Physics with Light n-rich Rare Ion Beams

^{6,8}He

“... beams must be made 1000 times more intense than currently available ...”

Helium beams

Currently produced in various facilities with beam intensities:

→ ^{6}He ($t_{½}$ = 0.8 s) ~ 10^{7} ions/s

→ ^{8}He ($t_{½}$ = 0.1 s) ~ 10^{5} ions/s

Recent developments!!!

SPIRAL2 *(M.G. Saint-Laurent in2p3-00420784, version 1 - 24 Nov 2009)*

→ ^{2}H on spallation source as a neutron converter 1.5 kW followed by ^{9}Be(n,α)^{6}He

Expected intensities 10^{9} ions/s on target

CERN

→ Some 1.4 GeV proton on spallation source followed by ^{9}Be(n,α)^{6}He. 10^{13} ions/bunch!!

^{6}He at iTL

Liquid lithium target?

→ ^{7}Li(p,2p)^{6}He @ 70 MeV, I ~ 350 μA (24 kW)

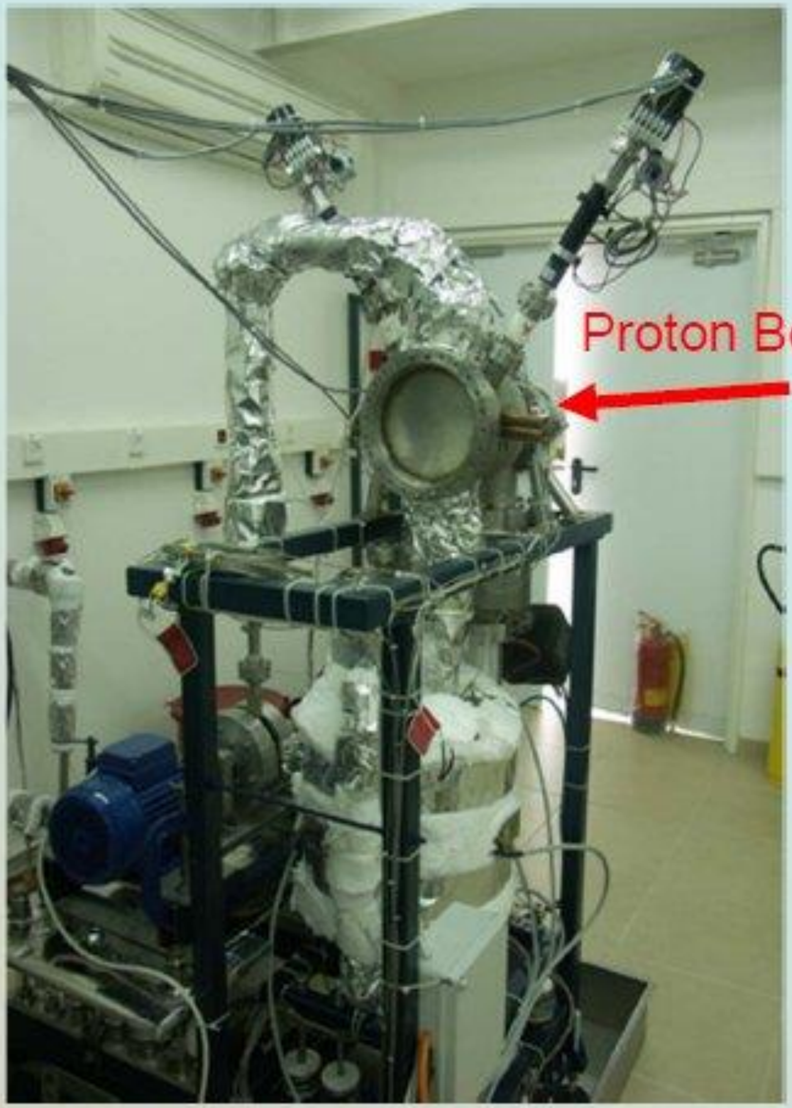
Effective thickness 50mm (Ep > 50MeV)

σ ~ 20mb *V.B. Shostak et al. Nucl. Phys. A643 (1998).*

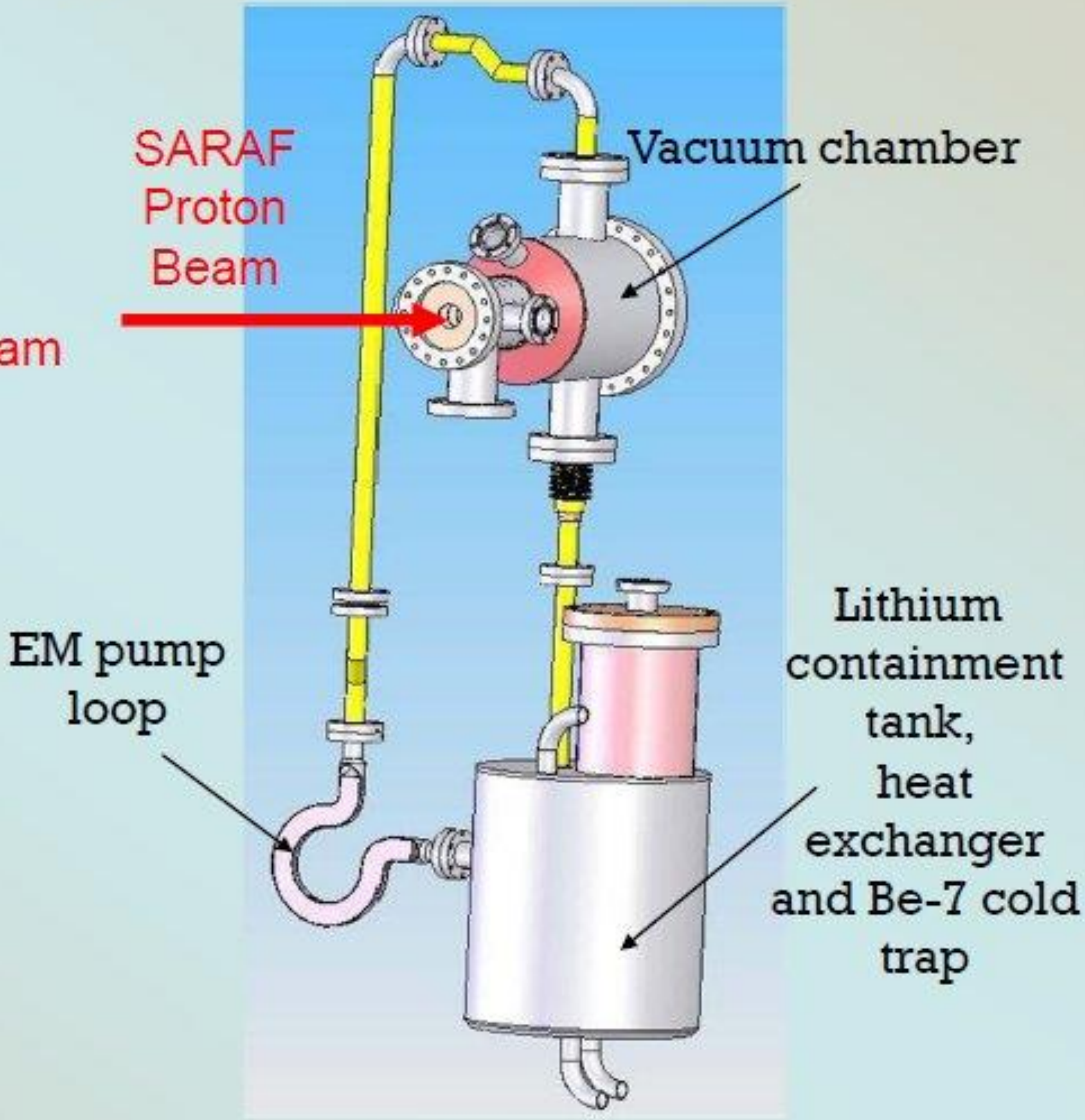
Produce 10^{12} ion/s

Don't know how fast Helium comes out of Liquid lithium?

