On the existence of high-Z electron screening in metals

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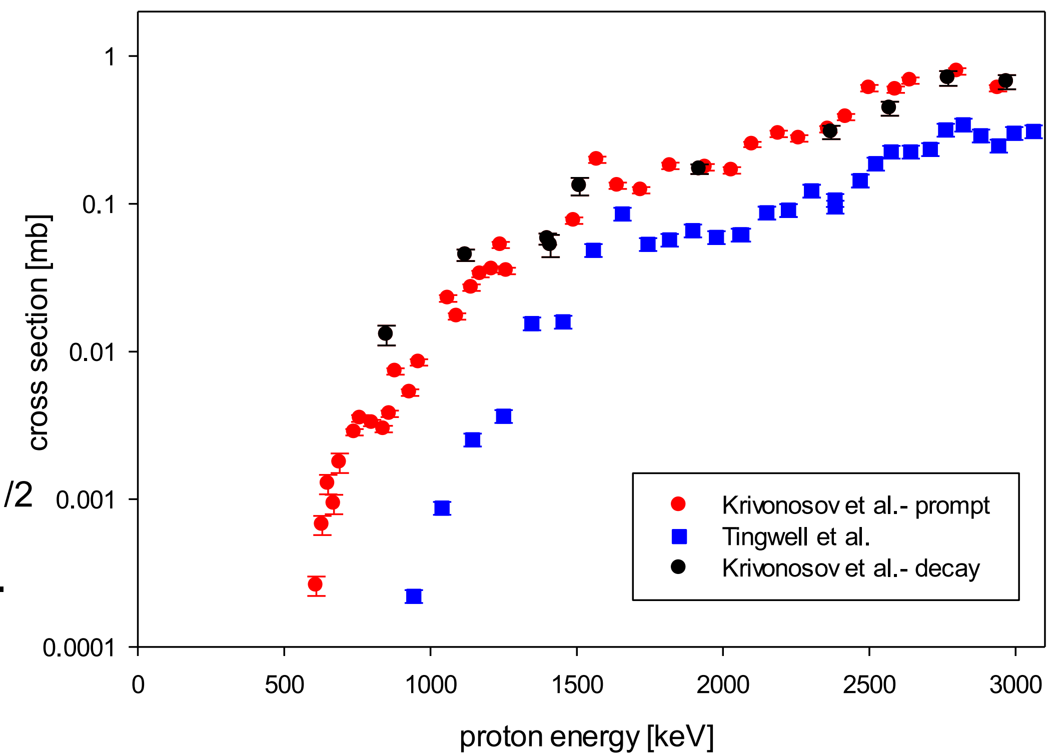
Nuclear Reactions at Low Energies

Due to Coulomb repulsion the cross section σ for charged particle induced nuclear reactions drops rapidly with decreasing beam energy.

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

where $\eta = Z_1 Z_2 e^2 / 4\pi\varepsilon_0 \hbar (2E/\mu)^{1/2}$ is the Sommerfeld parameter. Exponential (Gamow) factor approximates barrier penetration probability.

$^{60}Ni(p,\gamma)^{61}Cu$ Cross Section



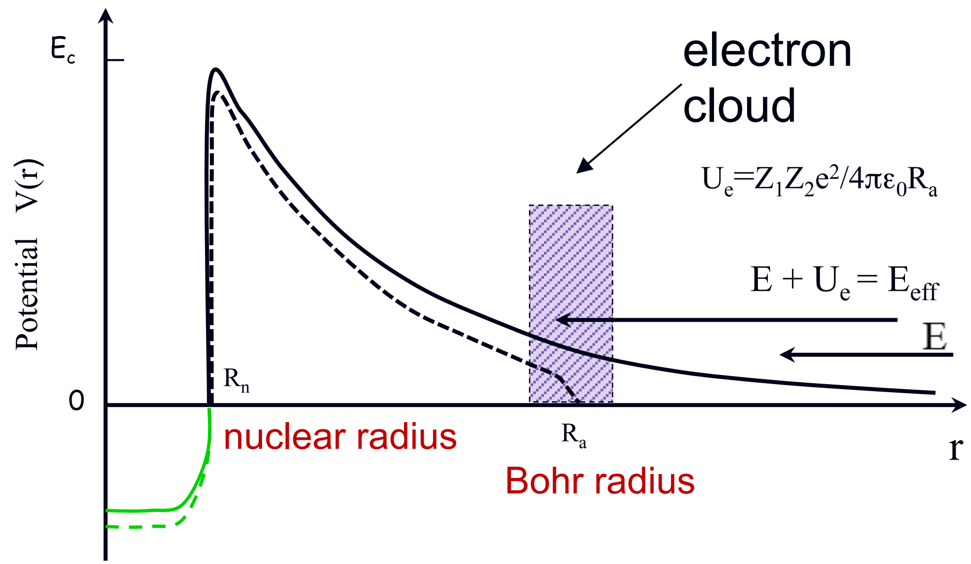
G. A. Krivonosov et al., Izv. Akad. Nauk SSSR **41** (1977) 2196.
C. I. W. Tingwell et al., Nucl. Phys. **A496** (1989) 127.

Electron Screening

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

$$f(E) = \frac{\sigma(E+U_e)}{\sigma(E)},$$

where U_e is the screeening potential.

