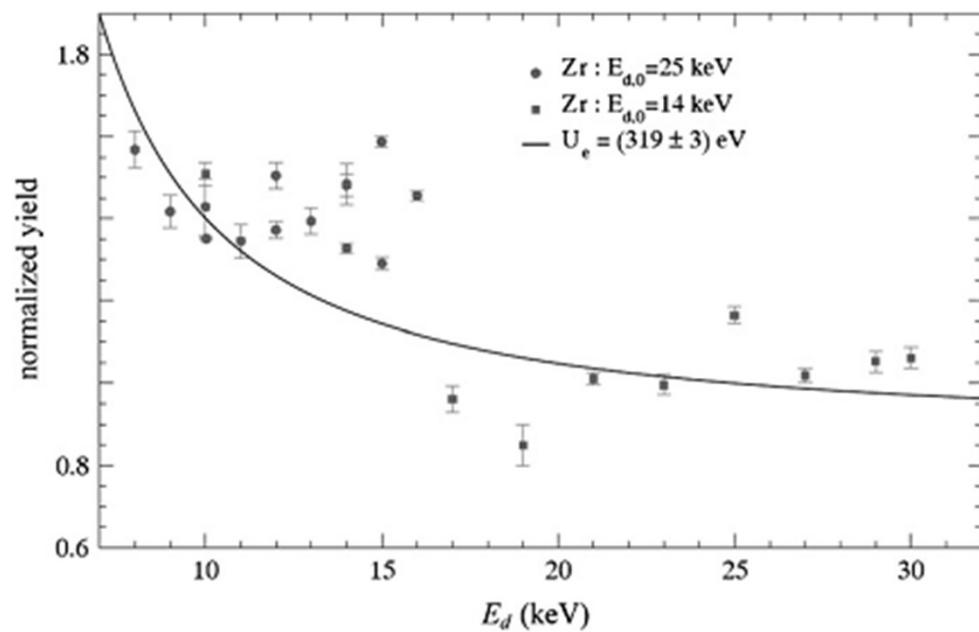
J. Kasagi, Prog. Theo. Phys.  
Suppl. 154 (2004) 365.

for the  $d(d,p)t$  reaction  
 $U_e = 310 \pm 30 \text{ eV}$  @ 7% H/Pd

=> concentration dependence

# Previous Results 3

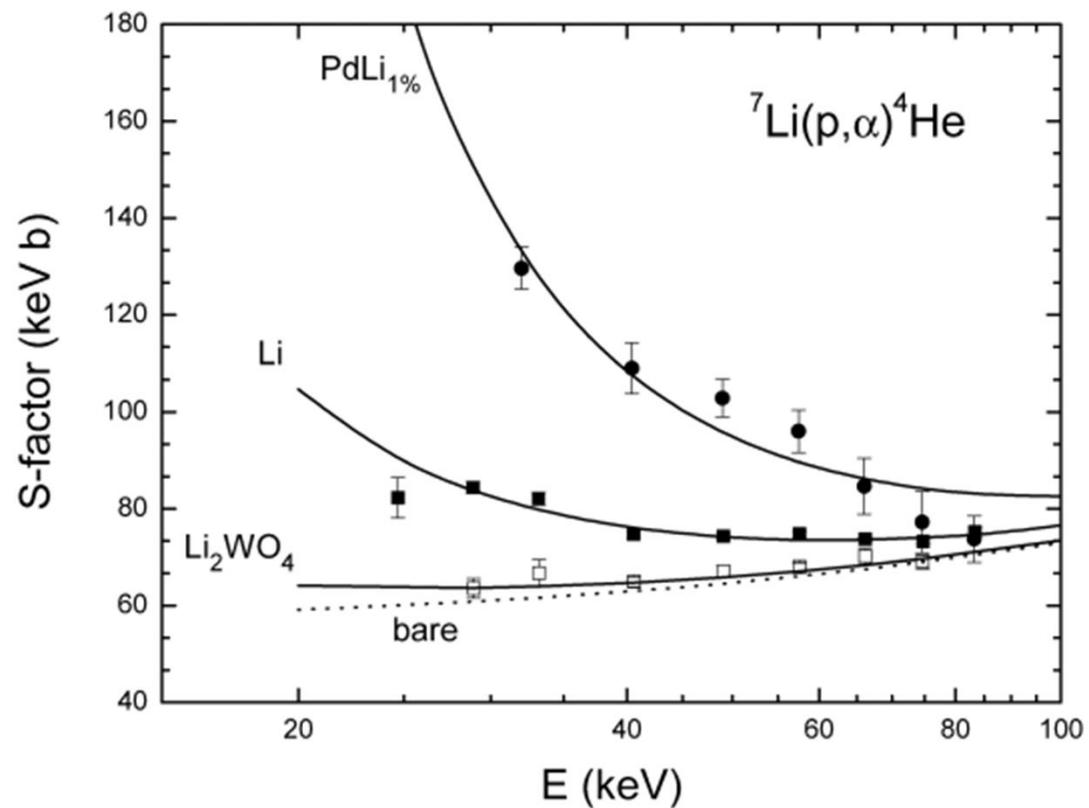
for d(d,p)t reaction from K. Czerski et al., J. Phys. G **35** (2008) 014012.



for zirconium metal  
 $U_e = 319 \pm 3 \text{ eV}$

# Previous Results 4

J. Cruz et al., Phys. Lett. B 624 (2005) 181; J. Phys. G 35 (2008) 014004.

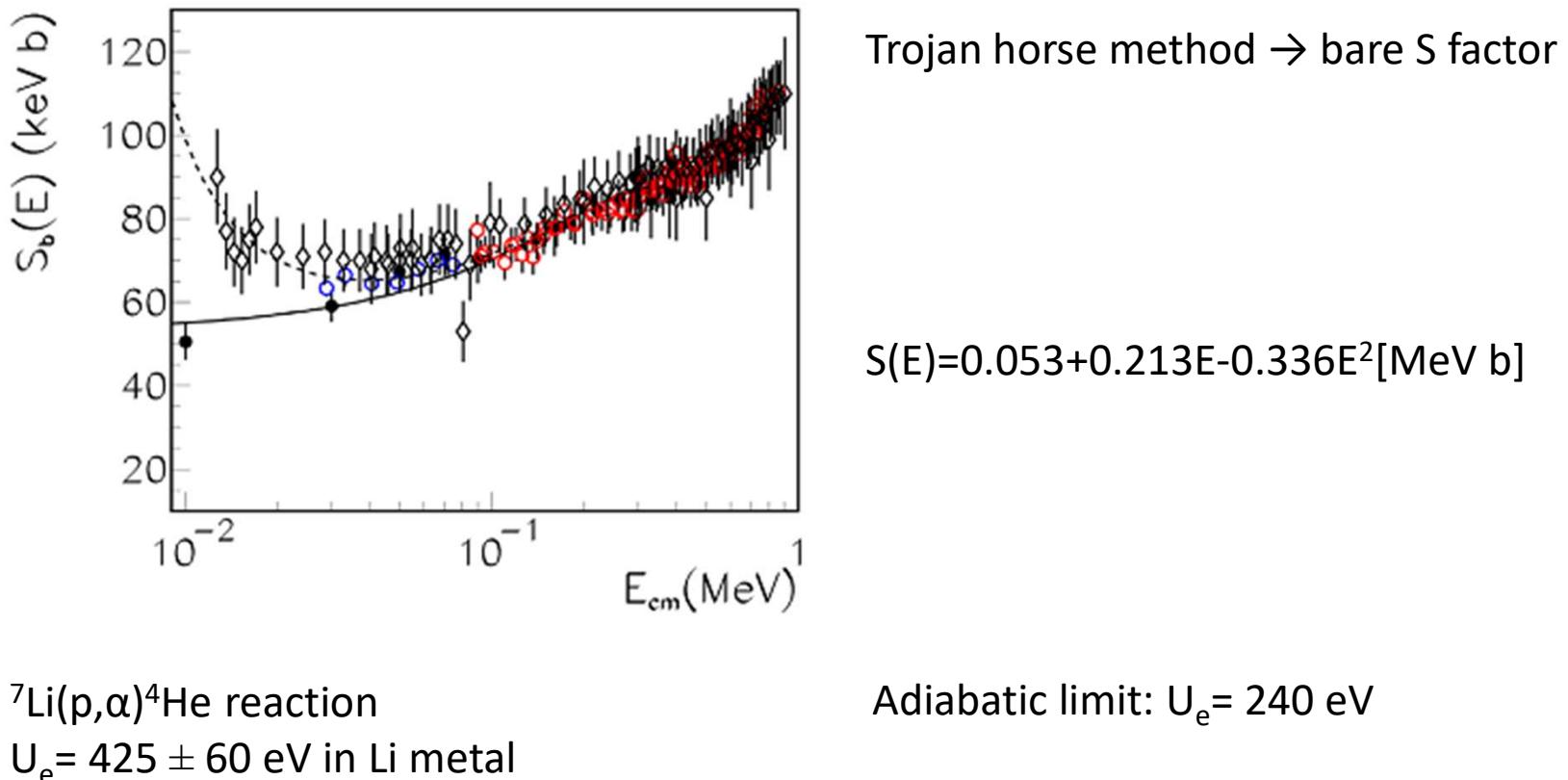


$$\text{PdLi}_{1\%}: U_e = 3.7 \pm 0.3 \text{ keV}$$
$$\text{Li metal: } U_e = 1.18 \pm 0.06 \text{ keV}$$
$$\text{Li}_2\text{WO}_4: U_e = 237^{+133}_{-77} \text{ eV}$$

