Physics at SARAF

The Soreq Applied Research Accelerator Facility

@ IRFU seminar

Dan Berkovits

September 3rd 2015

SARAF – Soreq Applied Research Accelerator Facility

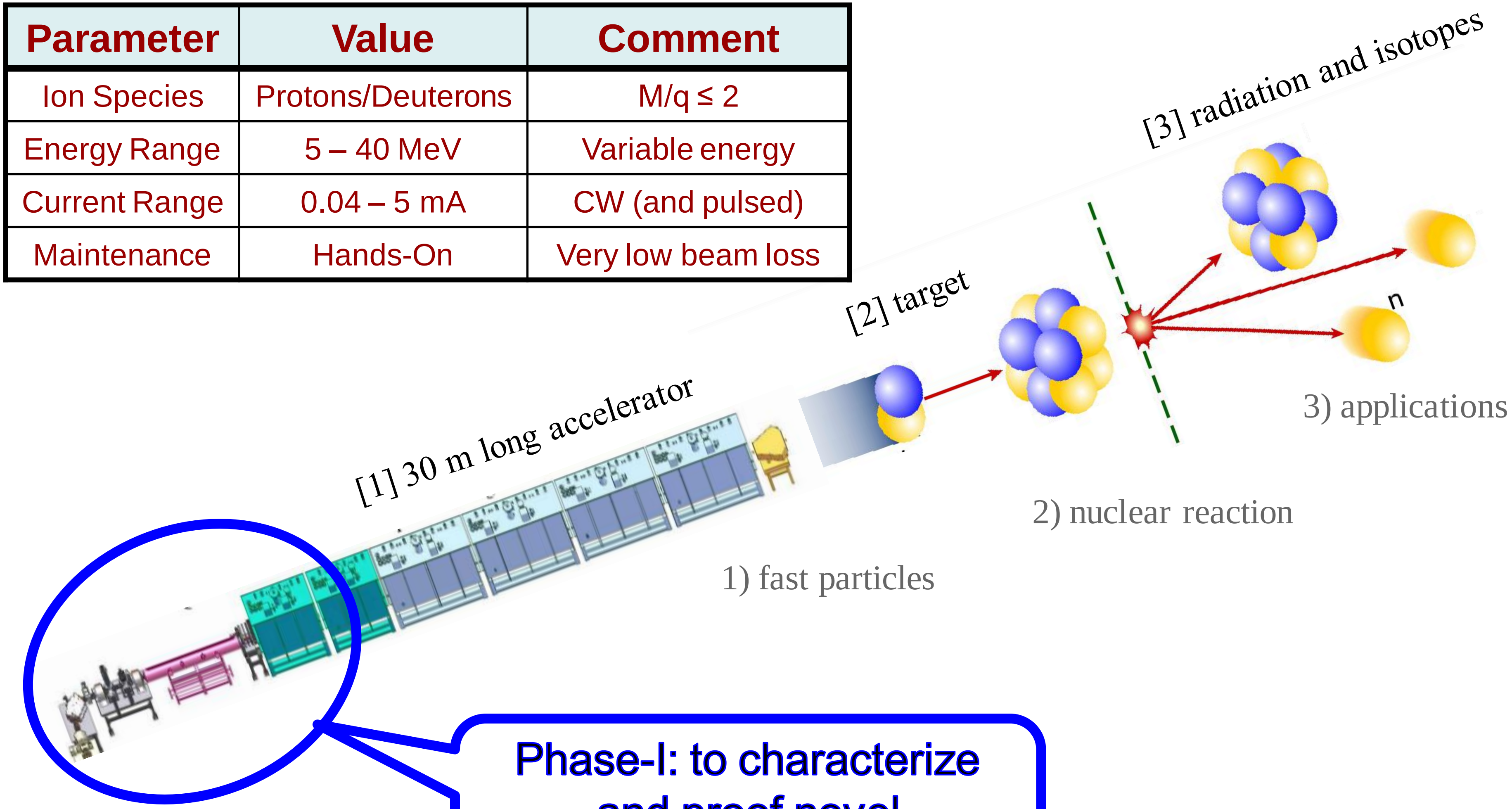
- To enlarge the experimental nuclear science infrastructure and promote research in Israel

- To develop and produce radioisotopes for bio-medical applications

- To modernize the source of neutrons at Soreq and extend neutron based research and applications