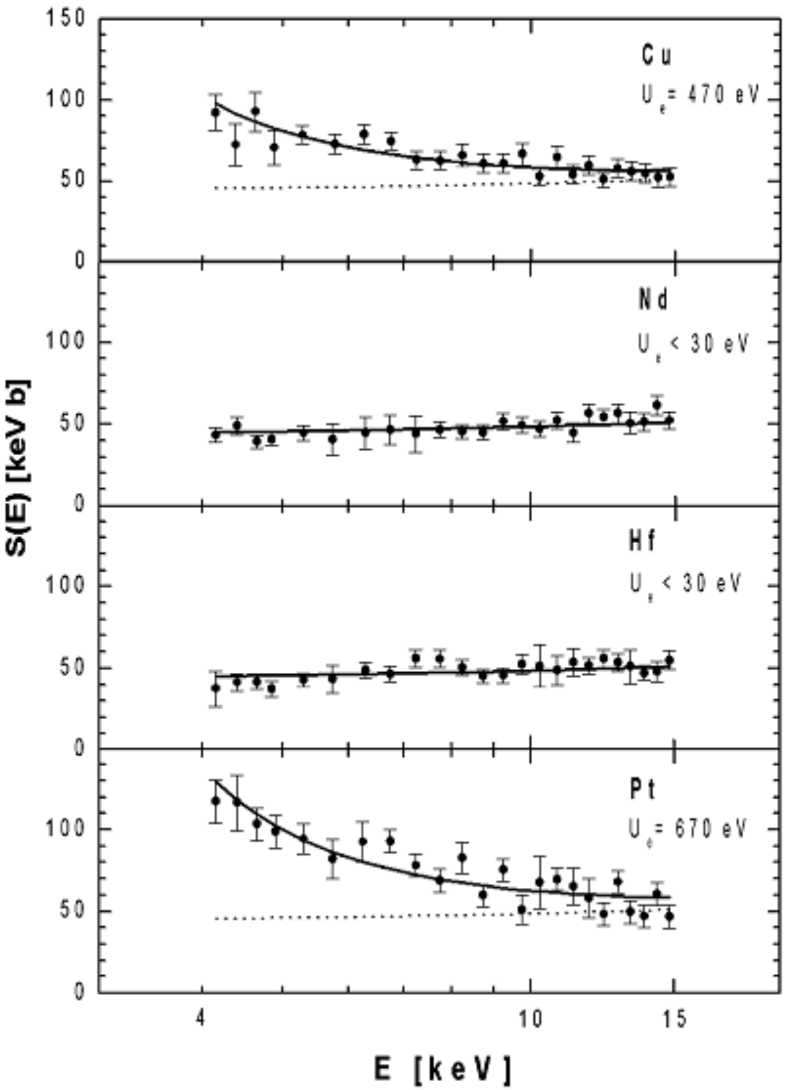


H. J. Assenbaum, K. Langanke and C. Rolfs, Z. Phys. A **327** (1987
269 citations (Web of Science, March 2014).

$$\frac{R_n}{R_a} \approx 10^{-5} \Rightarrow U_e = \frac{e^2}{4\pi\varepsilon_0 R_a} = 27 \text{ eV for d+d reaction}$$

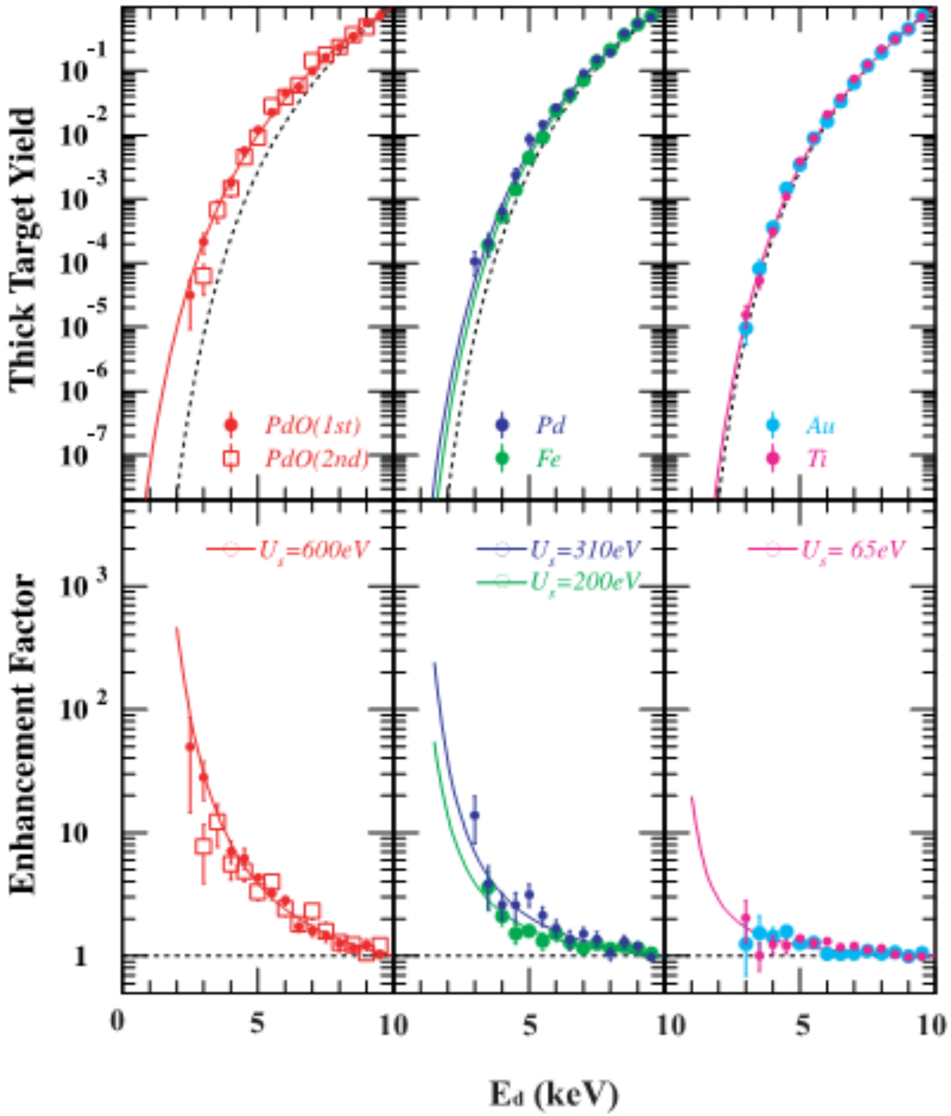
Previous Results 1

for d(d,p)t reaction from F. Raiola et al., Eur. Phys. J. A**19** (2004) 283.



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

Previous Results 2



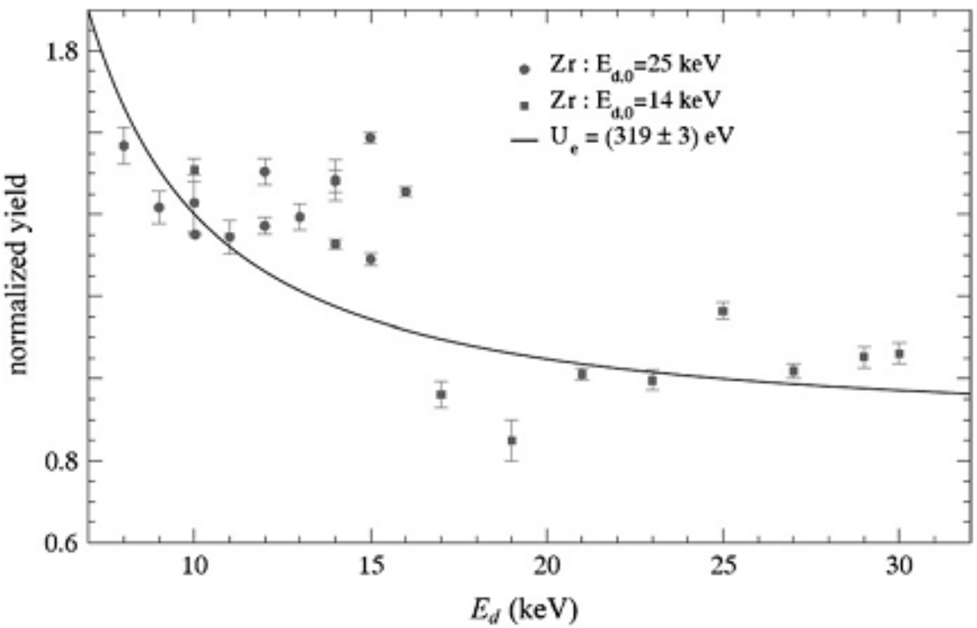
J. Kasagi, Prog. Theo. Phys. Suppl. 154 (2004) 365.