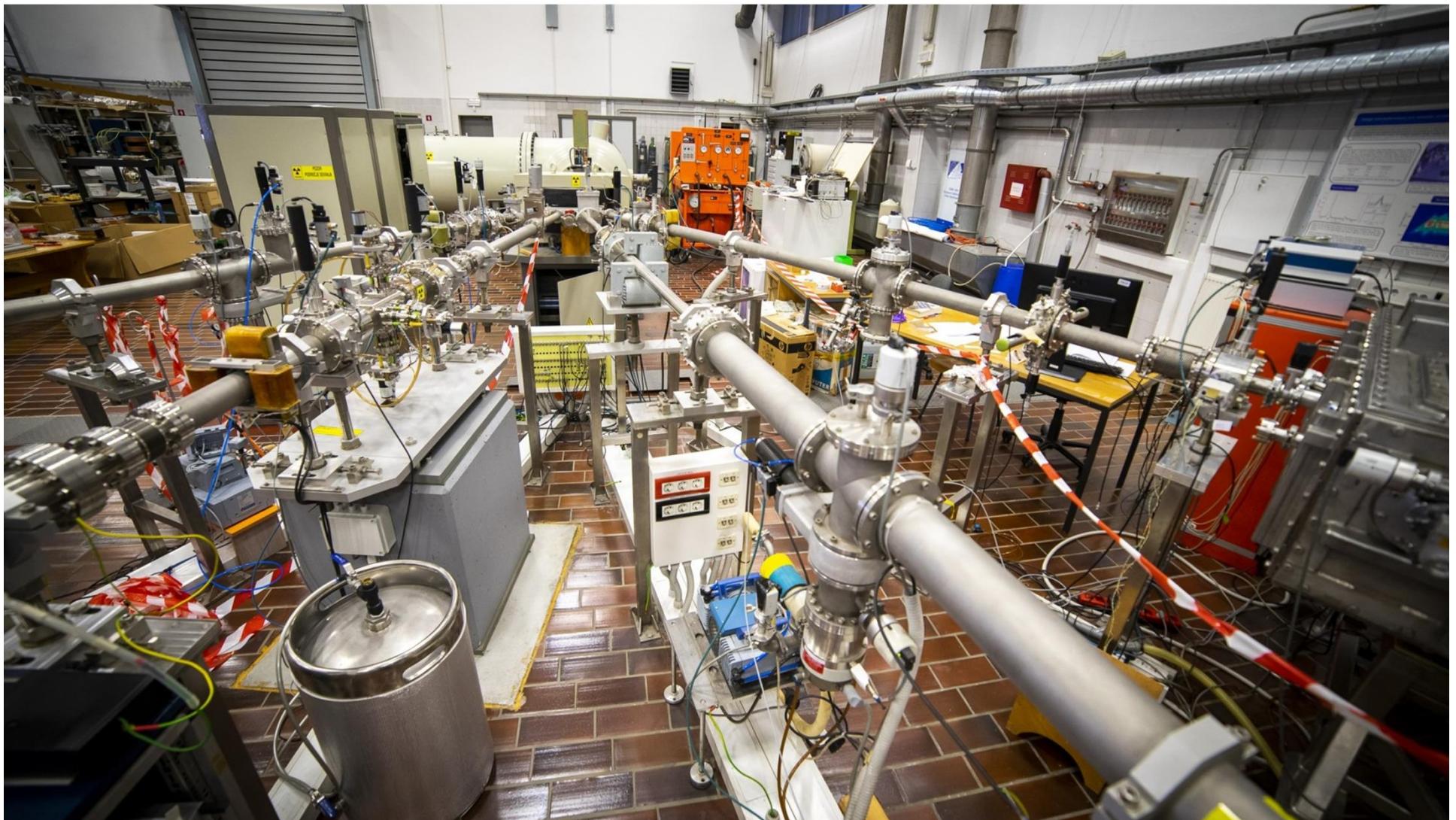
$$S(E) = 0.055 + 0.21E - 0.31E^2 [\text{MeV b}]$$