The accelerator that covers the needs

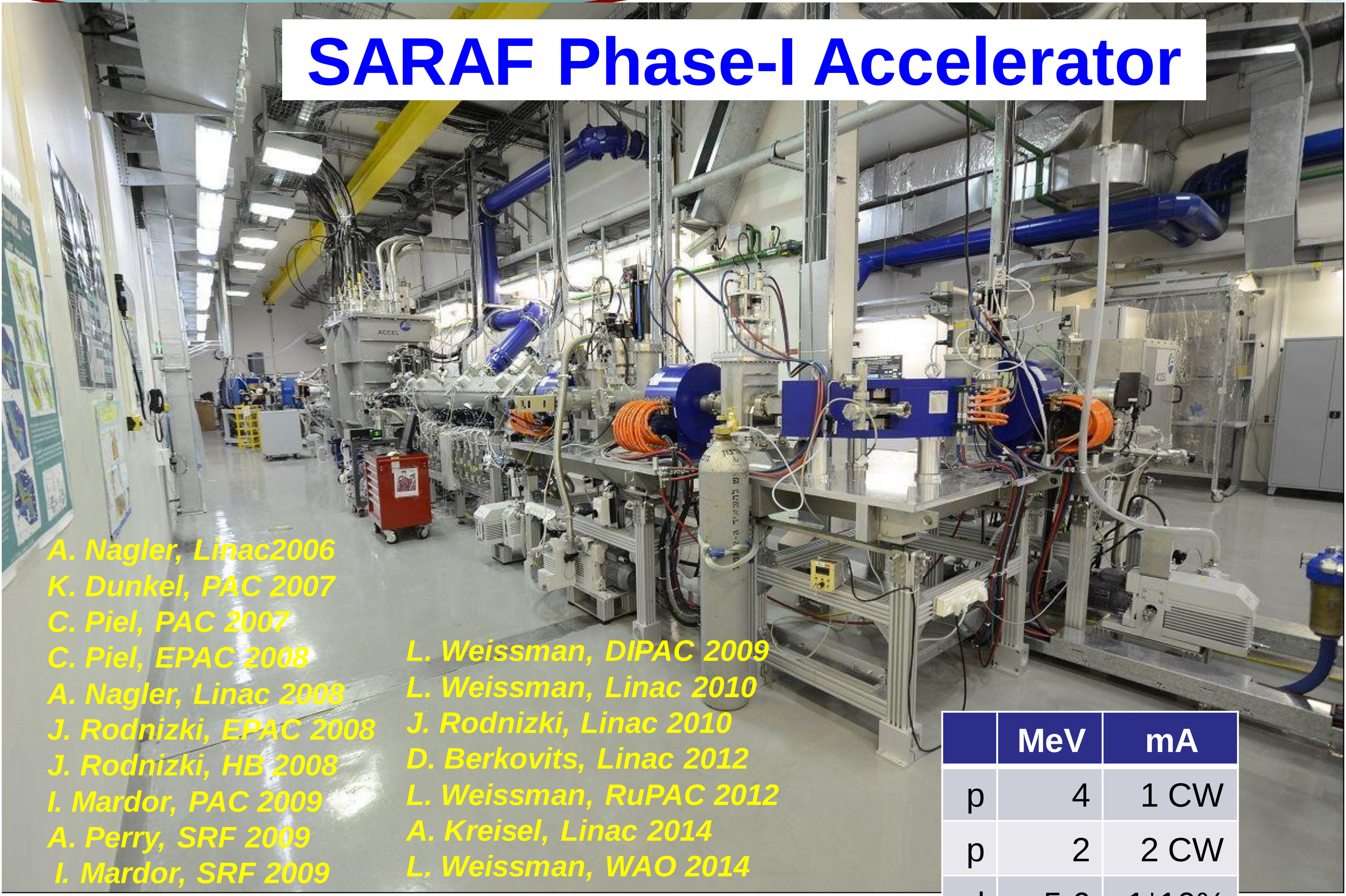
Parameter	Value	Comment
Ion Species	Protons/Deuterons	M/q ≤ 2
Energy Range	5 – 40 MeV	Variable energy
Current Range	0.04 – 5 mA	CW (and pulsed)
Maintenance	Hands-On	Very low beam loss



Phase-I: to characterize and proof novel acceleration technologies

For Phase-II design see N. Pichoff *et al.*, IPAC 2015

SARAF Phase-I Accelerator



A. Nagler, Linac2006
K. Dunkel, PAC 2007
C. Piel, PAC 2007
C. Piel, EPAC 2008
A. Nagler, Linac 2008
J. Rodnizki, EPAC 2008
J. Rodnizki, HB 2008
I. Mardor, PAC 2009
A. Perry, SRF 2009
I. Mardor, SRF 2009