for the d(d,p)t reaction
U_e=310±30 eV @ 7% H/Pd

=> concentration dependence

Previous Results 3

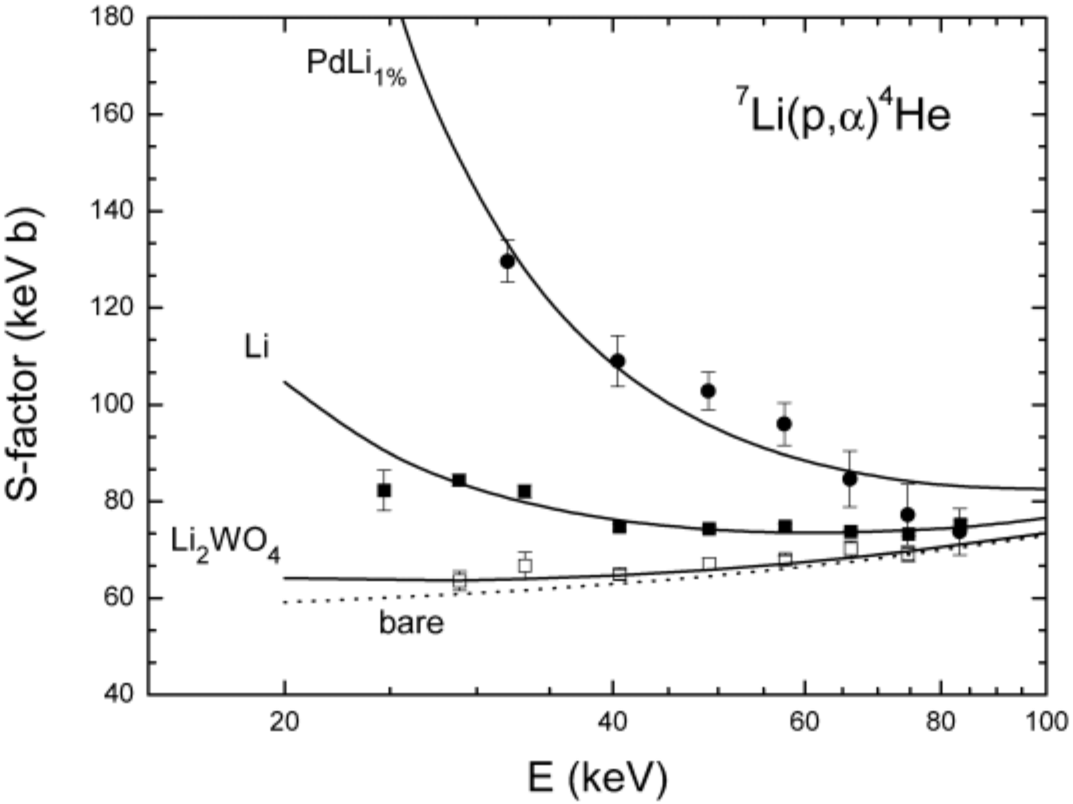
for d(d,p)t reaction from K. Czerski et al., J. Phys. G **35** (2008) 014012.