# Previous Results 5

L. Lamia et al., Astron. Astrophys. 541, A158 (2012).

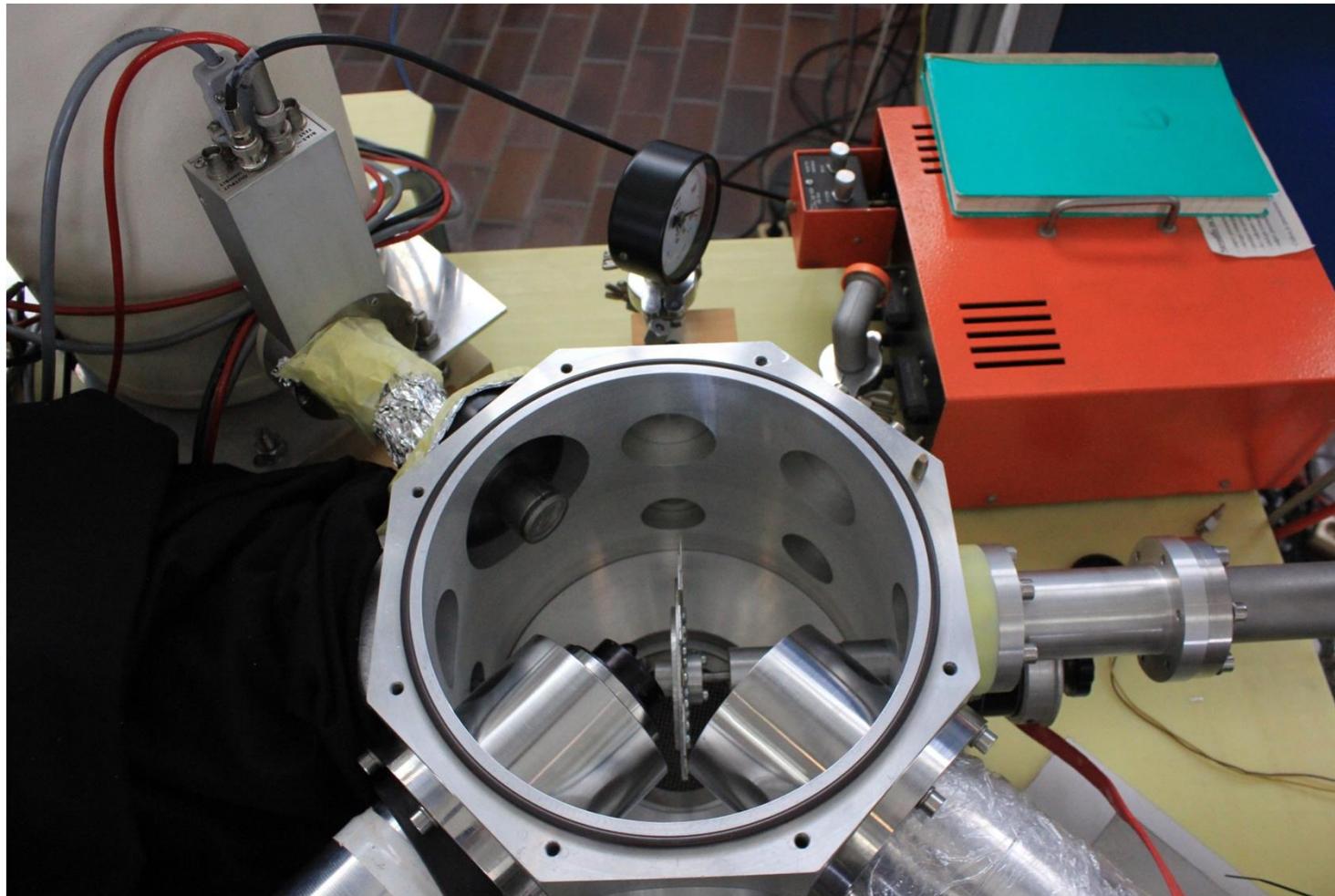


# 2 MV accelerator at JSI



# Measurements @ JSI

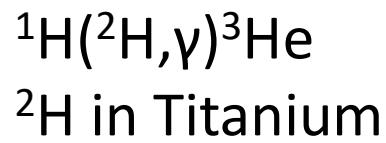
2 MV Tandem van de Graaf accelerator



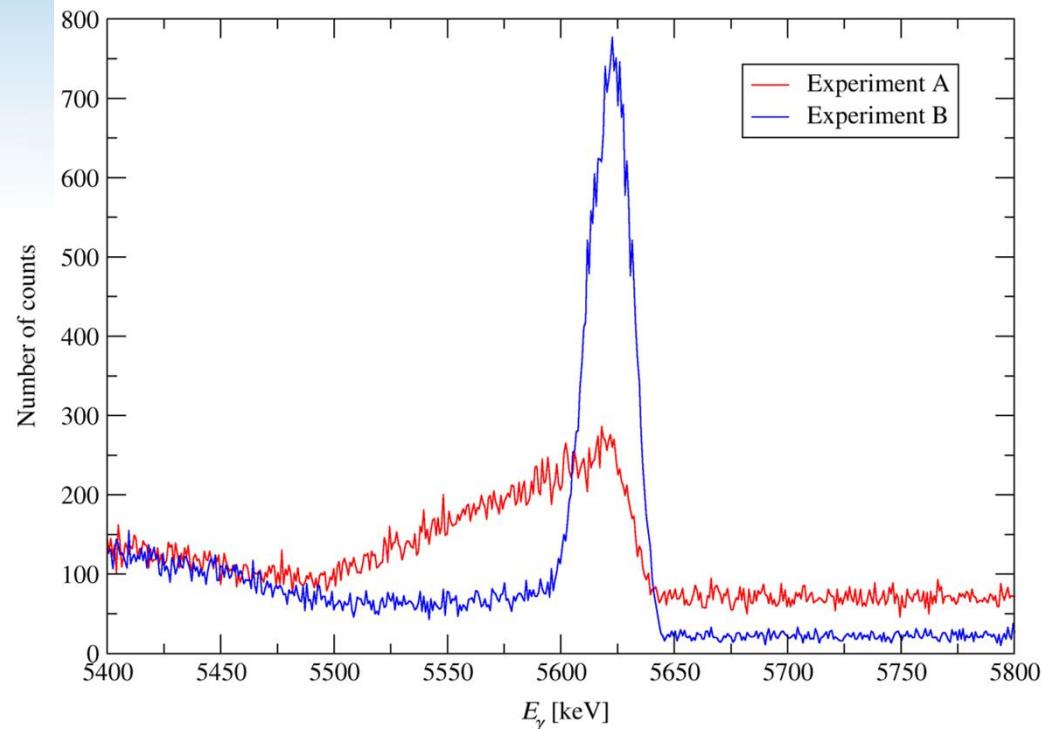
# Implanted deuterium targets



Proton beam energy between 260 and 300 keV from the 2MV Tandetron accelerator.



Deuterium implanted into graphite or titanium at 3.5 kV resulting in up to 150 at. % deuterium concentration.

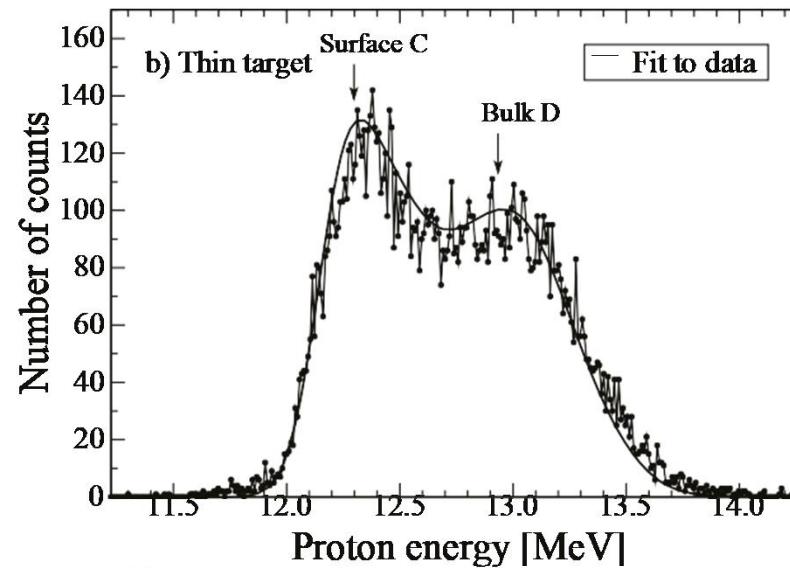
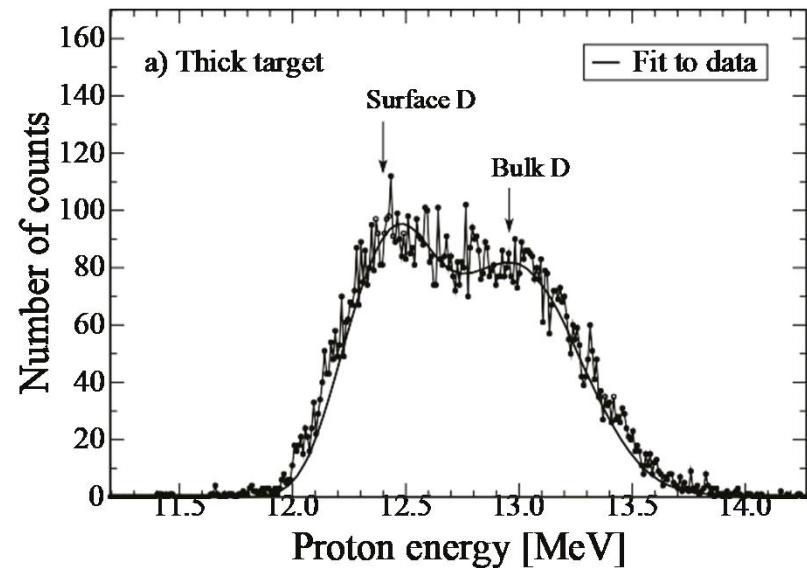


# Gas loaded deuterium targets

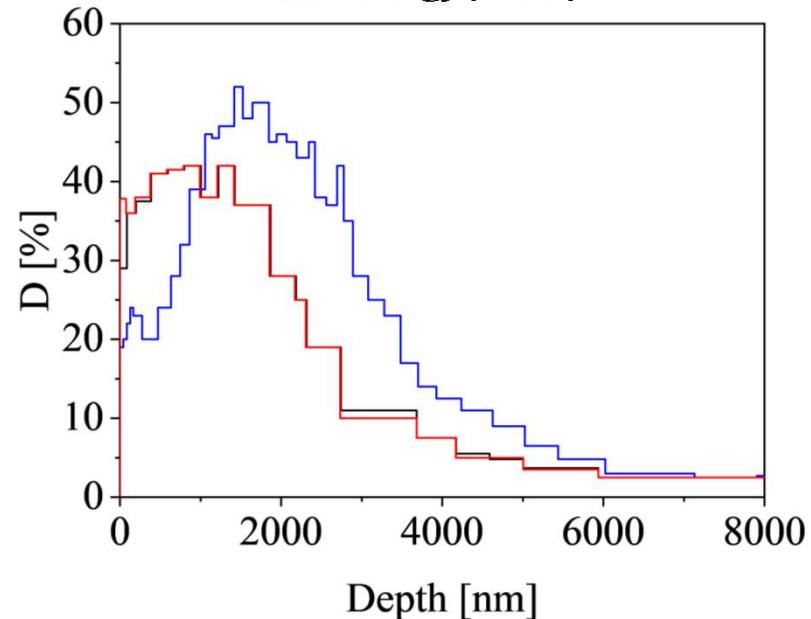


Gas loading at room temperature, 1 atm.  
Up to 70 at. % of hydrogen in Pd determined gravimetrically and checked by NRA.