Liquid lithium loop



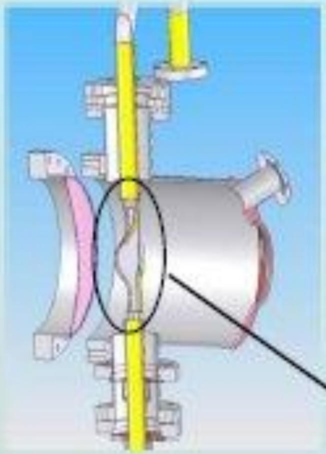
Neutron port



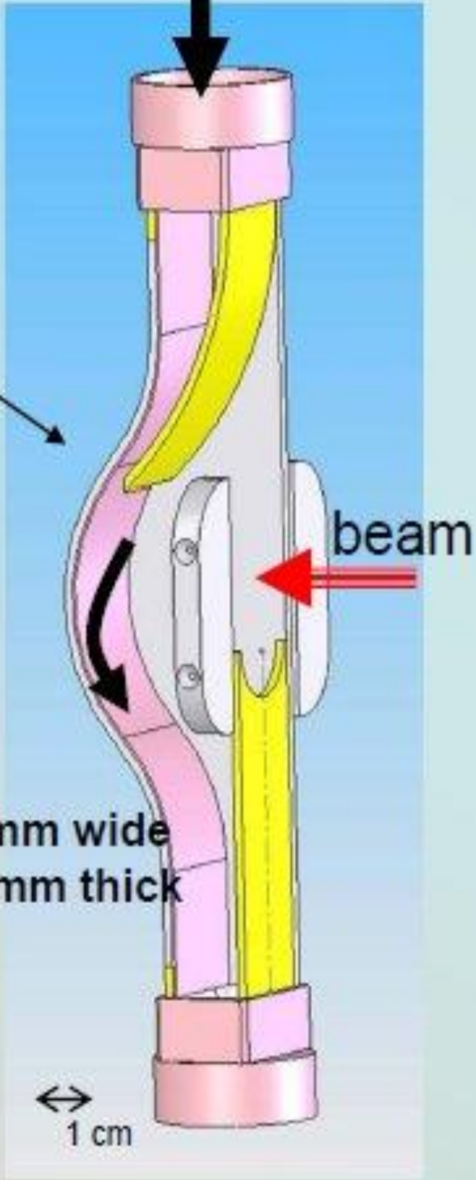
Accelerator port

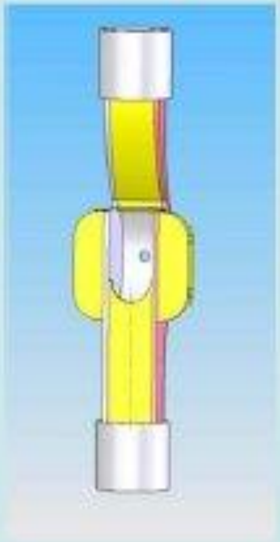
http://puhep1.princeton.edu/mumu/target/Halfon/halfon_050311.pdf

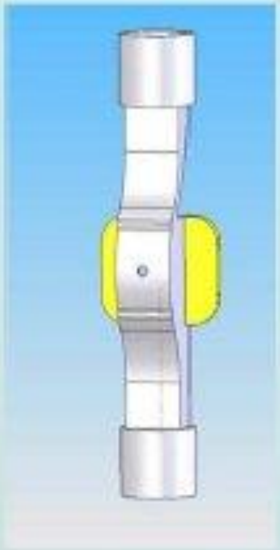
Lithium Nozzle

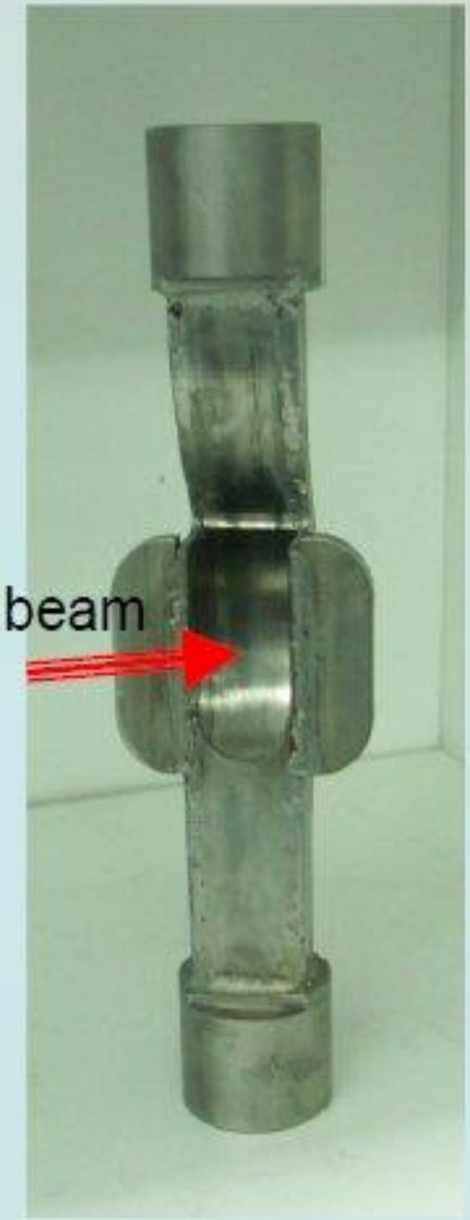


liquid
lithium



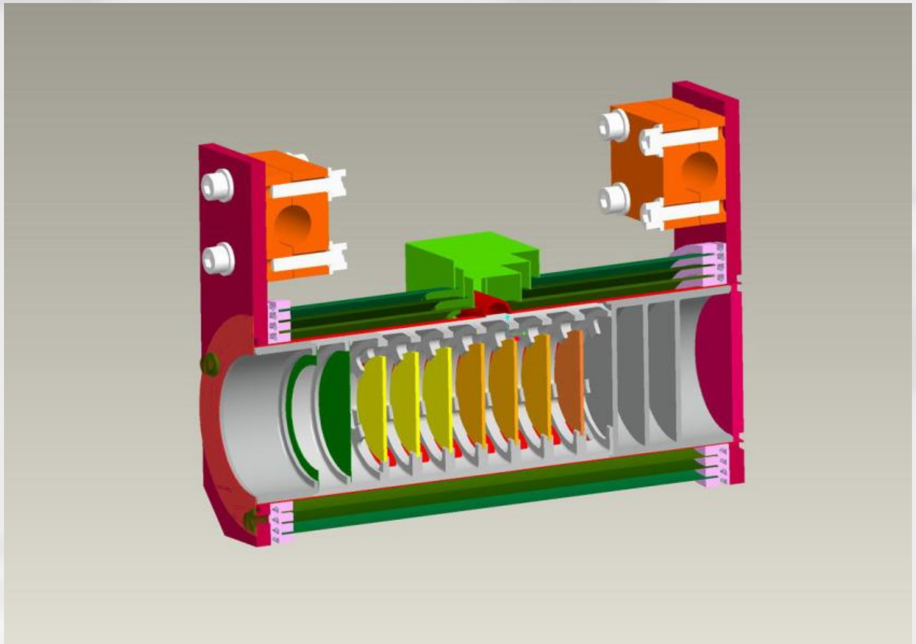






^{6,8}He from Boron targets:

→ Boron Carbide (B_4C) or Boron Nitride (BN) are the hardest materials after diamond



Can be used in the

SPES type design:

ISOL technique

^{6,8}He from Boron targets:

→ ^{11}B(p,4p)^{8}He @ 70 MeV, I ~ 350 μA

→ ^{11}B(p,α2p)^{6}He

→ ^{10}Be(p,3p)^{8}He

Effective target thickness 10mm (Ep > 50MeV), cross section σ ~ 1mb ??