for zirconium metal
U_e=319±3 eV

Previous Results 4

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

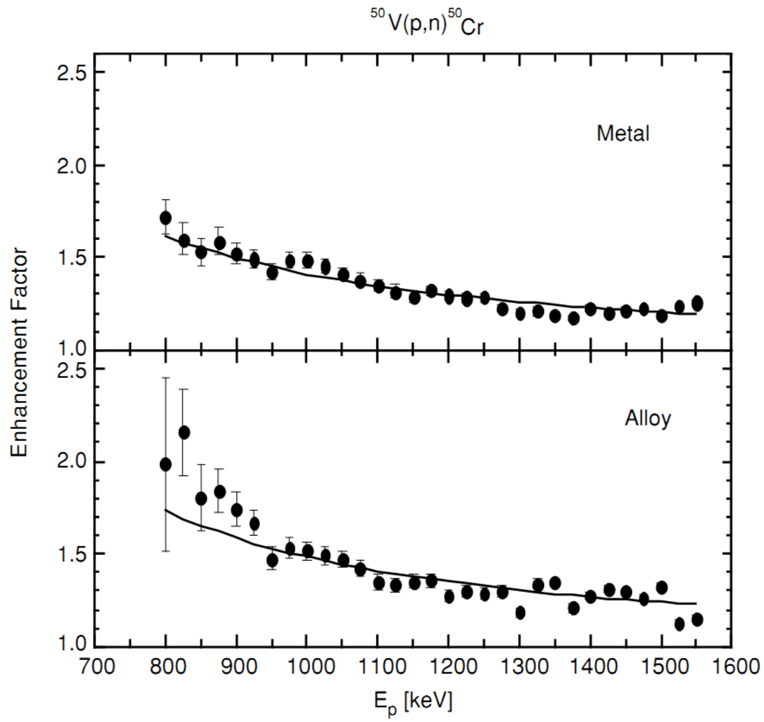


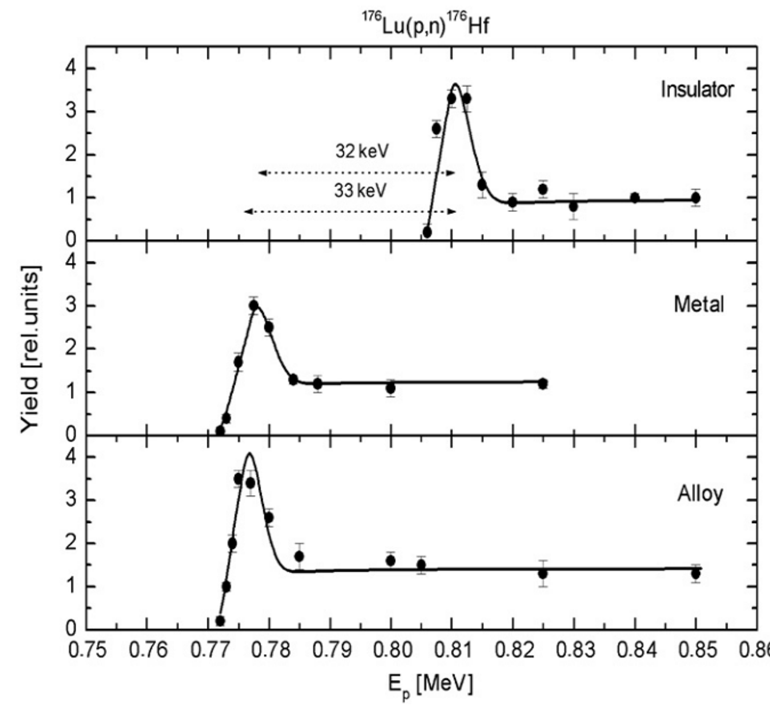
For $PdLi_{1\%}$: U_e= 3.8 ± 0.3 keV

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

Previous Results 5

K. U. Kettner et al., J. Phys. G **32** (2006) 489.





$^{50}V(p,n)^{50}Cr$ reaction relative to VO_2