L. Weissman, DIPAC 2009
L. Weissman, Linac 2010
J. Rodnizki, Linac 2010
D. Berkovits, Linac 2012
L. Weissman, RuPAC 2012
A. Kreisel, Linac 2014
L. Weissman, WAO 2014

	MeV	mA
p	4	1 CW
p	2	2 CW
d	5.6	1*10%

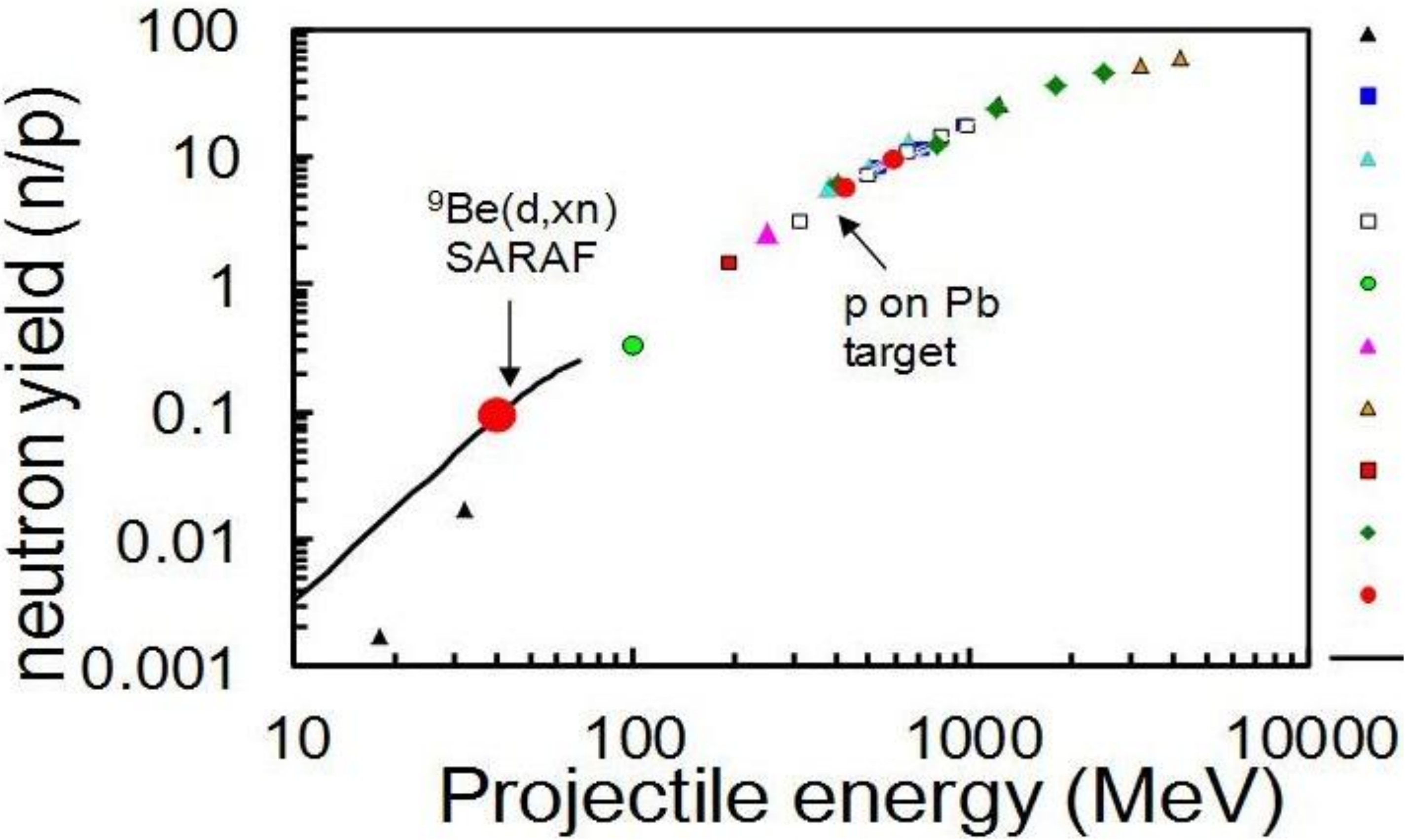
SARAF Phase-I linac status

❖ SARAF Phase-I is the first to demonstrate:

- ☑ 2.1 mA CW variable energy protons beam
- ☑ Acceleration of ions through HWR SC cavities
- ☑ Acceleration of ions through a separated vacuum SC module
- ☑ 1.7 mA CW proton irradiation of a liquid lithium jet target for neutron production