Produce ~ 10^{11} ions/s

Extract Helium through diffusion (T>2000K)

^{6,8}He from Beryllium Oxyde targets:

→ ^{9}Be(n,α)^{6}He (needs a neutron converter)

→ ^{10}Be(p,3p)^{8}He (needs loads of ^{10}Be)

Extract Helium through diffusion (T>2000K)

Cluster states

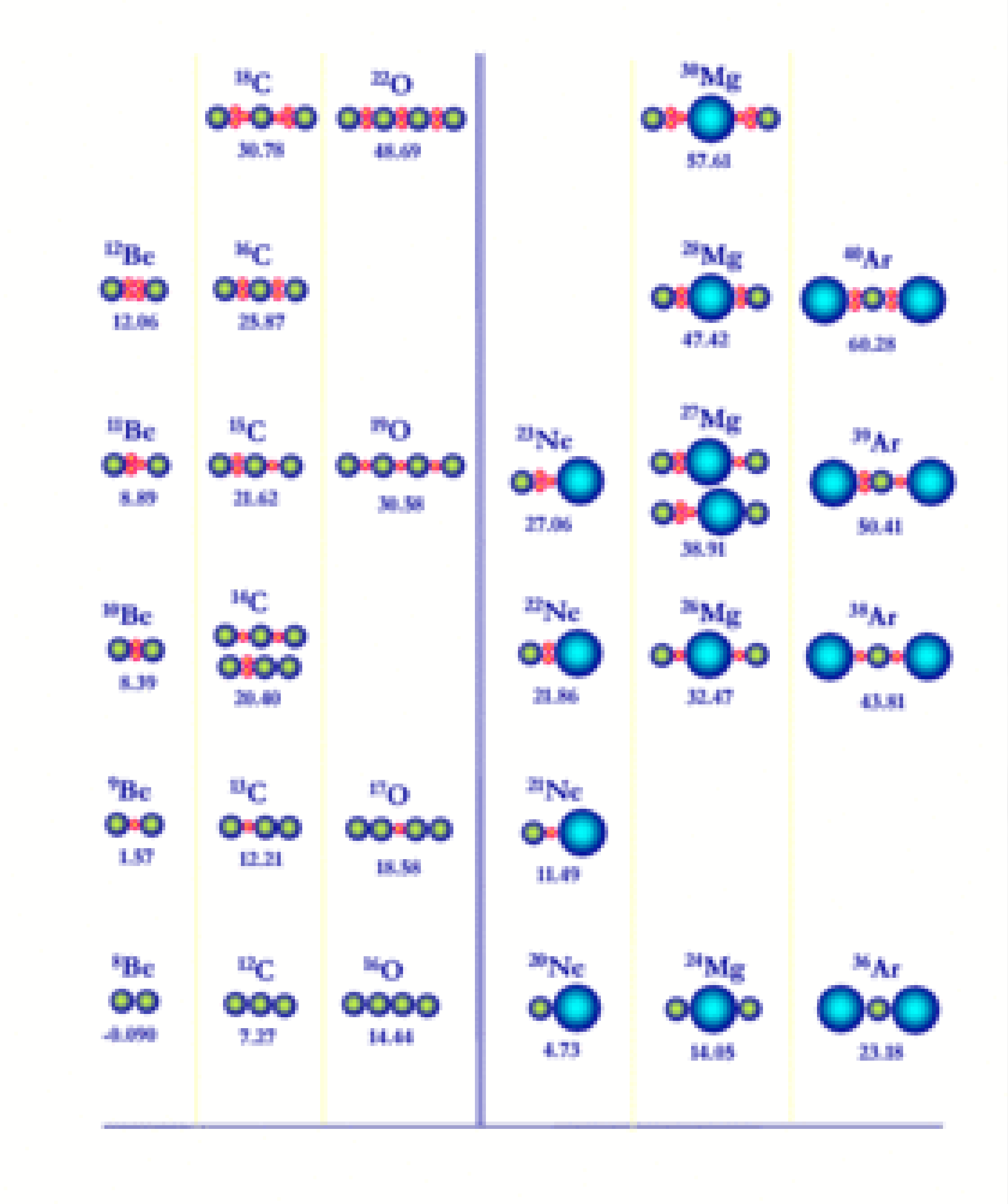
In light neutron rich

Nuclei:

Extended Ikeda

Diagram

(W. Von Oertzen)

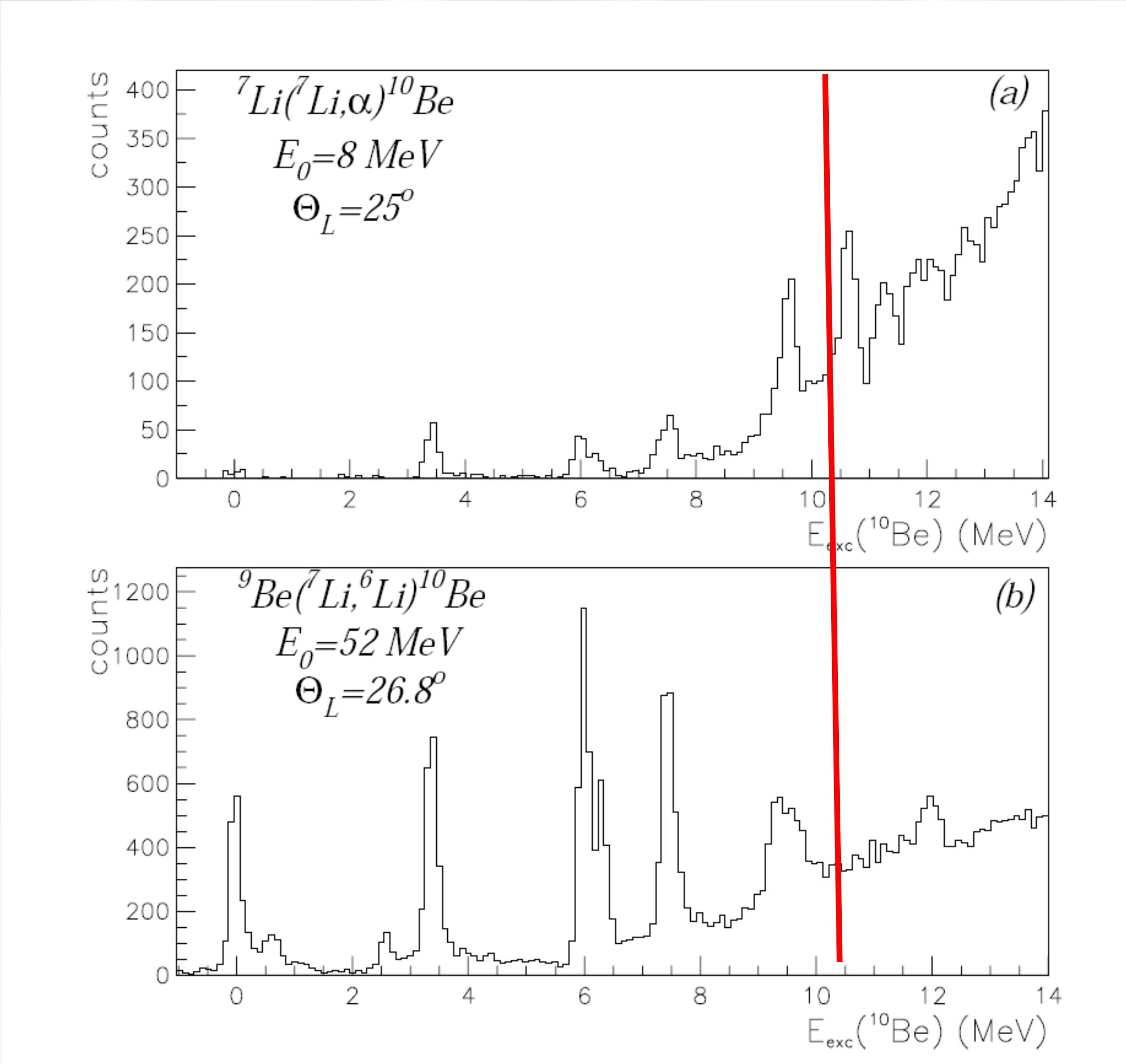


Cluster states in light neutron rich nuclei:

^{10}Be

Inclusive measurements

Đ. Miljanić et al,
Fizika B 10 (2001) 235

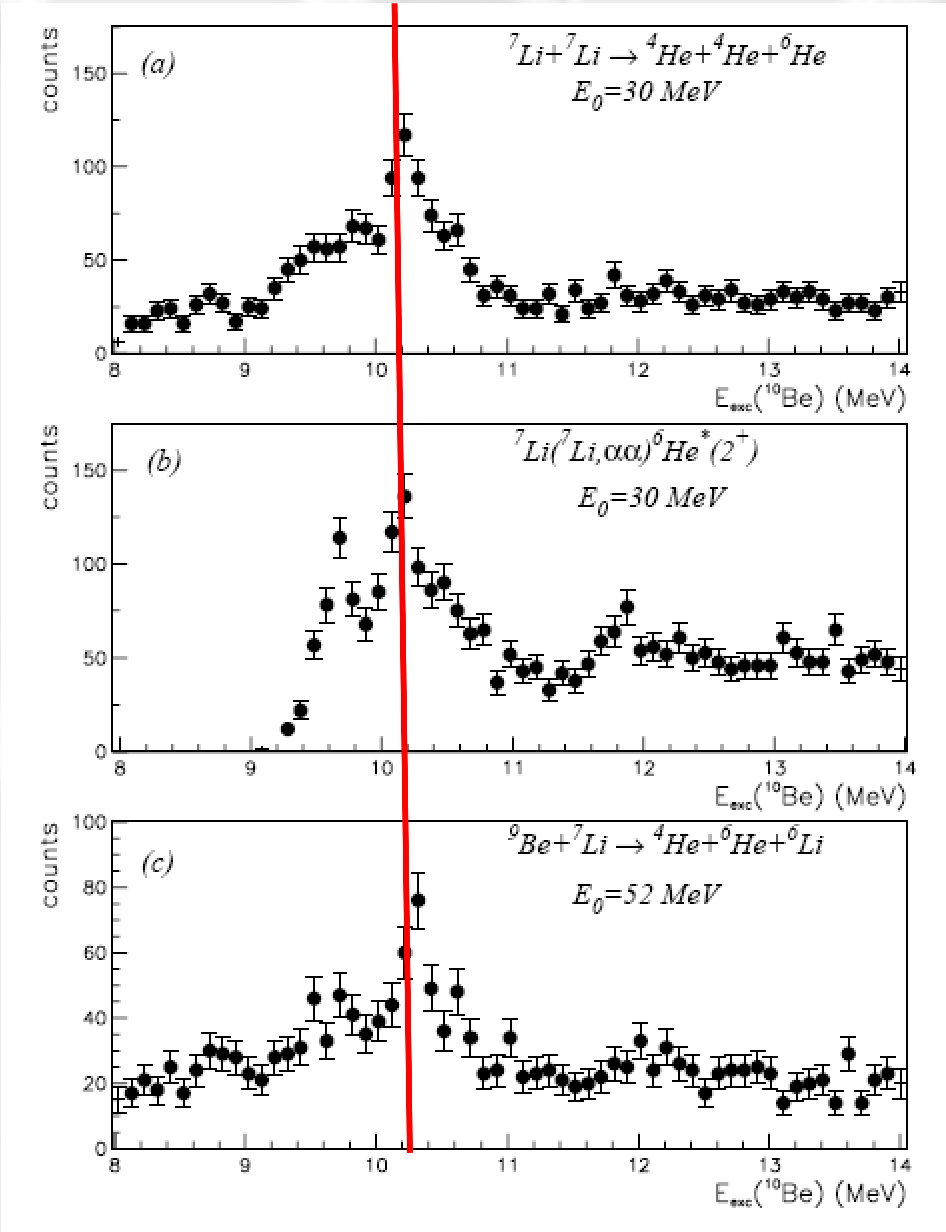


Cluster states in light neutron rich nuclei: ^{10}Be

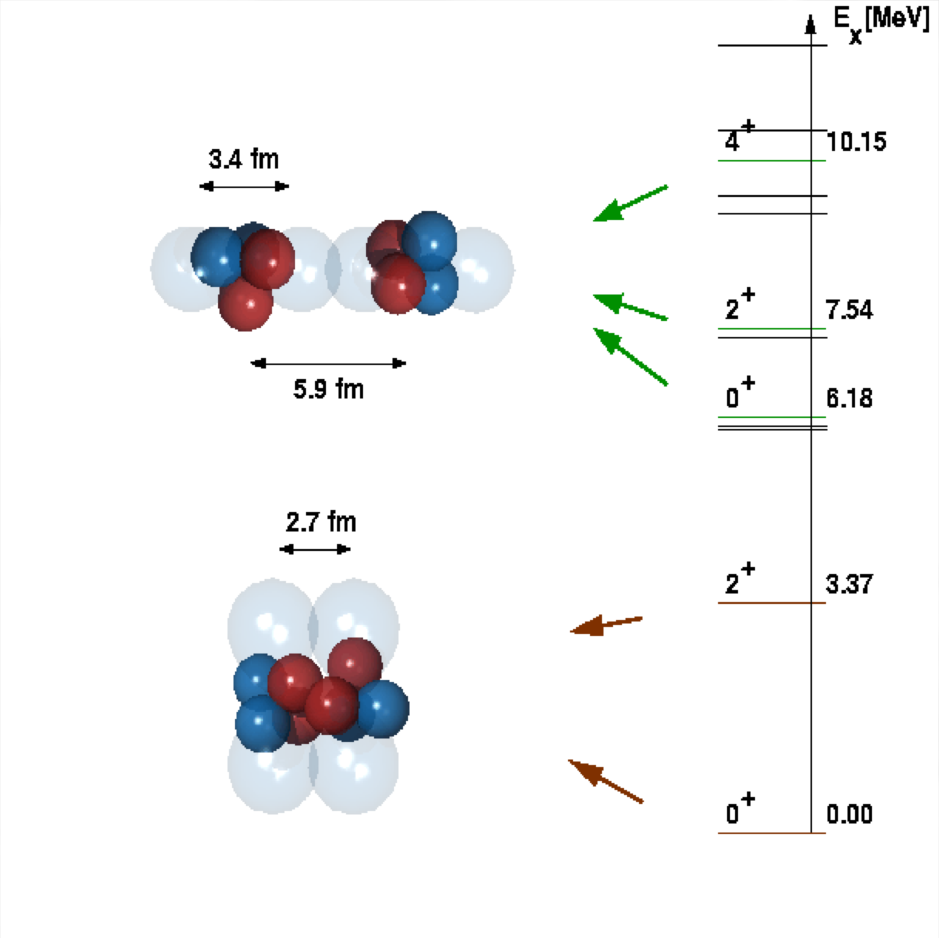
Selection of the decay channel

= selectivity

Đ. Miljanić et al,
Fizika B 10 (2001) 235



Cluster states in light neutron rich nuclei: ^{10}Be



10Be Ex = 10.15 MeV
Decays mostly via
α + 6He

moment of inertia
>2.5 times larger than
for already deformed
10Be ground state band

M. Milin et al.,
Nucl.Phys. A753 (2005) 263

Cluster states in light neutron rich nuclei

^{5}H

→ Three-body cluster configuration t + n + n

→ Two neutrons outside the N = 2 shell

Halo nucleus,

Loads of theoretical interest: Grigorenko et al., (2005), Descouvemont et al., (2008), Garrrrido et al. (2007), Nesterov et al. (2010)…

Cluster states in light neutron rich nuclei

^{5}H

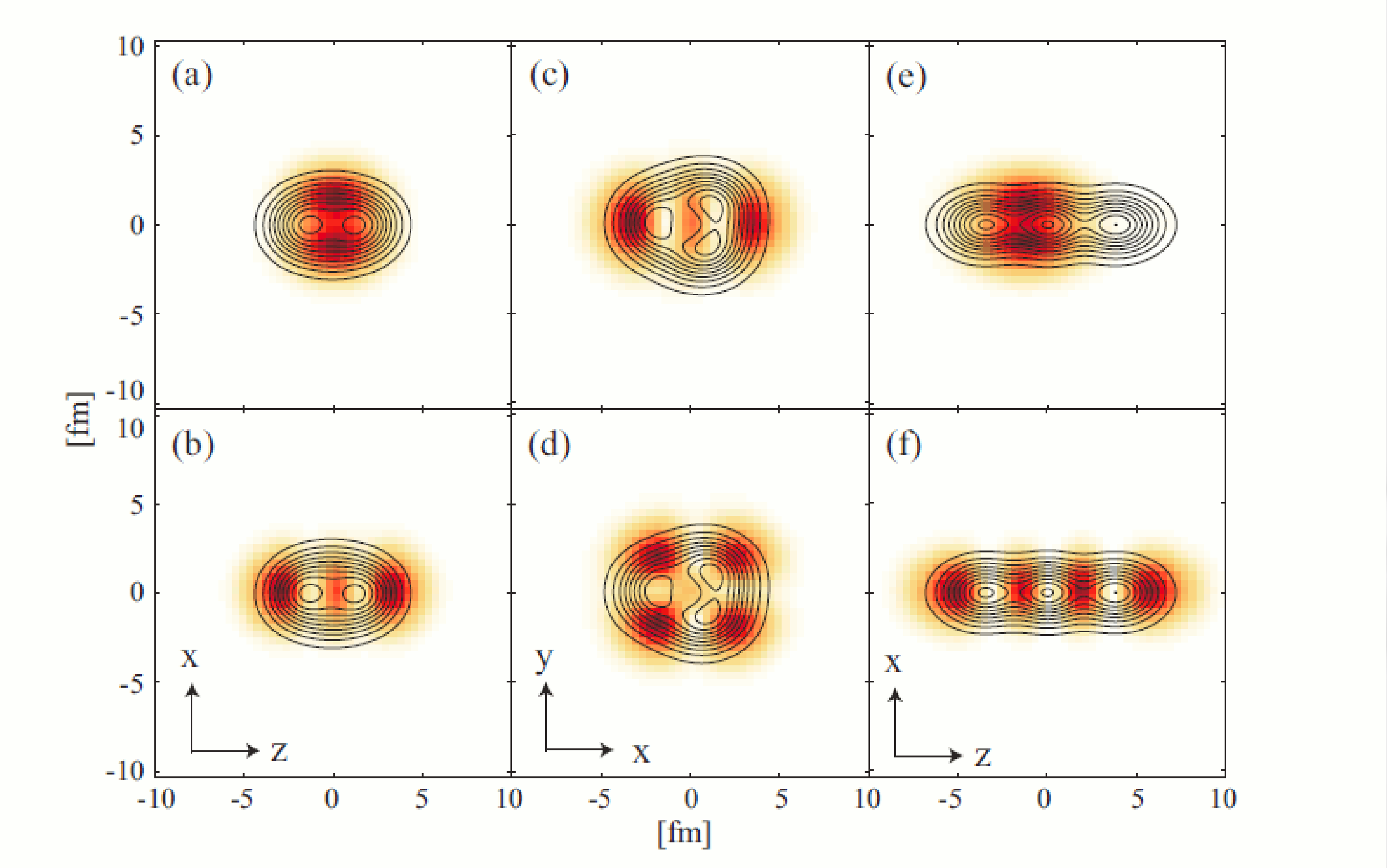
3H(t,p) reaction M.S. Golovkov et al., Phys. Rev. C72, 064612 (2005)