V metal: U_D= 27 ± 9 keV

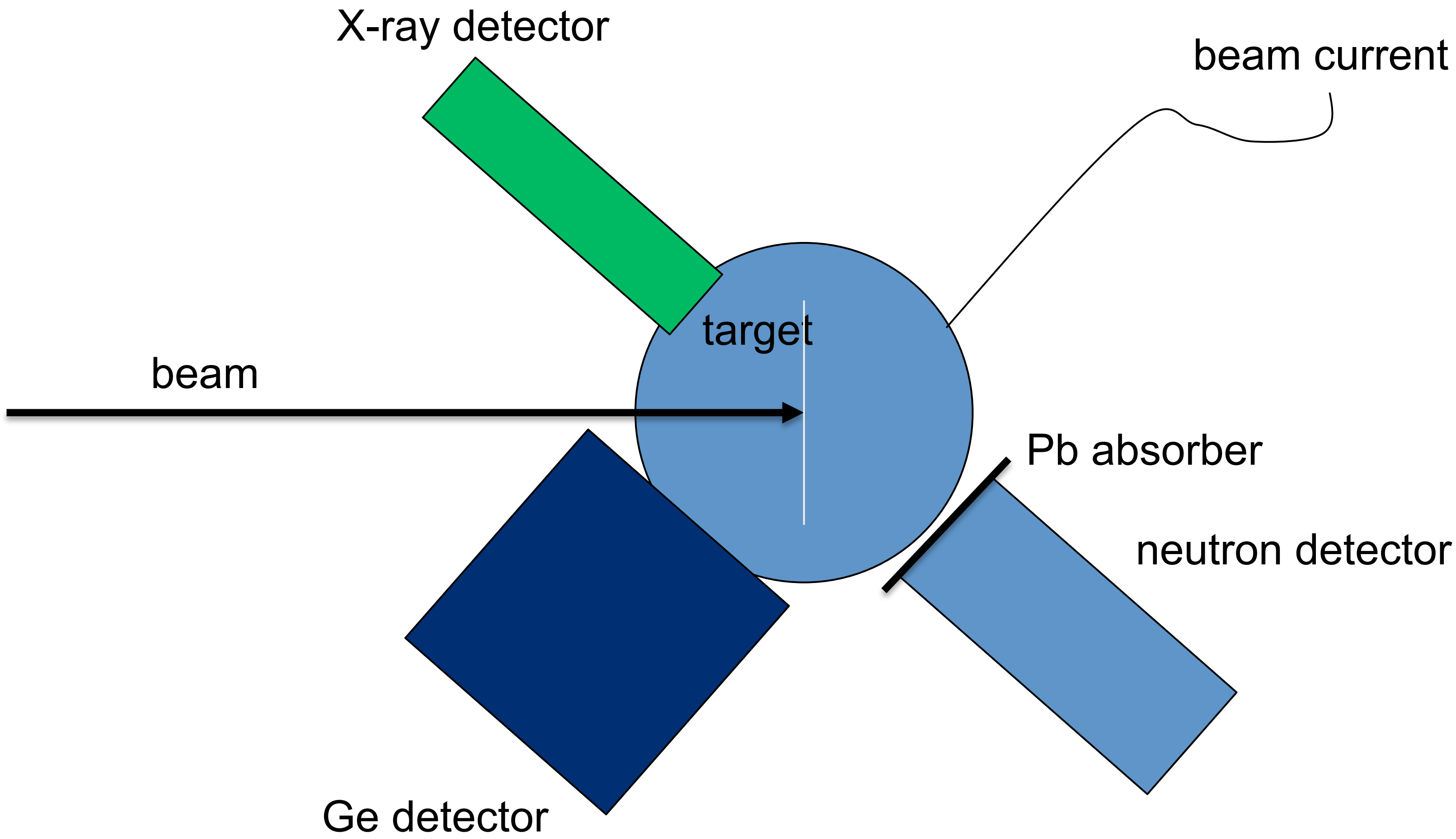
$PdV_{10\%}$ alloy: U_D= 34 ± 11 keV

$^{176}Lu(p,n)^{176}Hf$ reaction relative to Lu_2O_3

V metal: U_D= 32 ± 2 keV

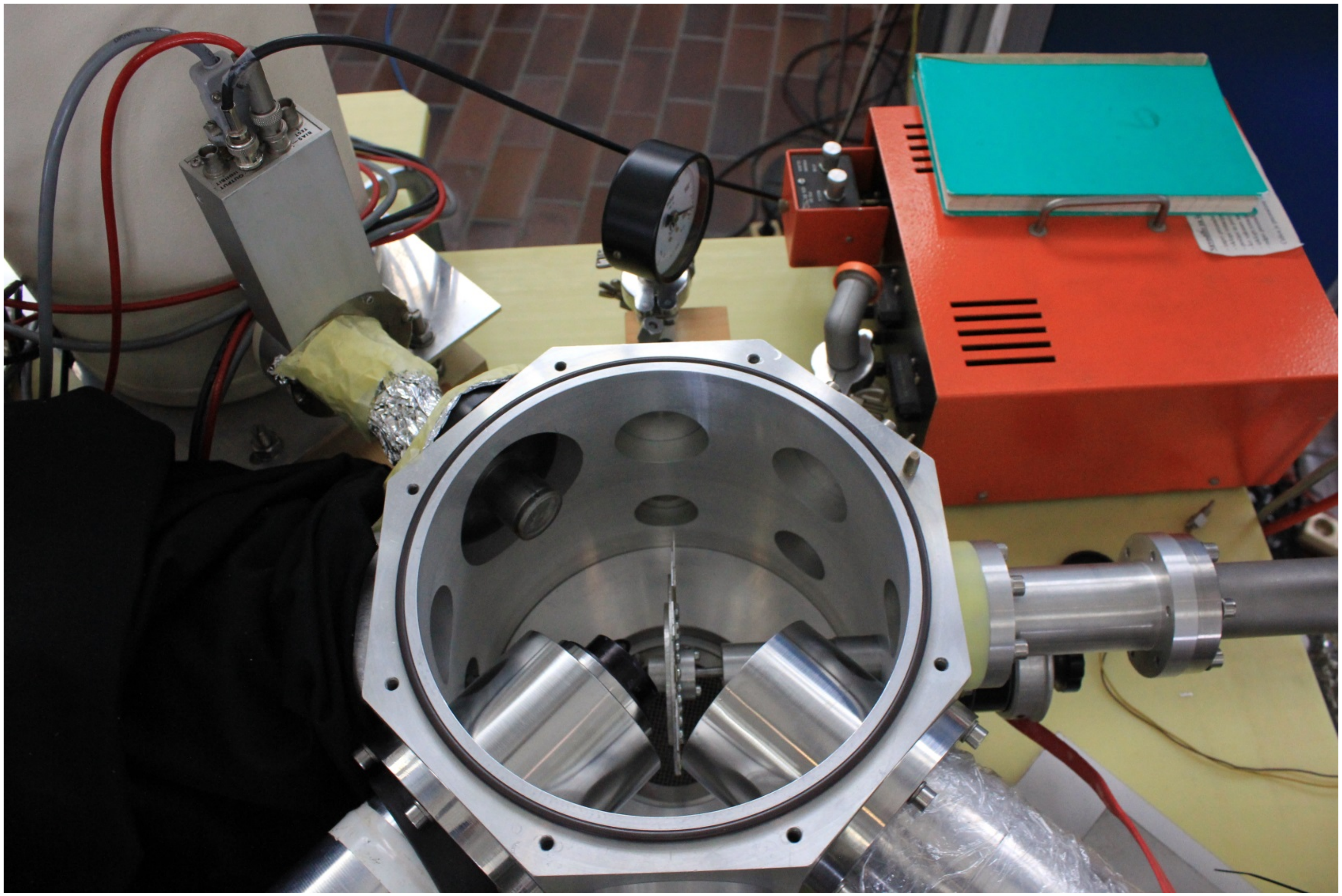
$PdLu_{10\%}$ alloy: U_D= 33 ± 2 keV

Measurements @ JSI

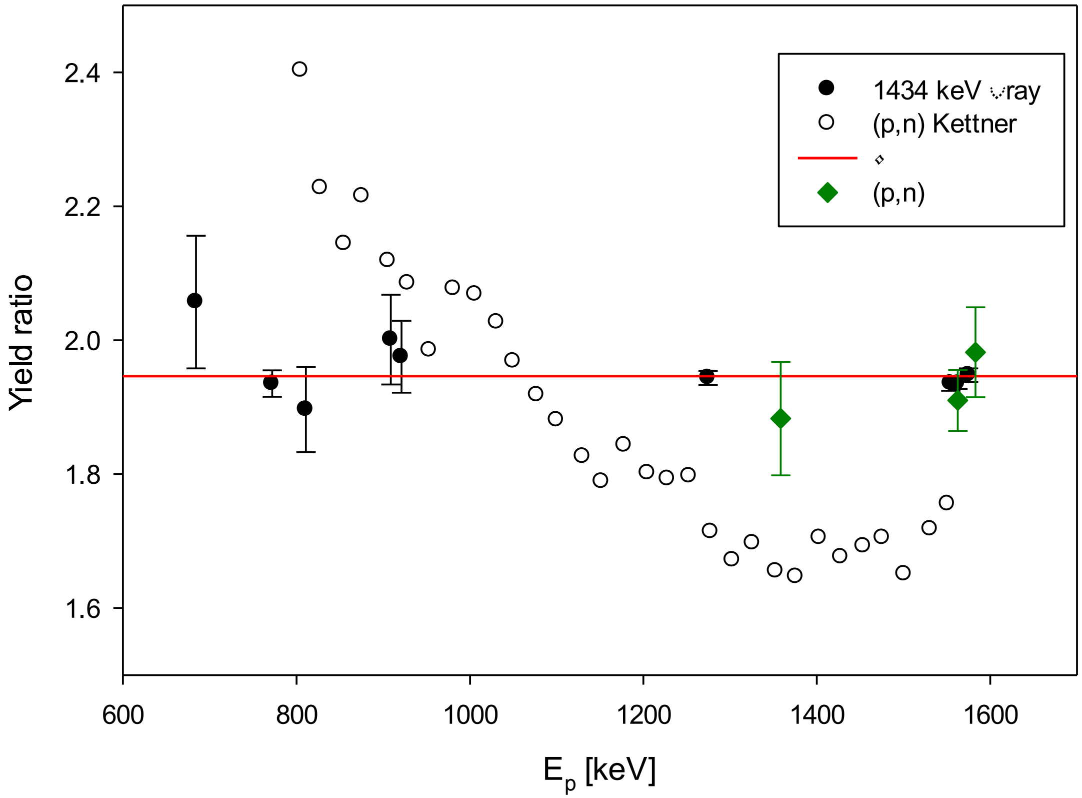


Measurements @ JSI

2 MV Tandem van de Graaf accelerator