Accelerator based thermal neutron source

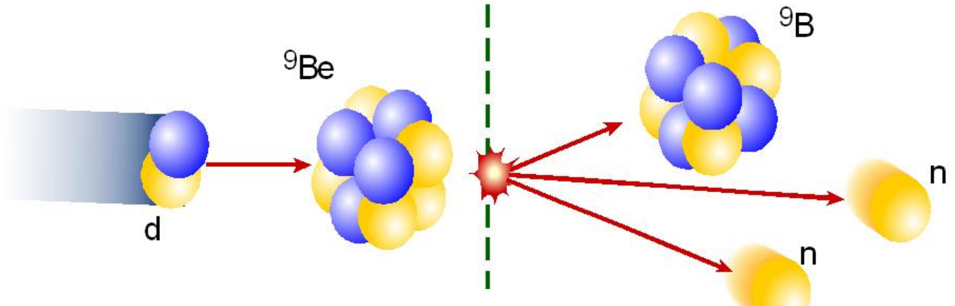
Neutron yield from d and p beams

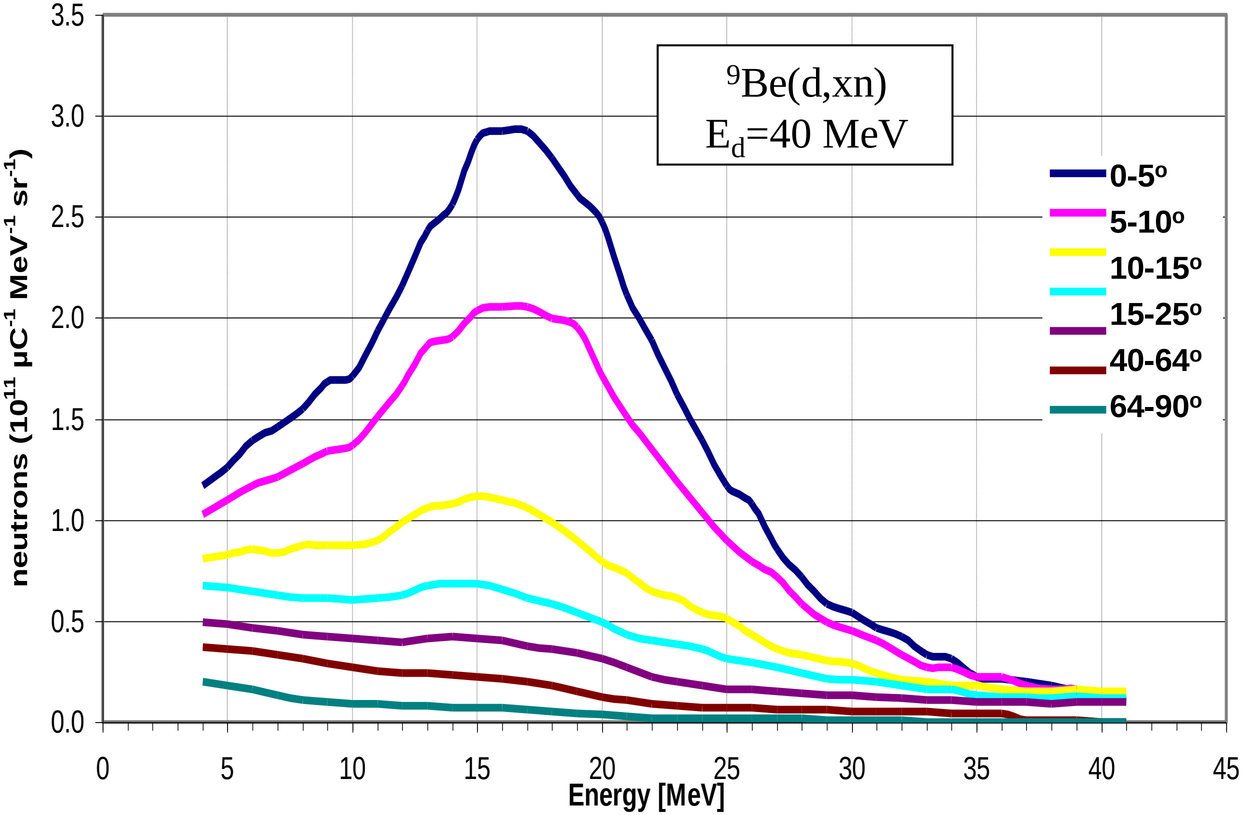


- In the range of tens of MeV projectiles, neutron yield from deuterons is higher than that of protons by a factor of 3