One proton knock-out using ^{6}He beam

Segmented Silicon Detectors + neutron detectors

Cluster states in light neutron rich nuclei:

^{16}C



T. Baba et al., Phys. Rev. C **90**, 064319 (2014)

Cluster states in light neutron rich nuclei:

^{16}C

Molecular resonances stabilized by valence neutrons:
molecular chain expected in this nucleus

Only a couple of unbound states known…

Little proton collectivity compared to neighbouring even carbon isotopes small B(E2) 2+-> 0+.
Y. Satou et al., Physics Letters B 728 (2014) 462–466
Wiedeking et al., Phys. Rev. Lett. ***100****, 152501 (2008).*

Shell model calculations very sensitive to NNN interaction!

Cluster states in light neutron rich nuclei:

^{16}C

No evidence of 6He decay channels…

P.J. Leask et al., J. Phys. G: Nucl. Part. Phys. 27 (2001) B9–B14

1 neutron knock out from 17C RIB at RIKEN:

Y. Satou et al., Physics Letters B 728 (2014) 462–466

^{18}O(^{6}He,^{8}Be)^{16}C at iTL

Experimental setup

6He at 22 MeV/u

8He at 12.5 MeV/u

Segmented silicon detector arrays

Magnetic spectrometer

ACTAR type detector

Neutron matter

4n bound state is theoretically excluded

I.V. Simenog Ukr.J.Phys. 51, 954 (2006)
R. Lazauskas et al. Phys.Rev. C 72, 034003 (2005)
K. Arai, Phys.Rev. C 68, 034303 (2003)
C.A. Bertulani J.Phys.(London) G29, 2431 (2003)
… and many more

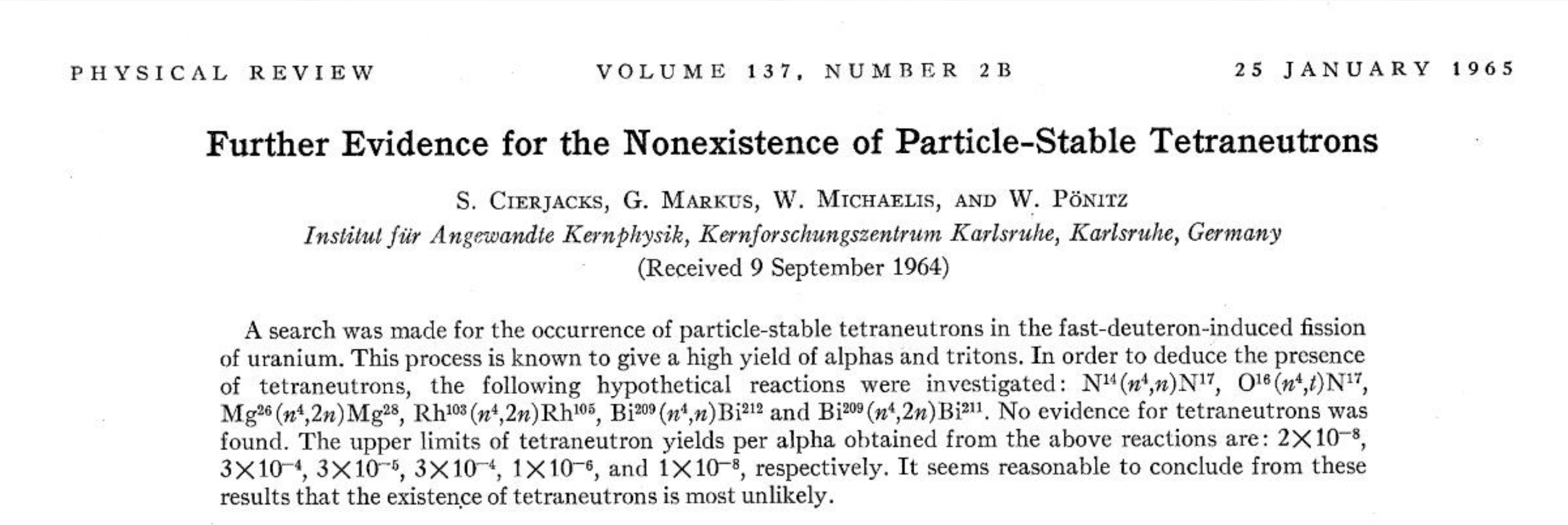
Neutron matter

8n, octoneutron, (where will we stop?)

V. A. Varlachev et al., Physics 73 (2), 143 (2009).
B. G. Novatsky, et al., JETP Letters 98 (11), 656 (2013).
G. N. Dudkin, et al., Nucl. Instr. Methods. A 760, 73 (2014).

Neutron matter

50 years later….



PHYSICAL REVIEW VOLUME 137, NUMBER 2B 25 JANUARY 1965

Further Evidence for the Nonexistence of Particle-Stable Tetraneutrons

S. Cierjacks, G. Markus, W. Michaelis, and W. Pönitz
Institut für Angewandte Kernphysik, Kernforschungszentrum Karlsruhe, Karlsruhe, Germany

(Received 9 September 1964)

A search was made for the occurrence of particle-stable tetraneutrons in the fast-deuteron-induced fission of uranium. This process is known to give a high yield of alphas and tritons. In order to deduce the presence of tetraneutrons, the following hypothetical reactions were investigated: $\mathrm{N}^{14}(n^4,n)\mathrm{N}^{17}$, $\mathrm{O}^{16}(n^4,t)\mathrm{N}^{17}$, $\mathrm{Mg}^{26}(n^4,2n)\mathrm{Mg}^{28}$, $\mathrm{Rh}^{103}(n^4,2n)\mathrm{Rh}^{105}$, $\mathrm{Bi}^{209}(n^4,n)\mathrm{Bi}^{212}$ and $\mathrm{Bi}^{209}(n^4,2n)\mathrm{Bi}^{211}$. No evidence for tetraneutrons was found. The upper limits of tetraneutron yields per alpha obtained from the above reactions are: 2×10^{-8}, 3×10^{-4}, 3×10^{-5}, 3×10^{-4}, 1×10^{-6}, and 1×10^{-8}, respectively. It seems reasonable to conclude from these results that the existence of tetraneutrons is most unlikely.