Electron screening in vanadium



$$\alpha = \frac{M_{VO2}\frac{dE}{dx\rho}(VO_2)}{M_V\frac{dE}{dx\rho}(V)}$$

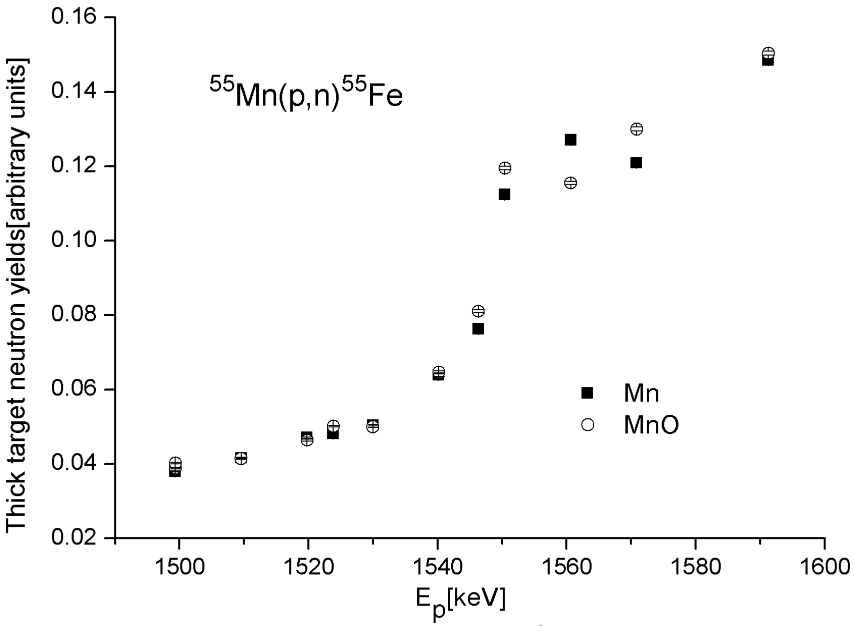
$$U_D(p,\gamma) < 2\ \mathrm{keV}$$

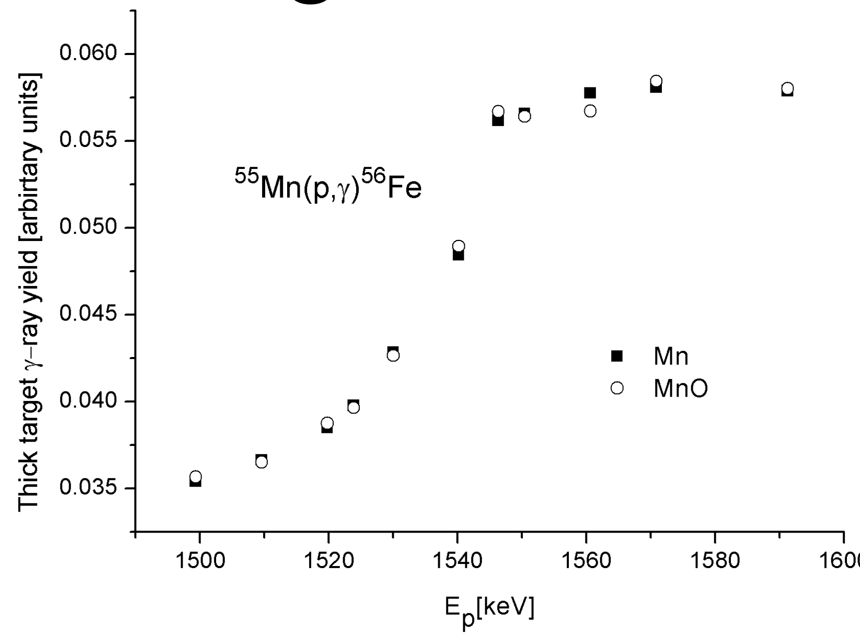
$$U_D(p,n) = 27 \pm 9\ \mathrm{keV}$$

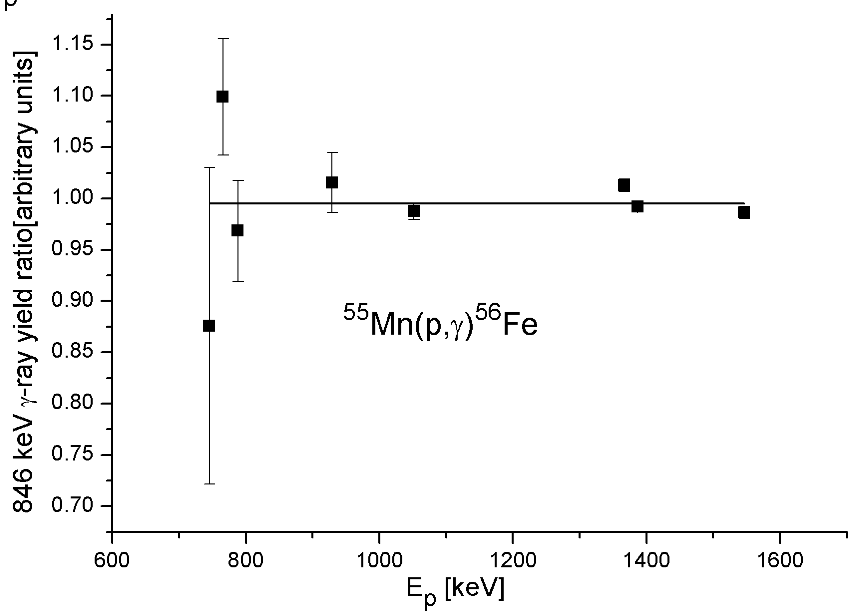
$^{51}V(p,\gamma)^{52}Cr$ - 1434 keV

$^{50}V(p,n)^{50}Cr$ - K. U. Kettner et al., J. Phys. G **32** (2006) 489.