K. van der Meer, M.B. Goldberg et al. NIM B (2004)

Neutron production with low energy deuterons



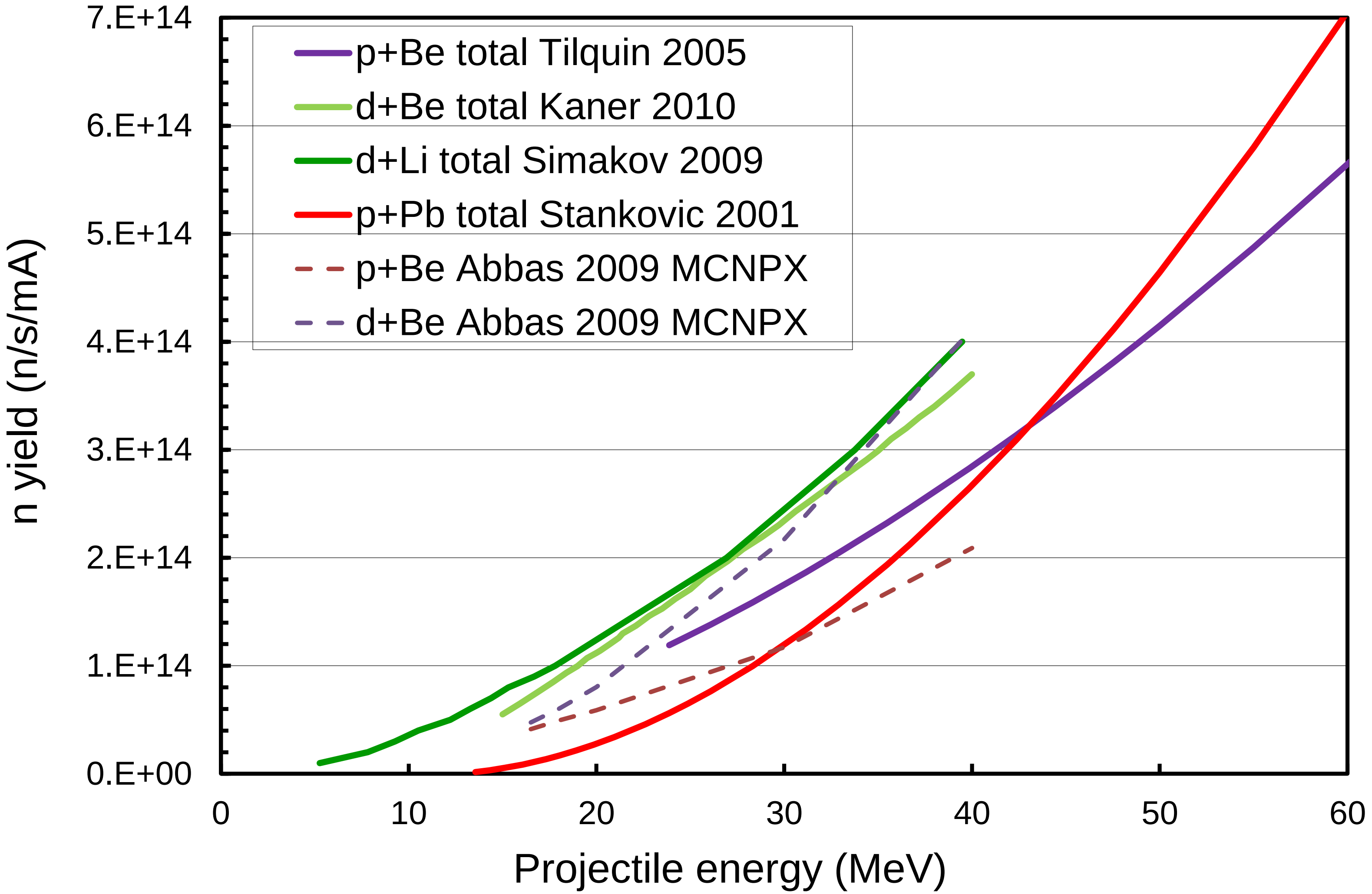


2×10^{15} fast n/s

(per 40 MeV 5 mA d)