looked for ^{4}n emission in fission events

Neutron matter

Break up of ^{14}Be

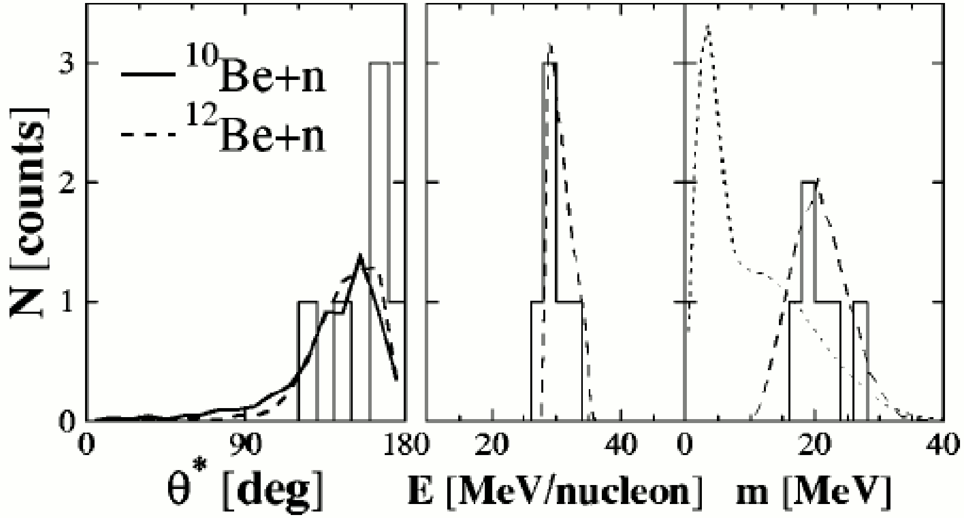
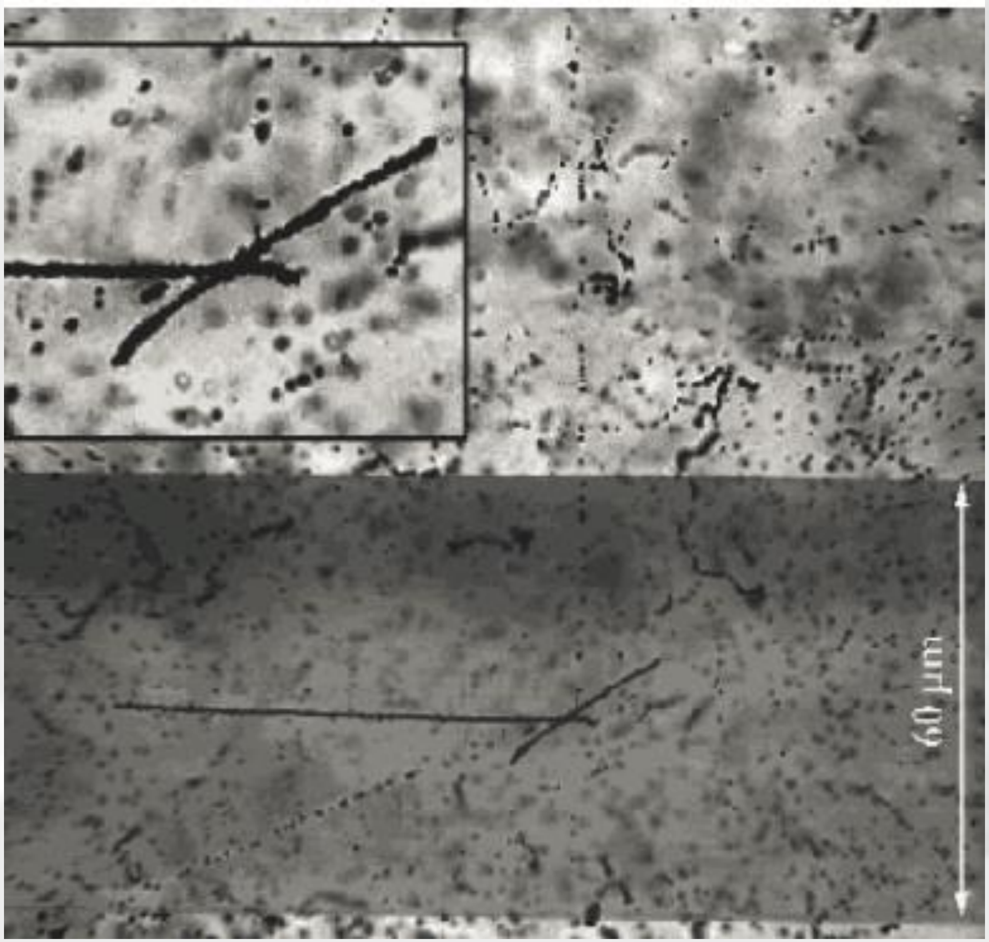


FIG. 13. Distributions for the six multineutron candidate events (histograms). Left: relative angle between the Be fragment and the neutron cluster in the average-beam-velocity frame, compared to the data for ^{10}Be+n (solid line) and to those for ^{12}Be+n (dashed line); both distributions have been normalized to six events. Middle-right: total kinetic energy and invariant mass with respect to the threshold for the ^{10}Be+^{4}n system; the dashed lines are the result of a simulation in which the input distribution (dotted line) has been filtered by the analysis conditions used in Fig. 6.

F.M. Marques et al. Phys. Rev. C65, 044006 (2002)

Neutron matter

Decay of ^{8}He in emulsion plates



D.A. Artemenkov et al. Few-Body Systems 55, 733 (2014) Few-Body Systems 55, 733 (2014)

Neutron matter

Look for correlations/resonance (2MeV?)