# Deuterium depth distribution

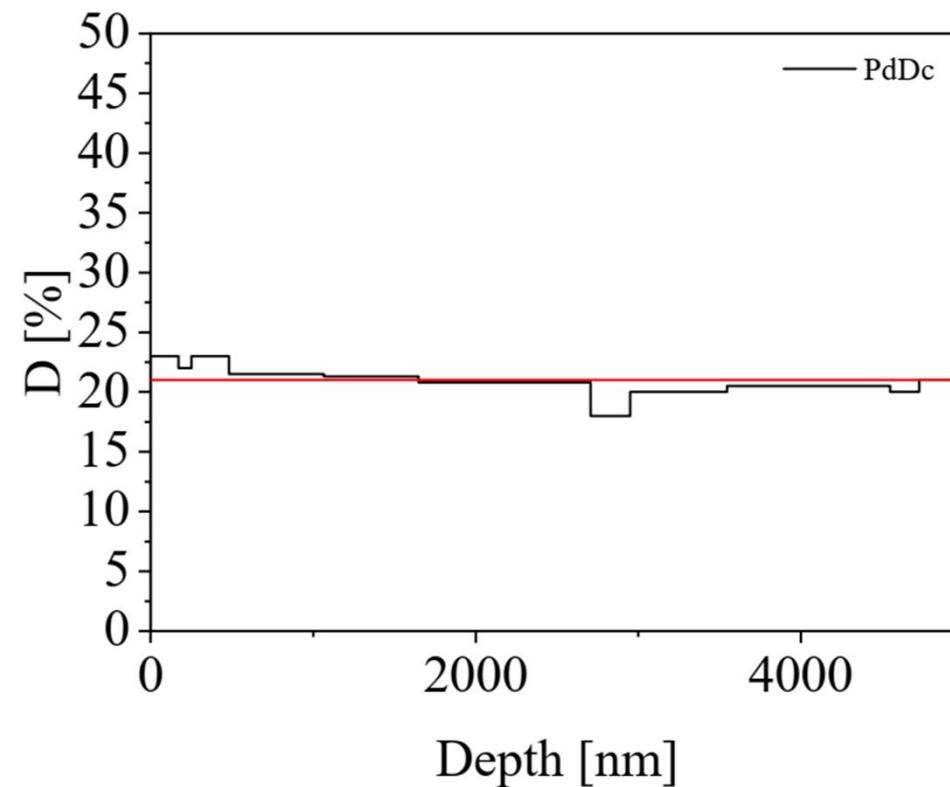


$^2\text{H}(\text{He}^3, \text{p})^4\text{He}$   
 $^2\text{H}$  in Titanium

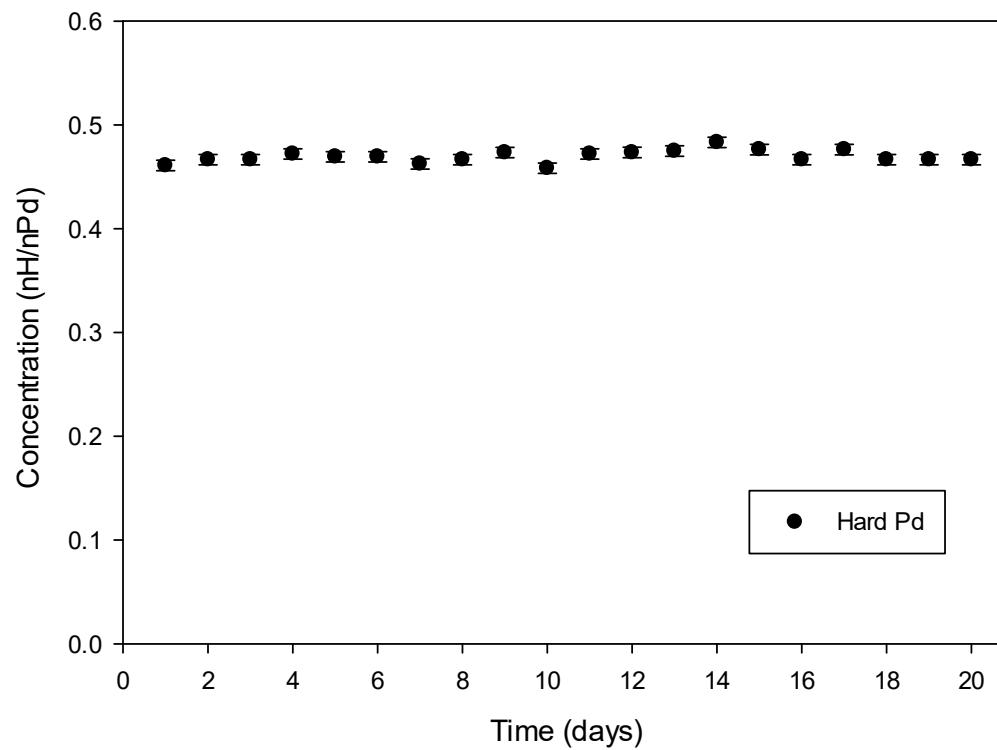


# Deuterium in Palladium

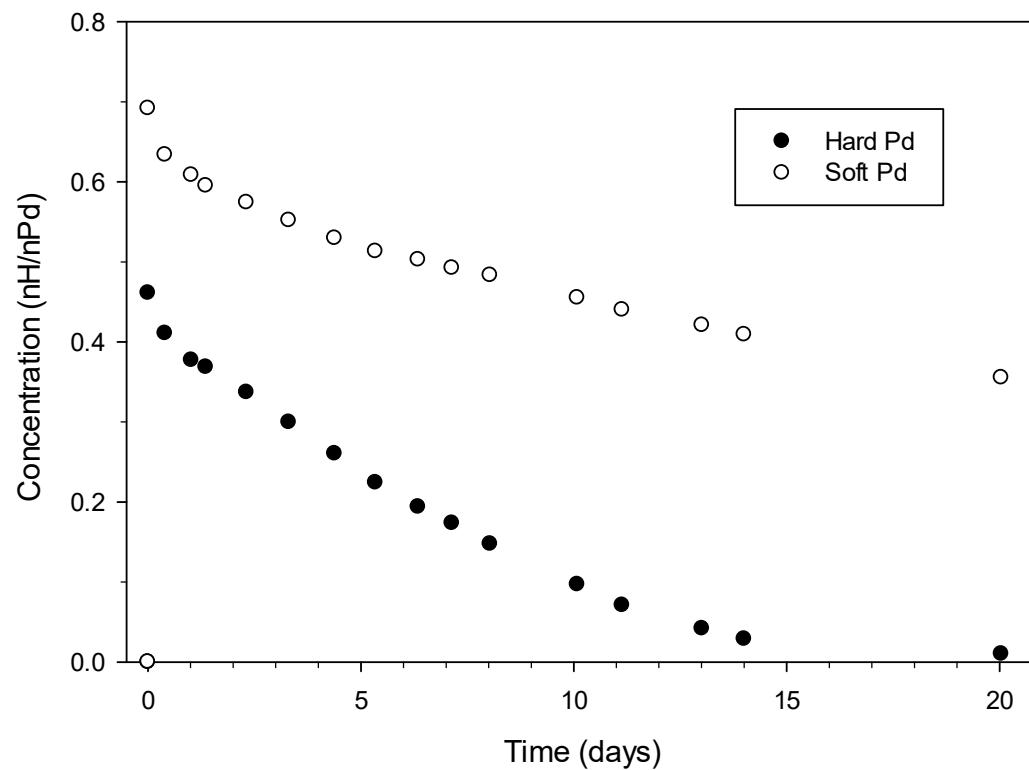
$^2\text{H}(\text{He}^3, \text{p})\text{He}^4$   
 $^2\text{H}$  in Palladium