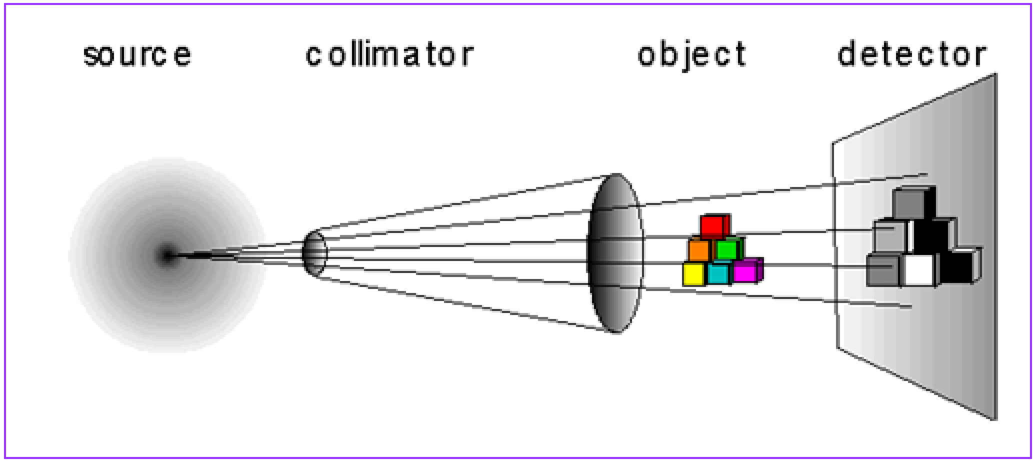
K. Lavie et al. INS 2004

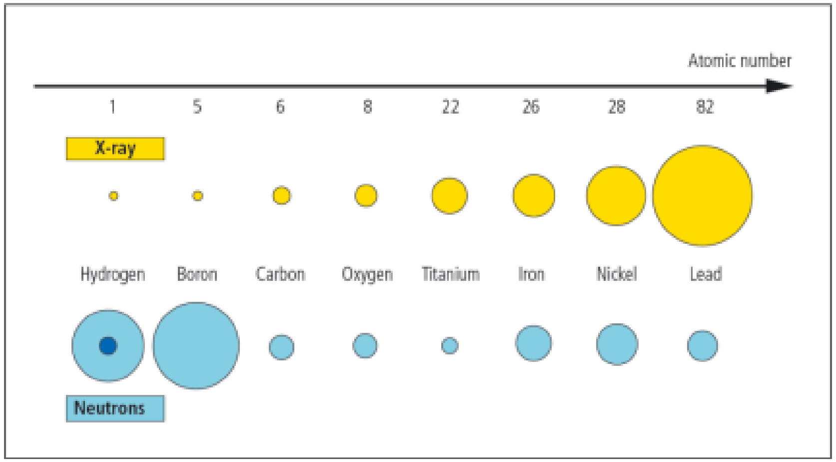
Total neutrons yield as function of projectile, energy and target – experiment vs simulation



Thermal Neutron Radiography

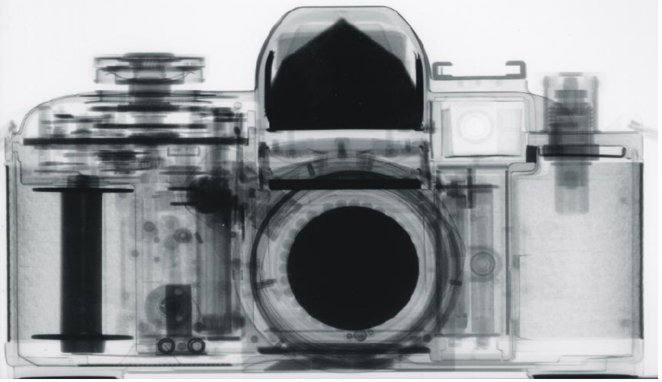
- Powerful non destructive imaging technique
- Provides images in the same manner as x-ray radiography