→ two proton stripping reactions

16O(6He,4n)18Ne*

→ double charge exchange reactions

18O(6He,6n)18Ne*, 18O(8He,8n)18Ne*
@ 10MeV/A

Identification of 18Ne via g-ray transition or/and MCP/tof

Detection of neutrons in a dedicated neutron wall

Neutron detectors … matter

Cheap scintillator

121 x 100 L

=12100L

X 1000R/L

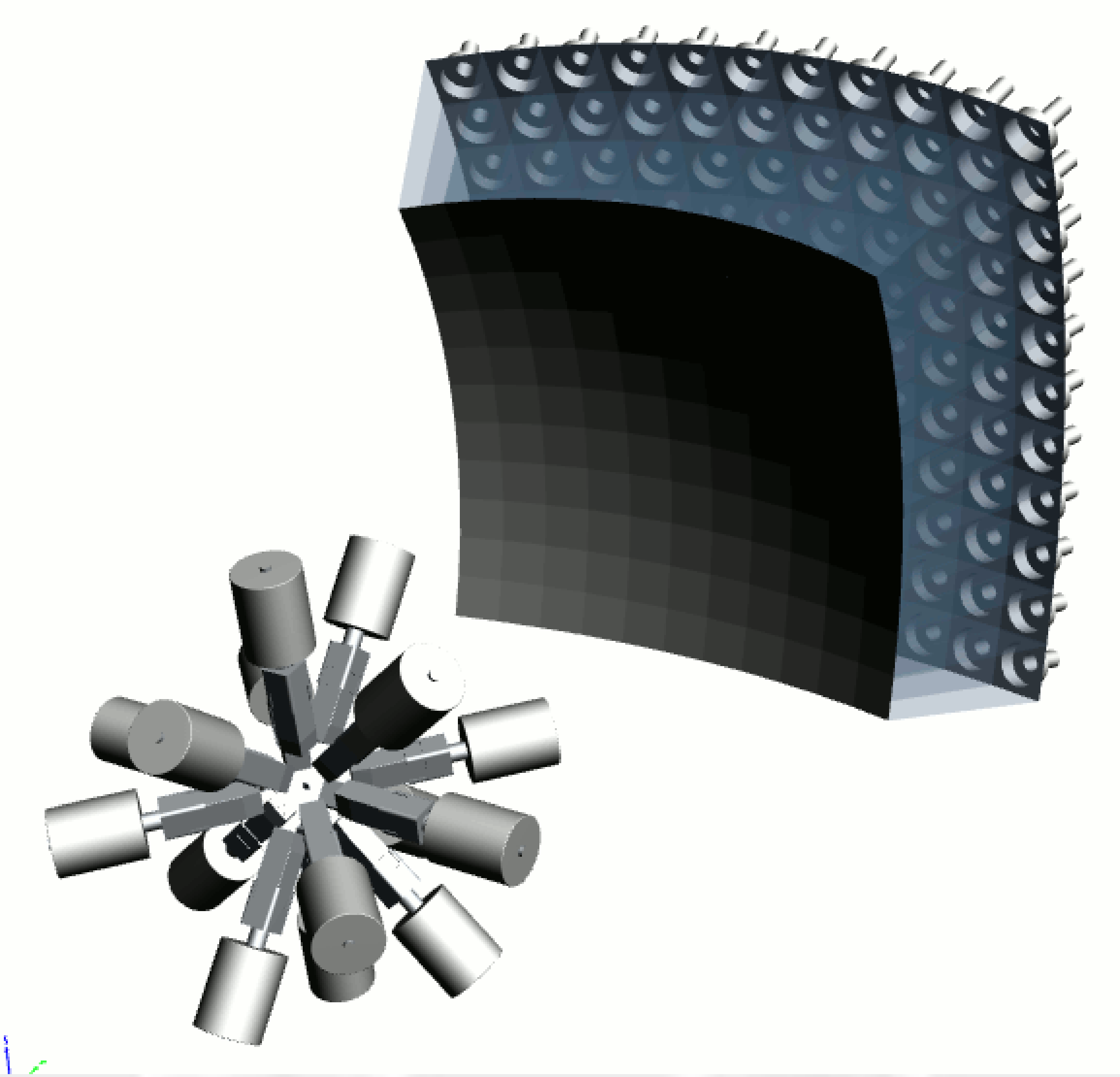
~12.0MR

10” tubes

+ 121 x 40000

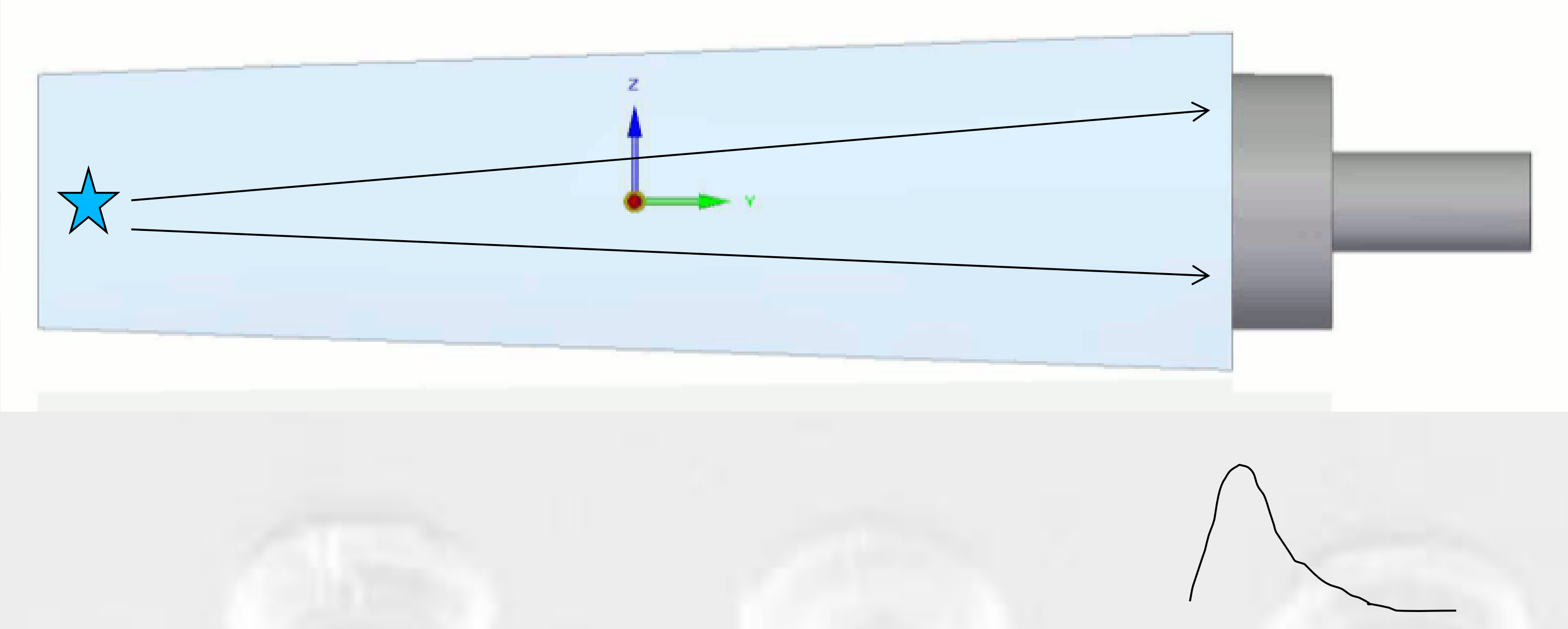
~ 5MR

Not too bad…



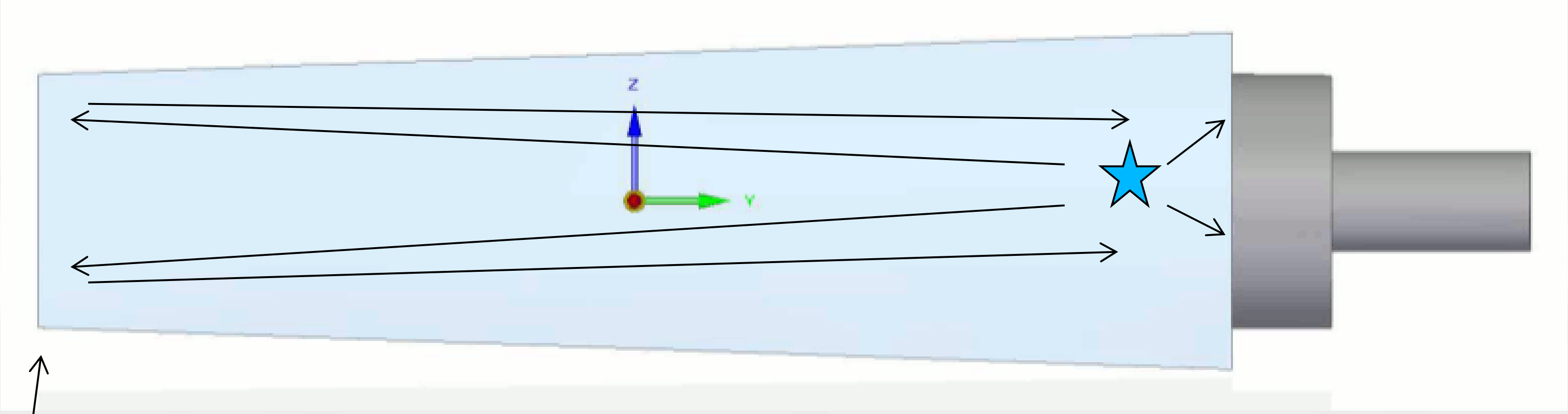
Neutron detectors … matter

Pulse shape analysis to deduce the interaction point



Neutron detectors … matter

Pulse shape analysis to deduce the interaction point



Reflective coating ☺

$\Delta t = 10$ns

Two nucleon transfer

Two nucleon stripping reaction important to probe neutron and proton pairing in nuclei.

(p,t) and (t,p) used extensively:

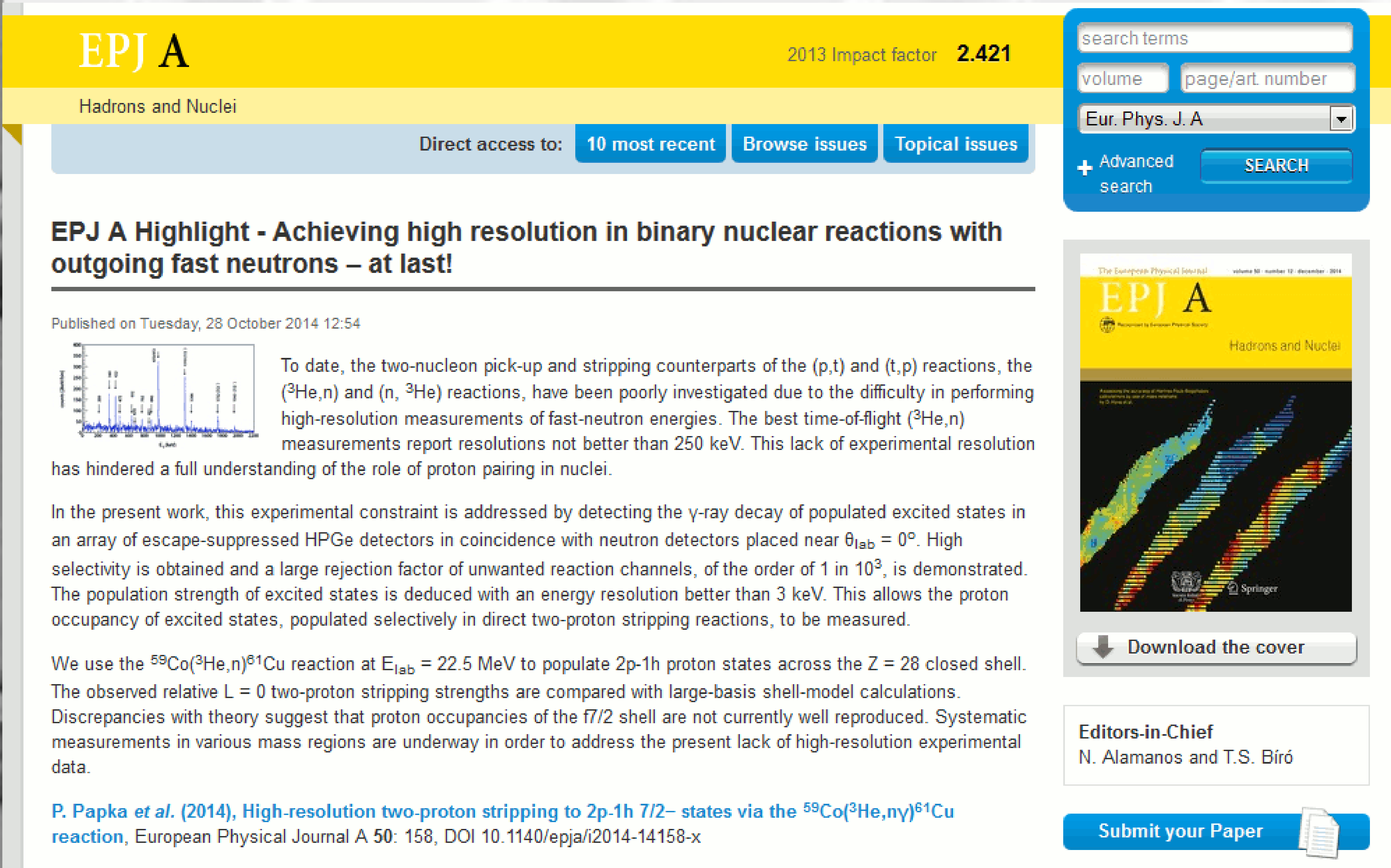
only the two-neutron components

Fewer measurement using (3He,n)

W.P. Alford et al. Phys. Rev. C 30, 67 (1984)

A. Roberts et al., Phys. Rev. C ***87****, 051305(R) (2013)*

Two nucleon transfer (3He,nγ) at iTL



EPJ A Highlight - Achieving high resolution in binary nuclear reactions with outgoing fast neutrons – at last!

Published on Tuesday, 28 October 2014 12:54

To date, the two-nucleon pick-up and stripping counterparts of the (p,t) and (t,p) reactions, the (^{3}He,n) and (n, ^{3}He) reactions, have been poorly investigated due to the difficulty in performing high-resolution measurements of fast-neutron energies. The best time-of-flight (^{3}He,n) measurements report resolutions not better than 250 keV. This lack of experimental resolution has hindered a full understanding of the role of proton pairing in nuclei.

In the present work, this experimental constraint is addressed by detecting the γ-ray decay of populated excited states in an array of escape-suppressed HPGe detectors in coincidence with neutron detectors placed near $\theta_{lab} = 0°$. High selectivity is obtained and a large rejection factor of unwanted reaction channels, of the order of 1 in 10^3, is demonstrated. The population strength of excited states is deduced with an energy resolution better than 3 keV. This allows the proton occupancy of excited states, populated selectively in direct two-proton stripping reactions, to be measured.

We use the ^{59}Co(^{3}He,n)^{61}Cu reaction at E_{lab} = 22.5 MeV to populate 2p-1h proton states across the Z = 28 closed shell. The observed relative L = 0 two-proton stripping strengths are compared with large-basis shell-model calculations. Discrepancies with theory suggest that proton occupancies of the f7/2 shell are not currently well reproduced. Systematic measurements in various mass regions are underway in order to address the present lack of high-resolution experimental data.

P. Papka *et al.* (2014), High-resolution two-proton stripping to 2p-1h 7/2− states via the ^{59}Co(^{3}He,nγ)^{61}Cu reaction, European Physical Journal A **50**: 158, DOI 10.1140/epja/i2014-14158-x

Editors-in-Chief
N. Alamanos and T.S. Bíró

Structure of ββ nuclei

Nuclear Matrix Elements

Transfer reactions to determine the wave functions

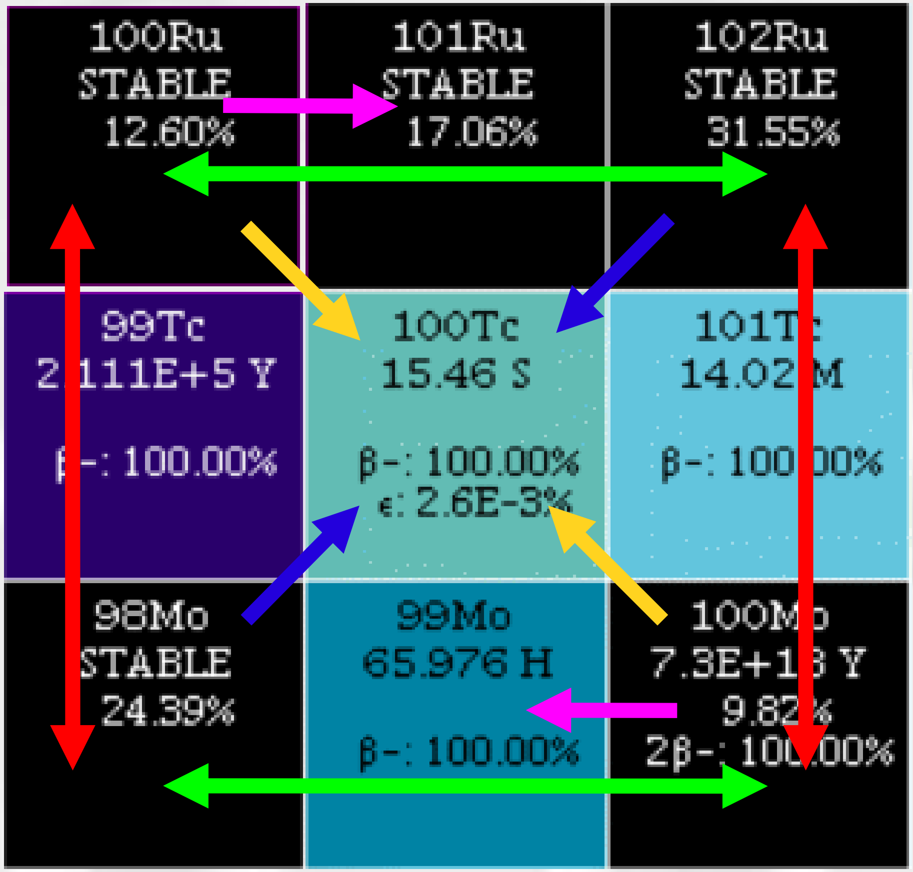
(p,t) (t,p)

$(^3\mathrm{He},t)$ $(t,{}^3\mathrm{He})$

$(^3\mathrm{He},n)$ $(^6\mathrm{He},{}^8\mathrm{Be})$

$(^3\mathrm{He},p)$ $(p,{}^3\mathrm{He})$

(d,p) (p,d)



100Ru STABLE 12.60%	101Ru STABLE 17.06%	102Ru STABLE 31.55%
99Tc 2.111E+5 Y β-: 100.00%	100Tc 15.46 S β-: 100.00% ϵ: 2.6E-3%	101Tc 14.02 M β-: 100.00%
98Mo STABLE 24.39%	99Mo 65.976 H β-: 100.00%	100Mo 7.3E+18 Y 9.82% 2β-: 100.00%

A. Roberts et al., Phys. Rev. C ***87****, 051305(R) (2013): 76Ge*

Two nucleon transfer

Two-neutron pick up

Two neutron stripping reaction (6He,α) could be purer than (t,p) (DWBA normalisations usually need factors of 2 to 3, unhappiness factor)

6He: halo nucleus

-> cigar configuration or two neutron correlated

-> two neutron transfer mostly from the two neutron correlated configuration: single step is favoured!

D. Smalley et al., Phys. Rev. C ***89****, 024602 (2014)*

Two nucleon transfer:

Two-proton pick up

Two proton pick-up reaction (6He,8Be) the simplest of all!

Heavier systems become messy very rapidly

(14C,16O)

Momentum mismatch for low relative angular momentum transfer

Structure of 14C is complicated makes DWBA calculations uncertain

Can be used systematically on all ββ nuclei…

Final remarks:

….Loads to do with 6He

tHe end