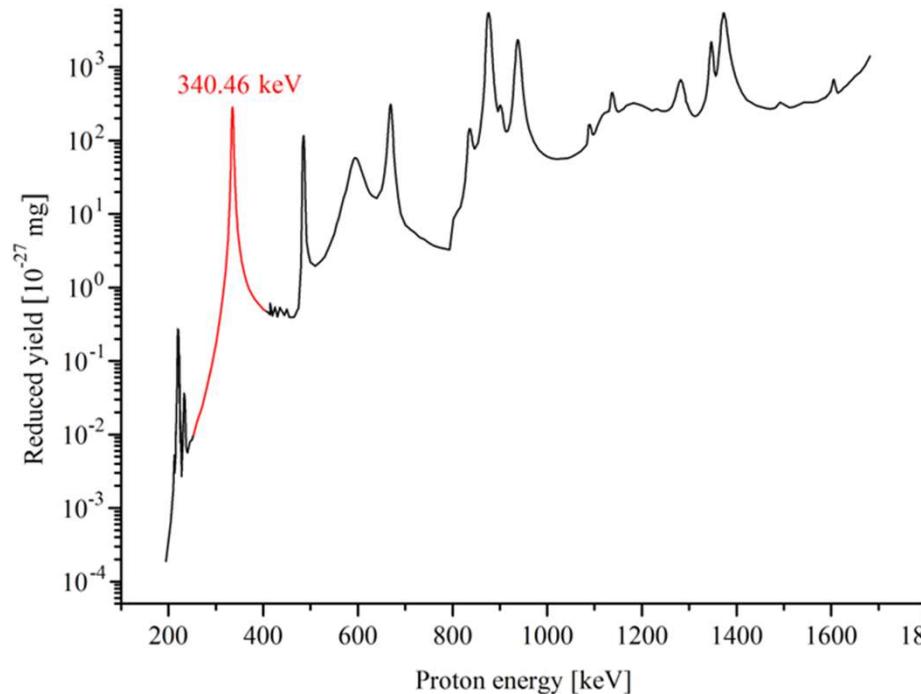
# Hydrogen in Palladium



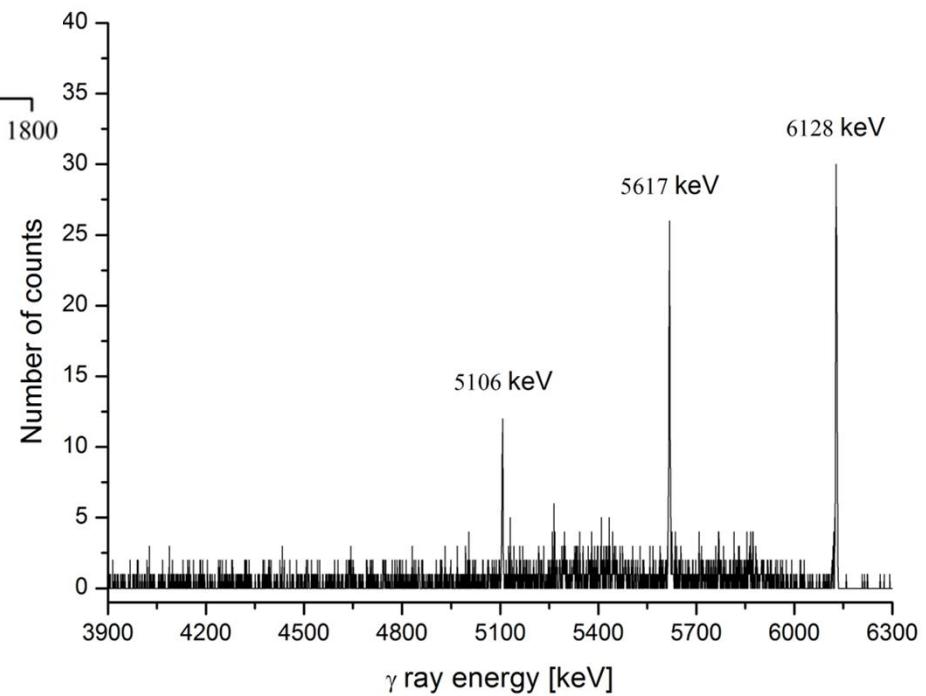
# Hydrogen in Palladium



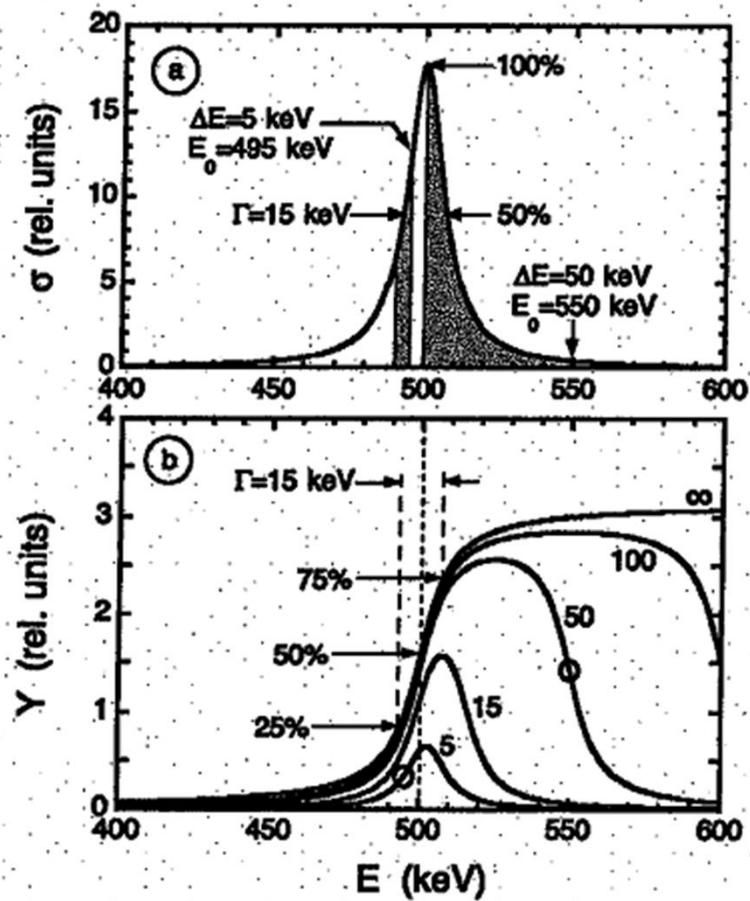
# The $^{19}\text{F}(\text{p},\alpha\gamma)^{16}\text{O}$ Reaction



K. Spyrou et al., Z. Phys. A **357** (1997) 283;  
Eur. Phys. J. A **7** (2000) 79.



# Thick targets and resonances



Breit Wigner resonance cross section

$$\sigma(E) = \frac{\lambda^2 \omega}{4\pi} \frac{\Gamma^2}{(E_r - E)^2 + \Gamma^2},$$

Infinitely thick target yield of narrow resonance

$$Y_\infty(E) = n_x \frac{\lambda^2 \omega \gamma}{2\pi \cdot dE/dx \rho} \left[ \arctg \left( \frac{E - E_r}{\Gamma/2} \right) + \frac{\pi}{2} \right],$$

Integral over the resonance

$$A_Y = n \frac{\lambda^2 \omega \gamma}{2}.$$

# Inverse Kinematics Results

Enhancement factor:

$$f = \frac{e^{-2\pi\eta(E+U_e)}}{e^{-2\pi\eta(E)}} = \frac{\omega\gamma_1}{\omega\gamma_2}$$

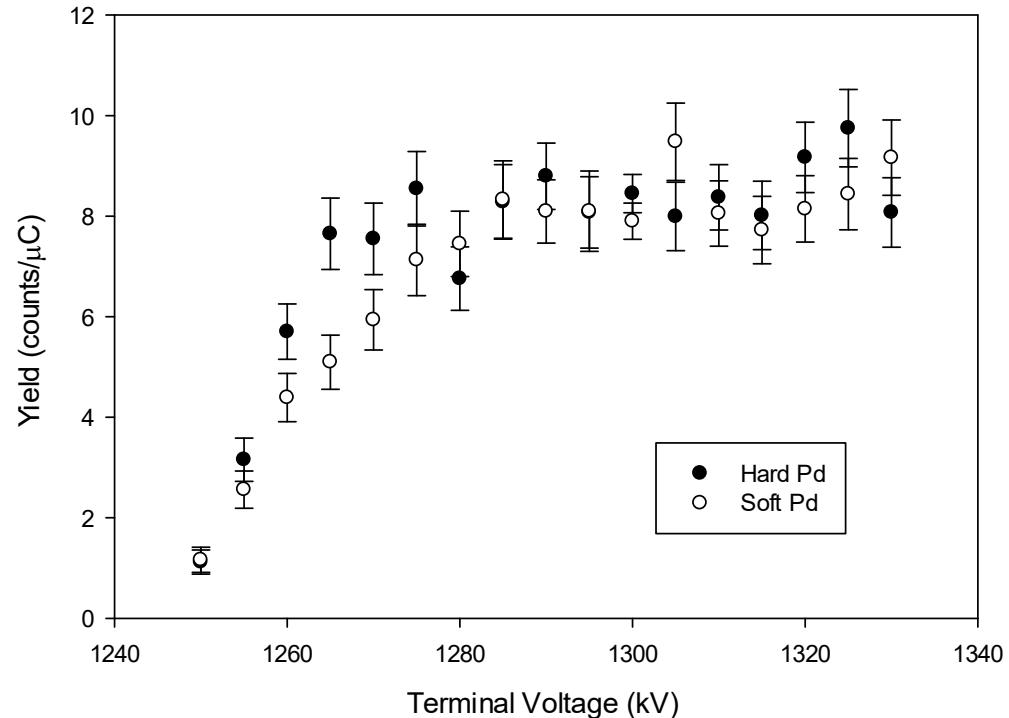
$$f = 1.53 \rightarrow$$

$$U_e = 18.7 \pm 1.5 \text{ keV}$$

$$\omega\gamma_2 = 24.6 \pm 2.6 \text{ eV}$$

Literature value:

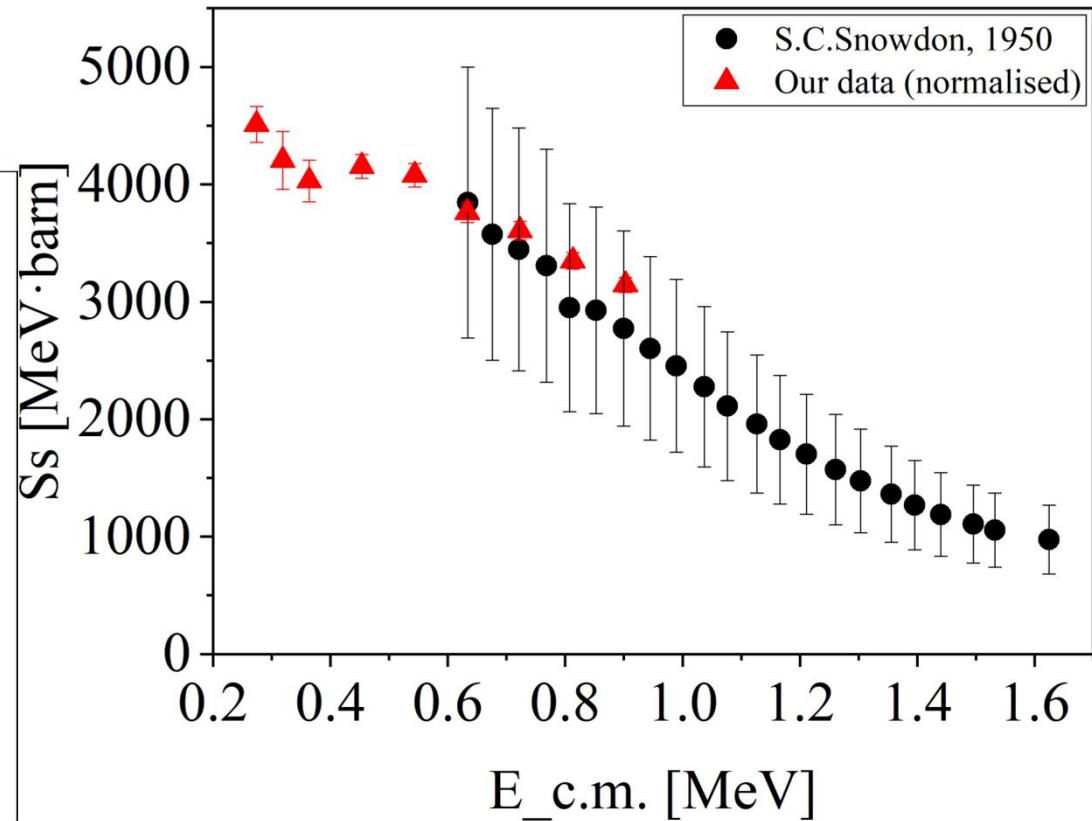
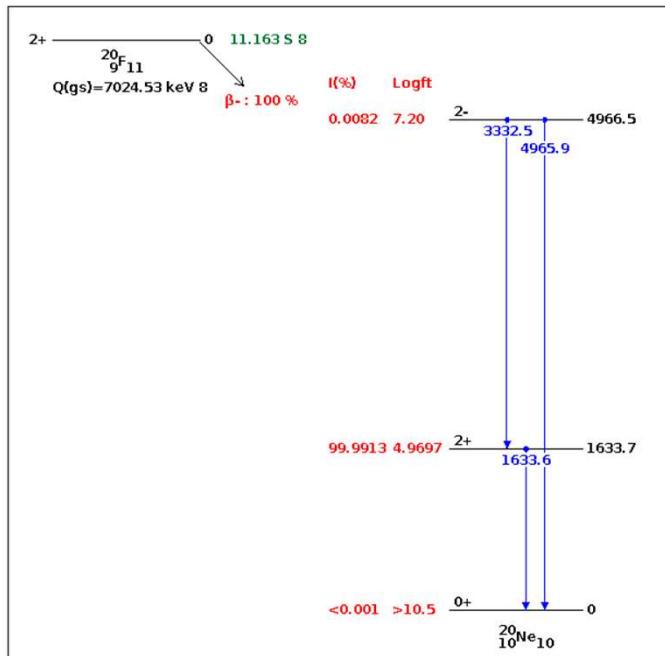
$$\omega\gamma_2 = 24.3 \pm 2.9 \text{ eV}$$



K. Spyrou et al., Z. Phys. A **357** (1997) 283; Eur. Phys. J. A **7** (2000) 79.

# Fluorine + Deuterium

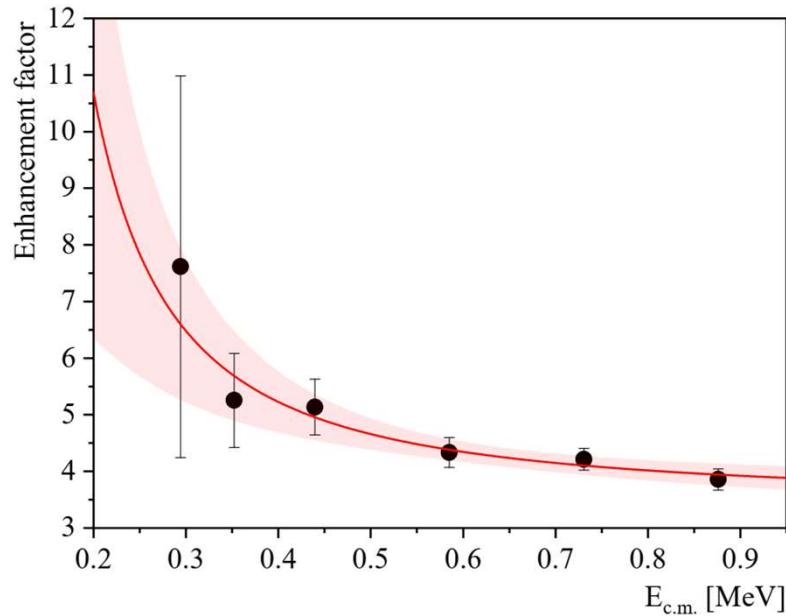
Normal kinematics:



$$^{20}\text{F} \rightarrow ^{20}\text{Ne} + e^- + \bar{\nu} + \gamma \quad E_\gamma = 1634 \text{ keV}$$

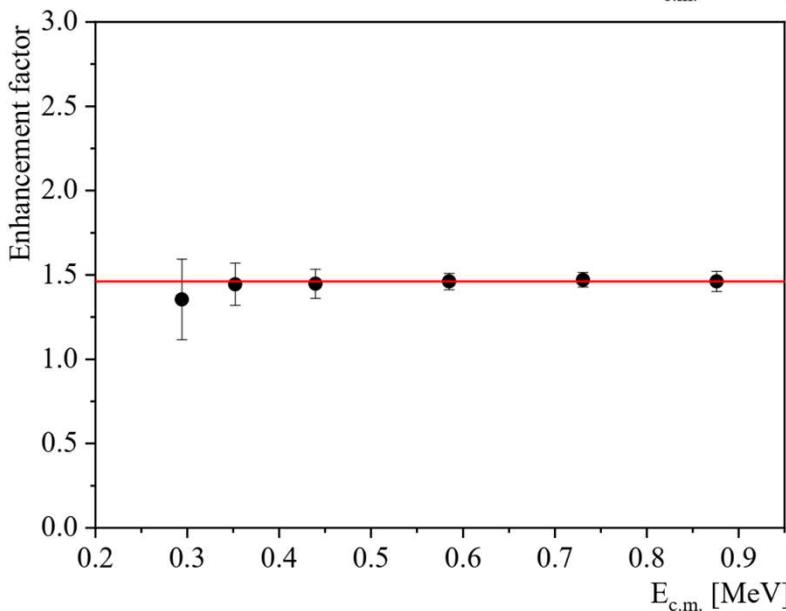
$\text{CaF}_2$  target vs. deuterium implanted titanium; JSI + MPI Garching