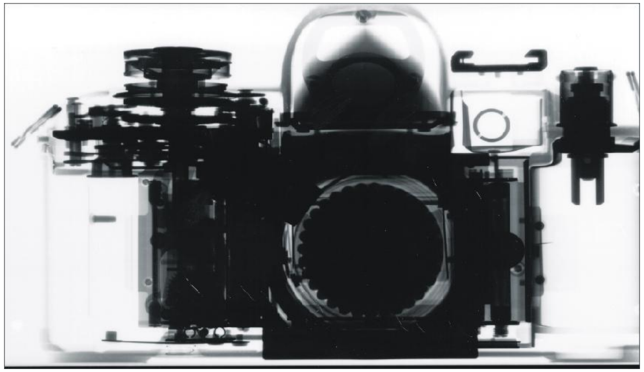


http://www.psi.ch/industry/MediaBoard/neutron_imaging_e_07.pdf

neutron radiography



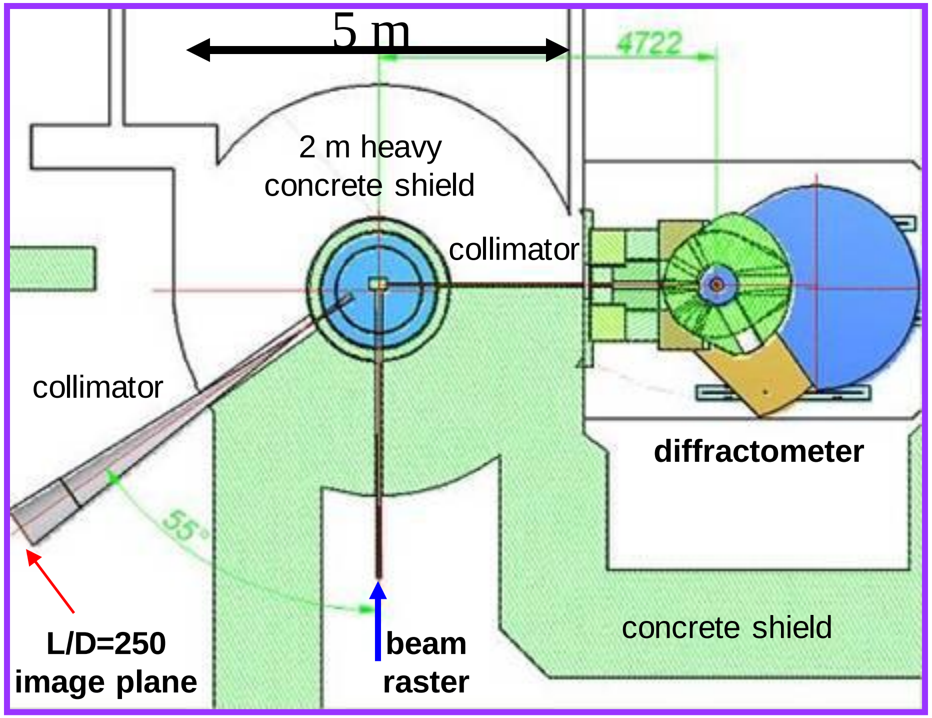
x-ray radiography

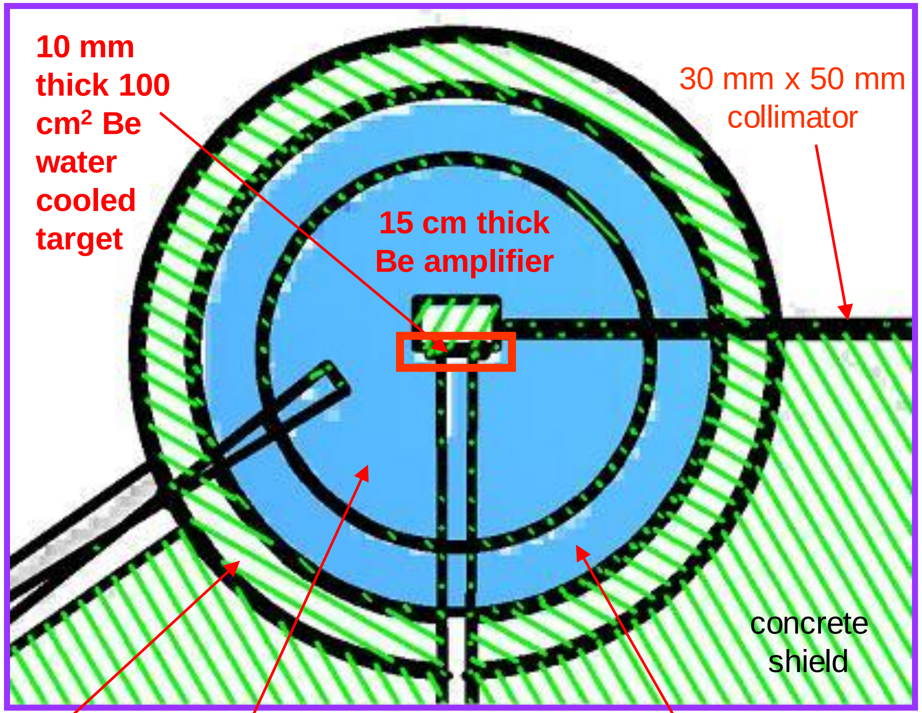


Differences in interaction probability are particularly marked at lower neutron energies

Paul Scherrer Institute - PSI

Thermal neutron source ^{9}Be(d,xn)