Electron screening in manganese



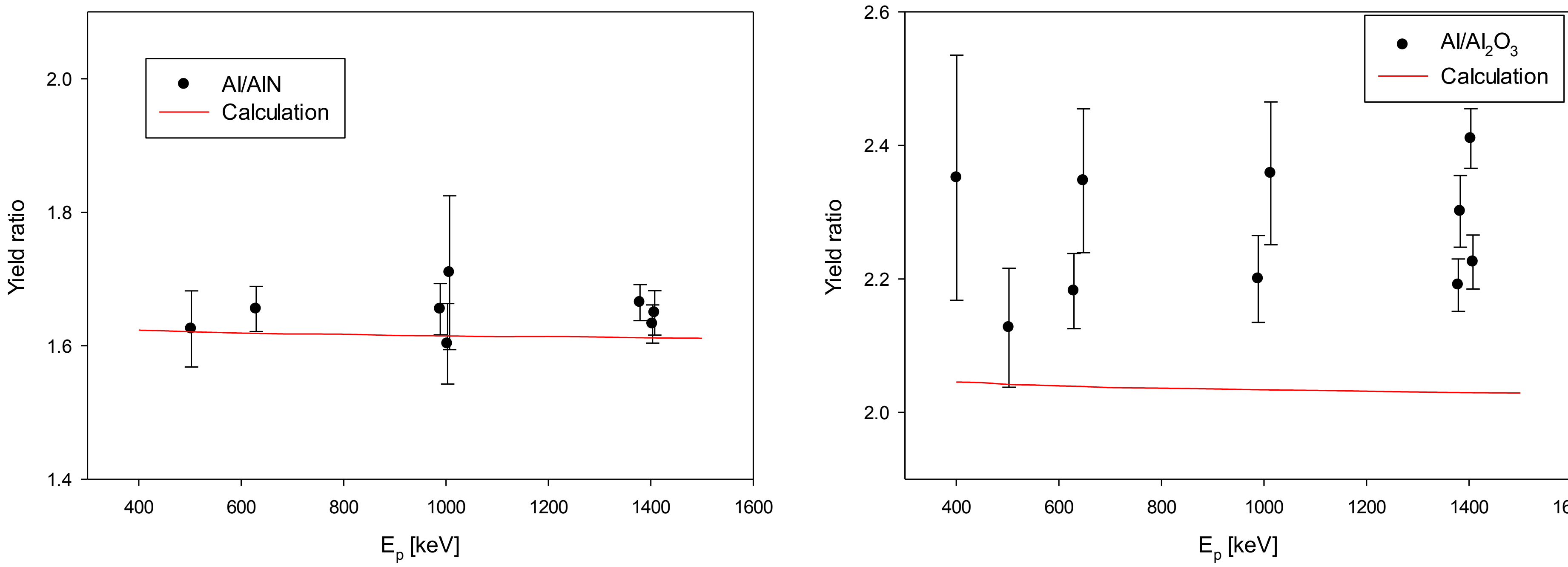




$$U_D(p,\gamma) < 3 \text{ keV}$$

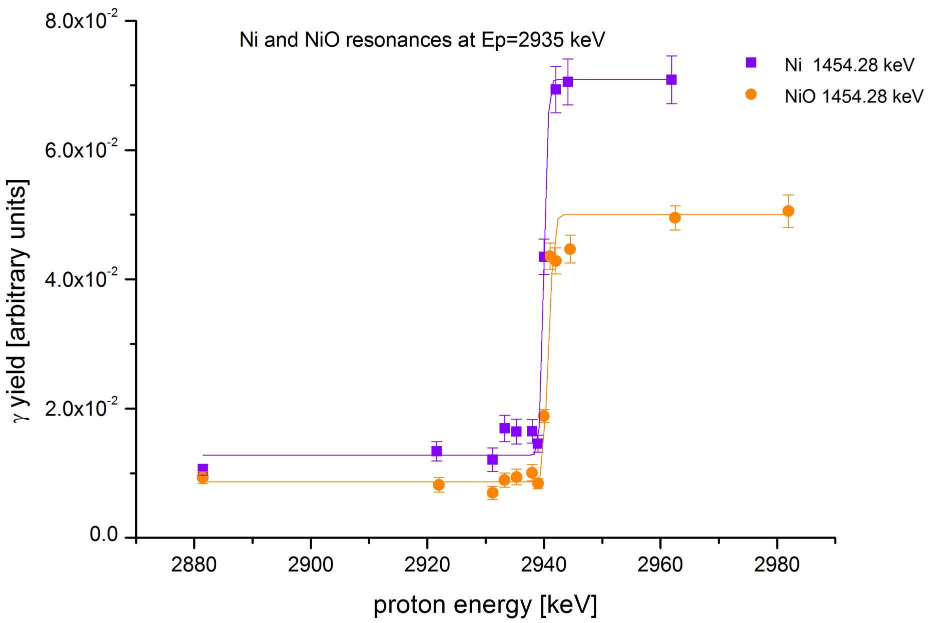
Aluminum results

1779 keV γ-ray ratio from $^{27}Al(p,\gamma)^{28}Si$ reaction

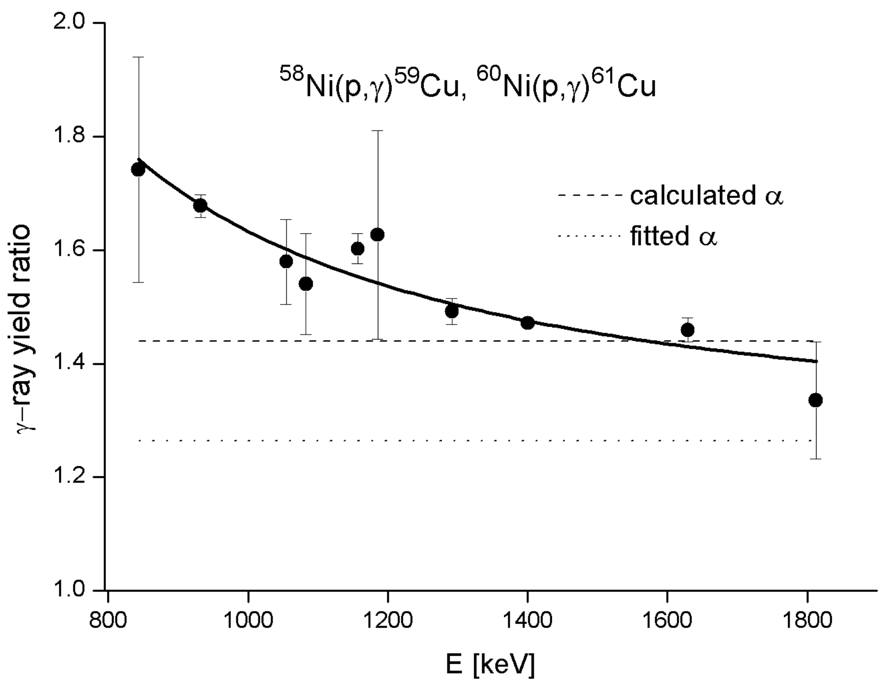


D.C. Turner et al., Nucl. Instr. Meth. B **103** (1995)

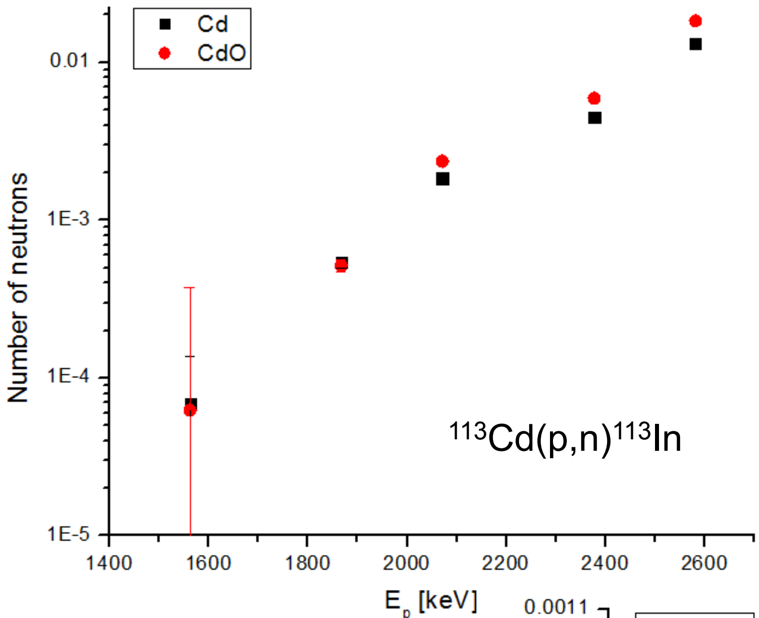
Nickel results

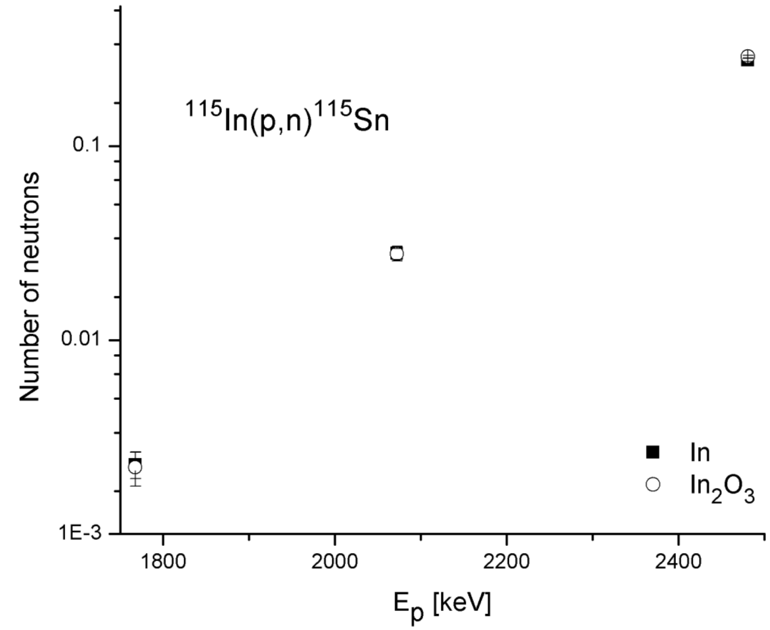


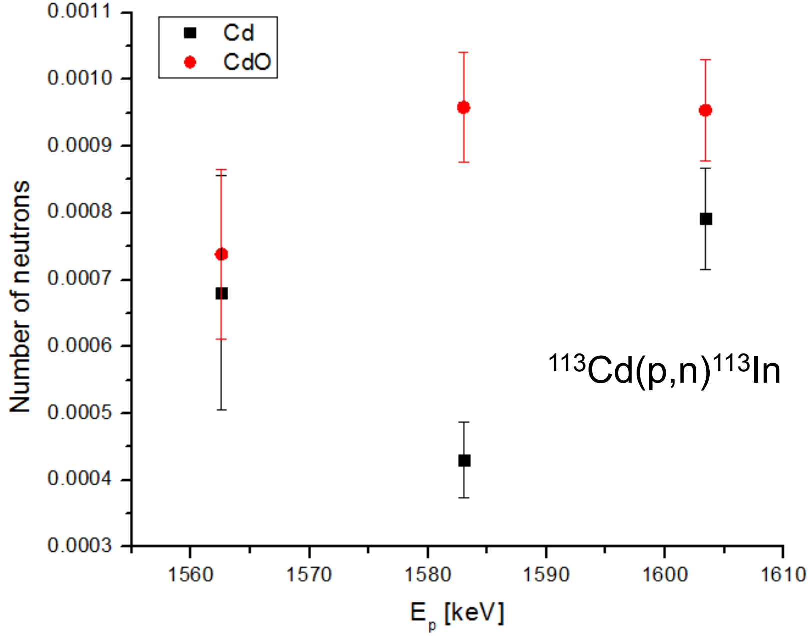
1454 keV γ ray from $^{58}Ni(p,p'\gamma)^{58}Ni$ reactio