# Deuterium in Palladium



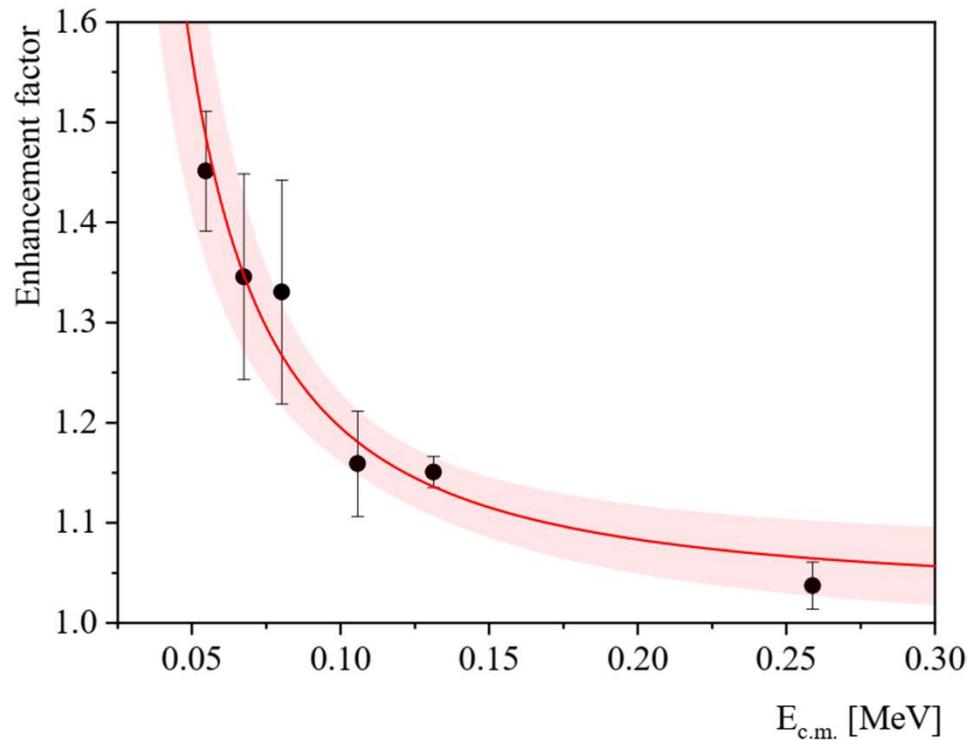
Hard Pd:  $U_e = 17.9 \pm 3.0$  keV

Adiabatic limit:  
 $U_e = 2.19$  keV



Soft Pd:  $U_e < 3.0$  keV

# p+<sup>7</sup>Li



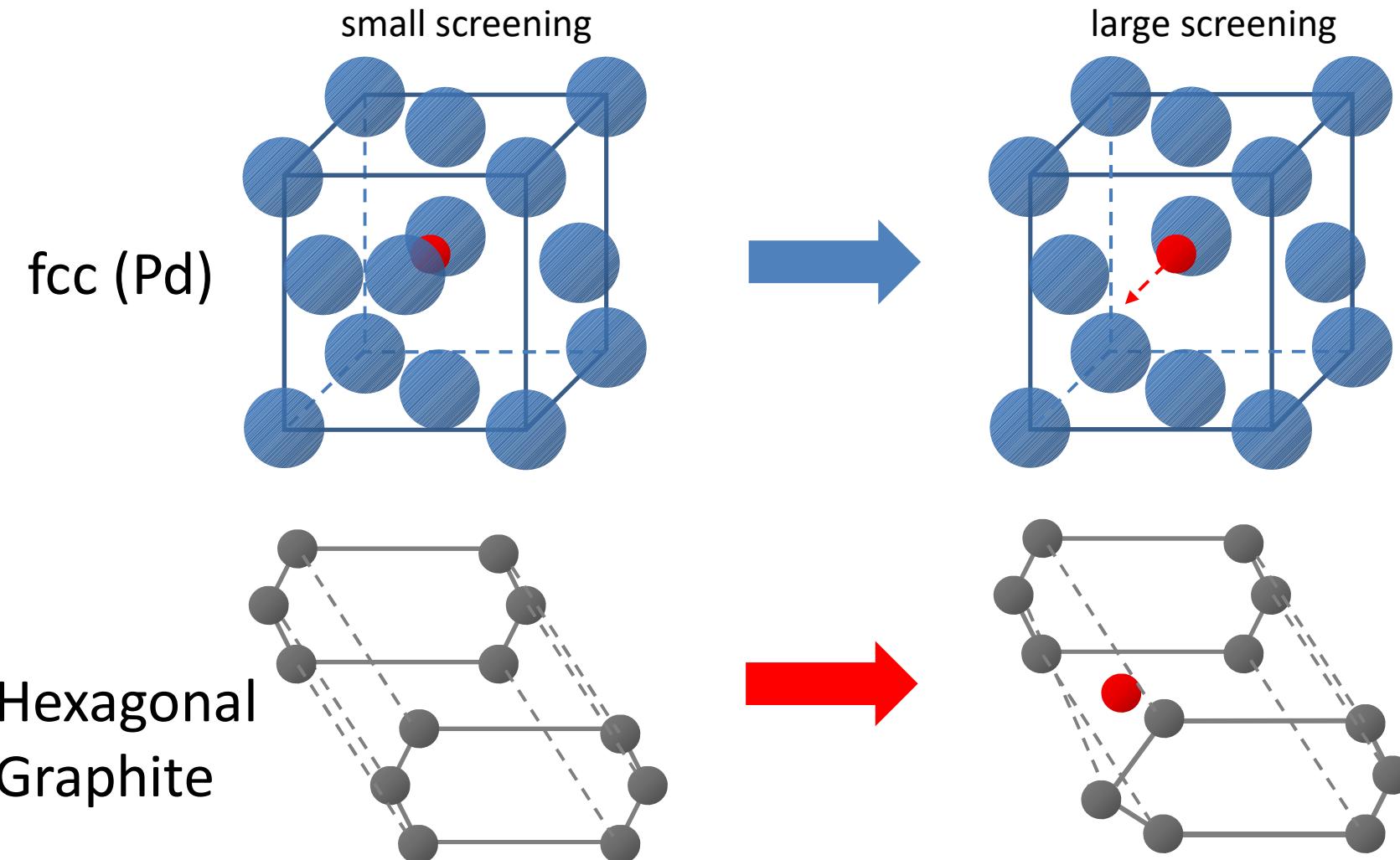
Hard Pd:  $U_e = 2.86 \pm 0.19$  keV

Adiabatic limit:

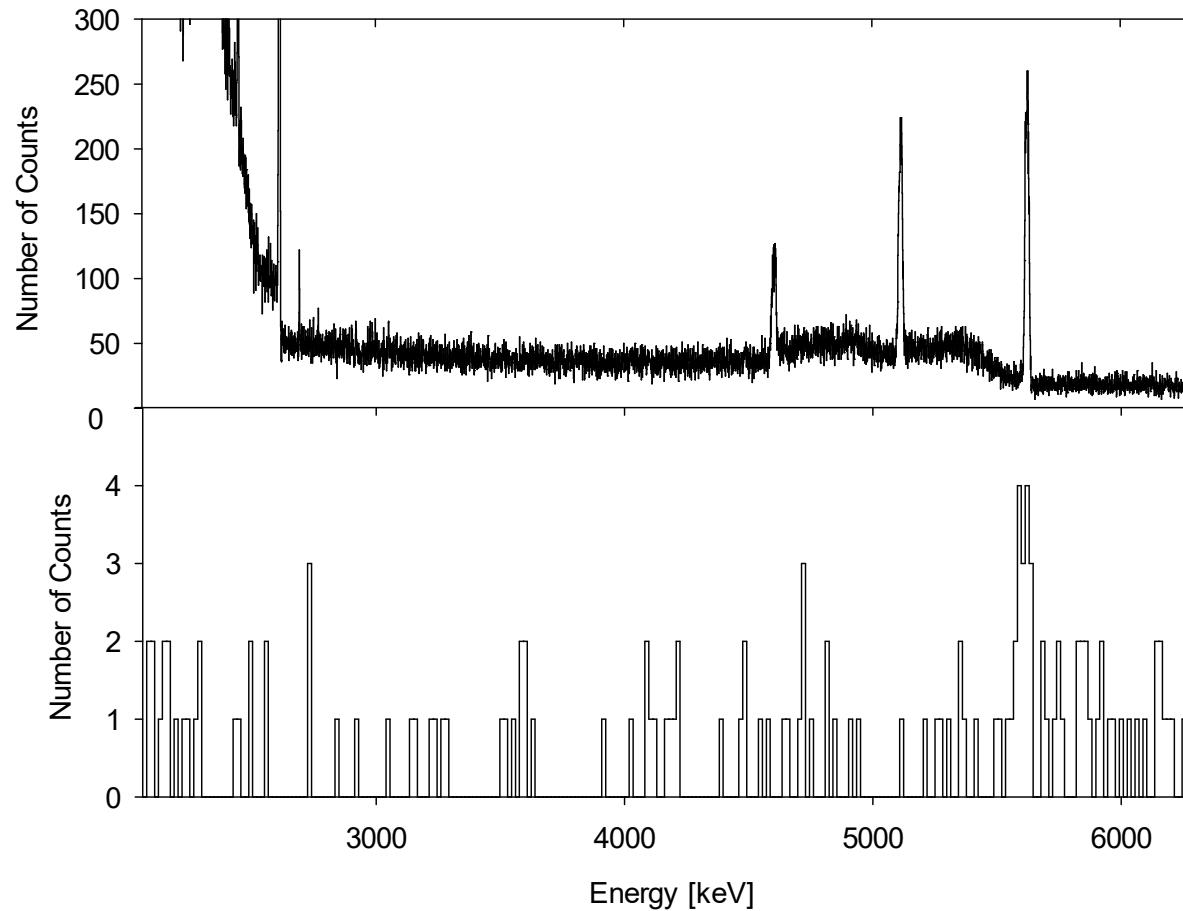
$$U_e = U_0 Z^2$$

$$U_0 \approx 300 \text{ eV}$$

# Crystal symmetry



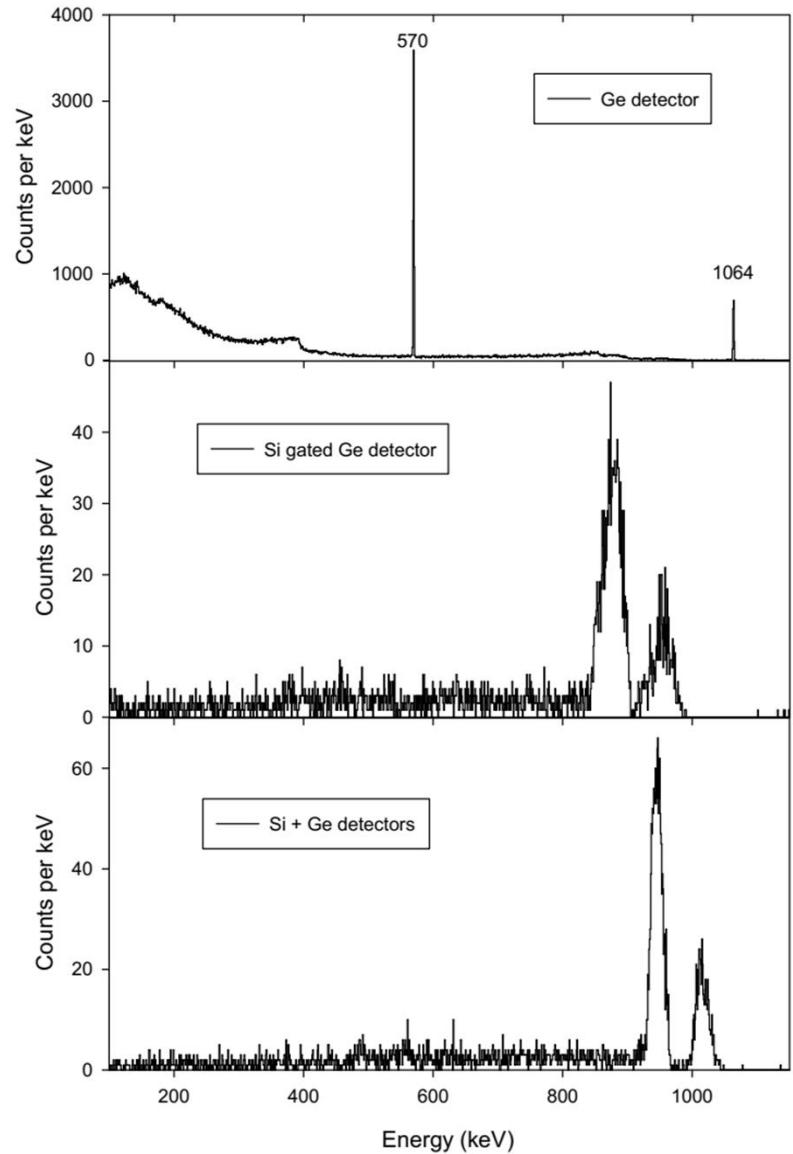
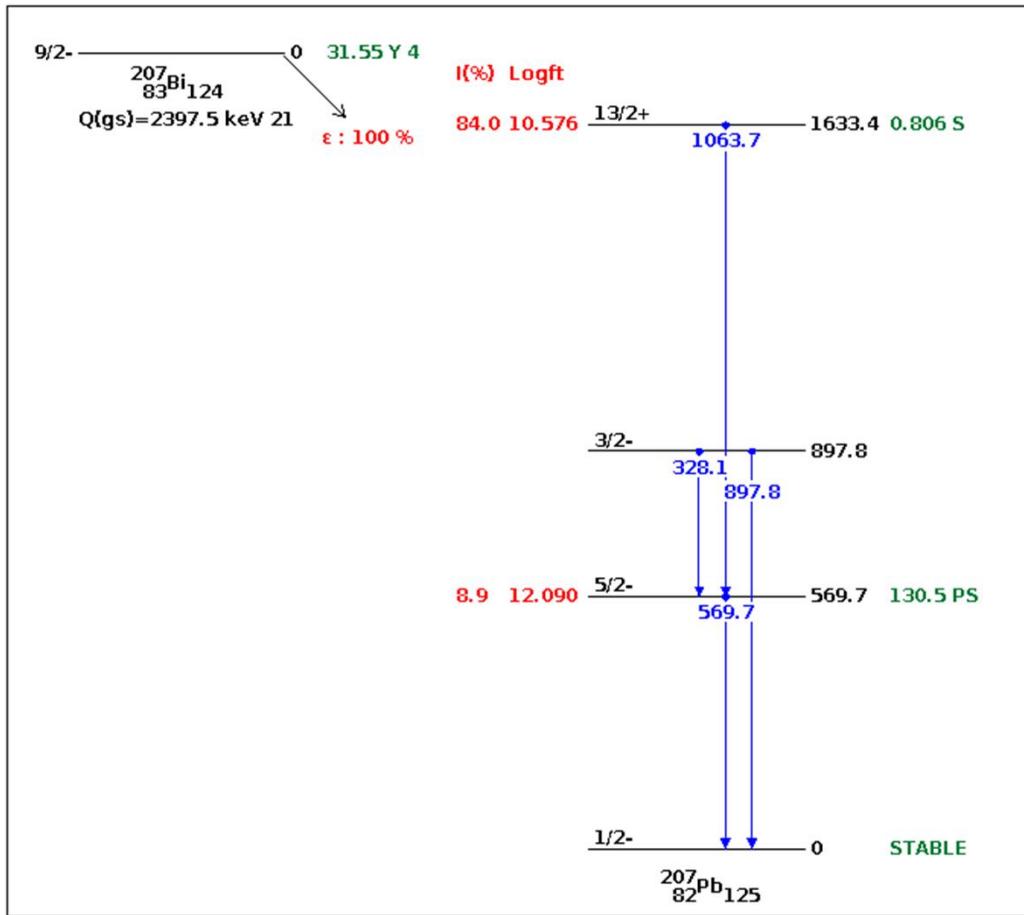
# Electrons



$^2\text{H}(\text{p},\gamma)^3\text{He}$

$^2\text{H}(\text{p},\text{e}^-)^3\text{He}$

# Bi-207 source



# Clean HME Horizon 2020 Project



Clean Hydrogen Metal Energy

## Project overview

CleanHME shall develop a new, clean, safe, compact and very efficient energy source based on Hydrogen-Metal and plasma systems, which could be a breakthrough for both private use as well as for industrial applications. The new energy source could be employed both as a small mobile system or alternatively as a stand-alone heat and electricity generator. We plan to construct a new compact reactor to test the HME technology during the long-term experiments and increase its technology readiness level. A comprehensive theory of HME phenomena shall be worked out as well. This project has received funding from the European Union's Horizon2020 Framework Programme under grant agreement no 951974.

<https://www.cleanhme.eu/>