Cadmium and indium

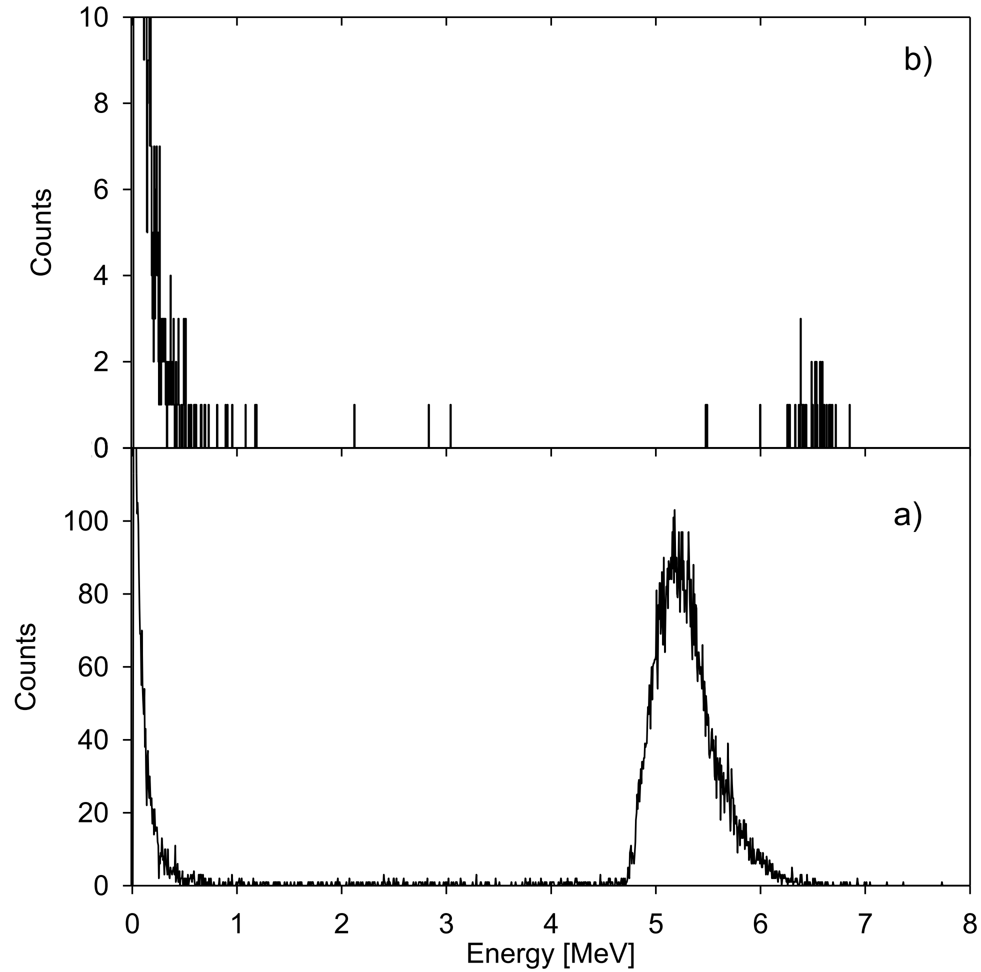






Electron screening in implanted metals

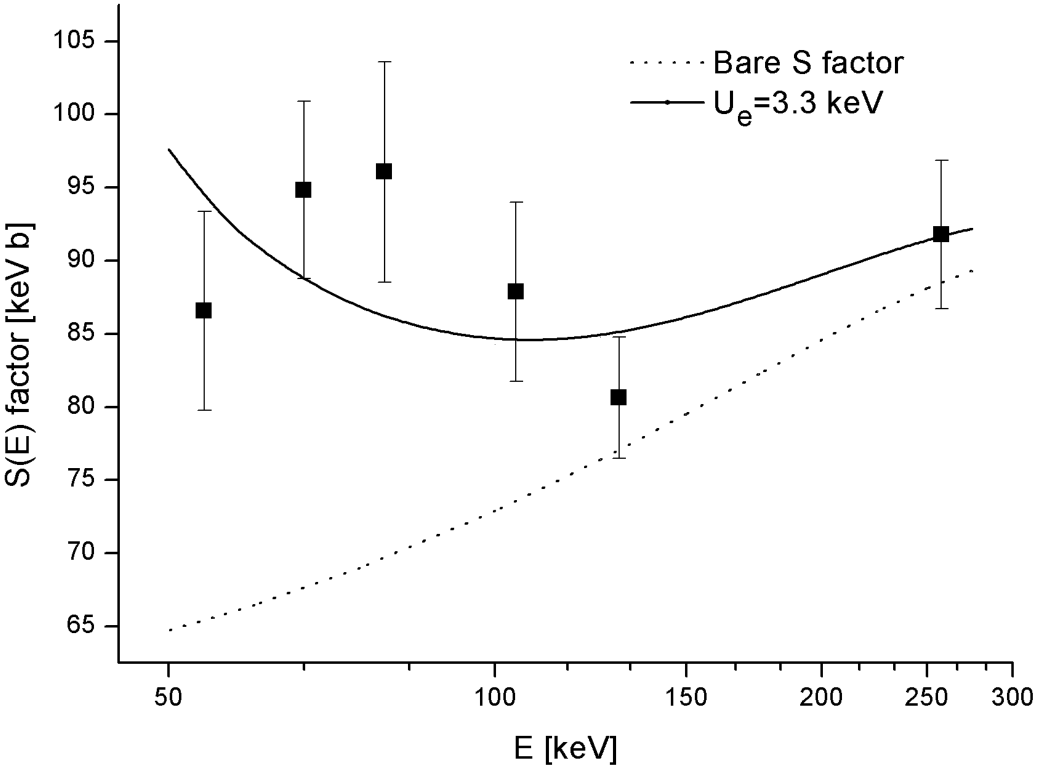
Inverse kinematics: $^{1}H(^{7}Li,\alpha)^{4}He$



Preliminary results:

Target	U_e [keV]	Stoichiometry
Ni	3.3 ± 0.9	0.0040±0.0007
Pd	1.5 ± 1.9	0.014±0.001
Pt	2.1 ± 1.2	0.024±0.001

Comparison to previous results



Target	Stoichiometry	
	^{7}Li+p	d+d
Ni	0.004	0.13
Pd	0.014	0.03
Pt	0.024	0.06

Target	Reaction U_e [keV]		
	^{7}Li+p	p+^{7}Li	d+d
Ni	3.3 ± 0.9		0.38 ± 0.04
Pd	1.5 ± 1.9	3.8 ± 0.3	0.80 ± 0.09

d+d F. Raiola et al., Eur. Phys. J. A**19** (2004) 2

p+^{7}Li J. Cruz et al., Phys. Lett. B 624 (2005) 1

Conclusions

- Electron screening is important in nuclear astrophysics.
- Large electron screening only happens on implanted nuclei in metallic targets.
- Electron screening is not a static but rather a dynamic effect, so the parameterization with a screening potential is only valid when all electrons are tightly bound.
- The size of the effect is not always proportional to target Z.
- For stellar plasma we really need to understand what happens in the laboratory experiments.

Thanks to: Jelena Gajević, Toni Petrovič, Urša Mikac, Andrej Likar, Žiga Šmit, Matjaž Ver
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Nuclear Structure and Dynamics III

Portorož-Portorose, Slovenia, June 14th – 19th, 2015