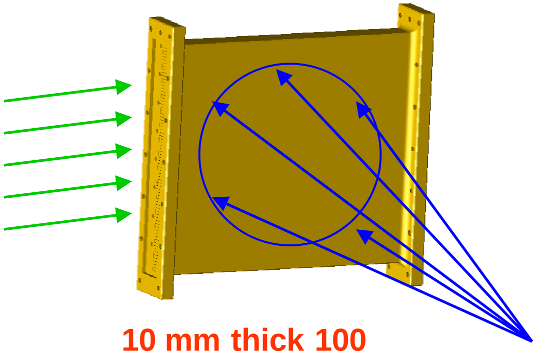


thermal Pb+Fe water cooled shield

beam

20 cm H_2O reflector

Φ=120 cm D_2O moderator



water cooling

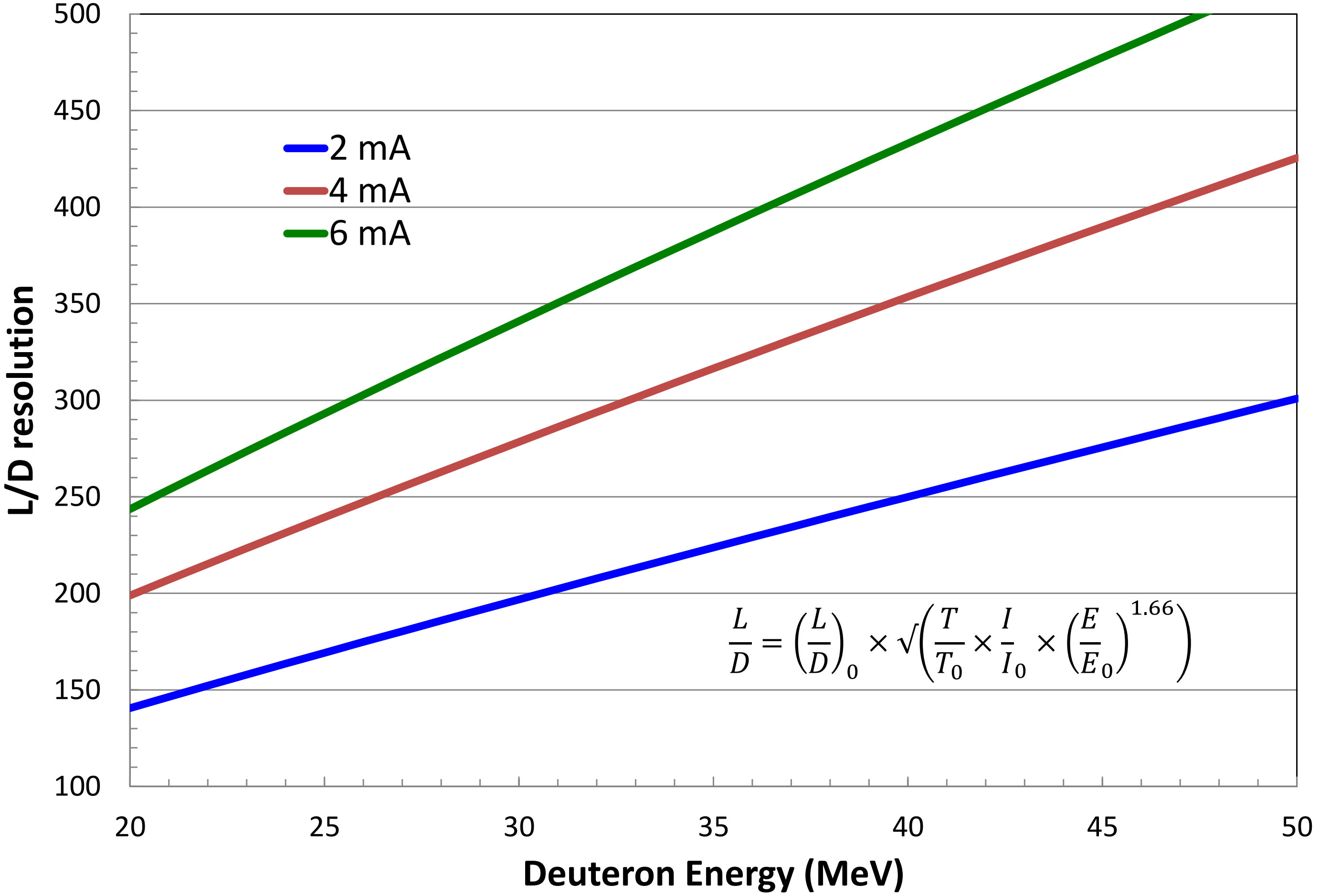
10 mm thick 100 cm² Be target

40 MeV x 2 mA d beam

➔ Need 2 mA x 40 MeV deuterons for the TNR

H. Hirshfeld et al. NIM A (2006)

Thermal neutron radiography resolution as function of current and energy @ SARAF setup

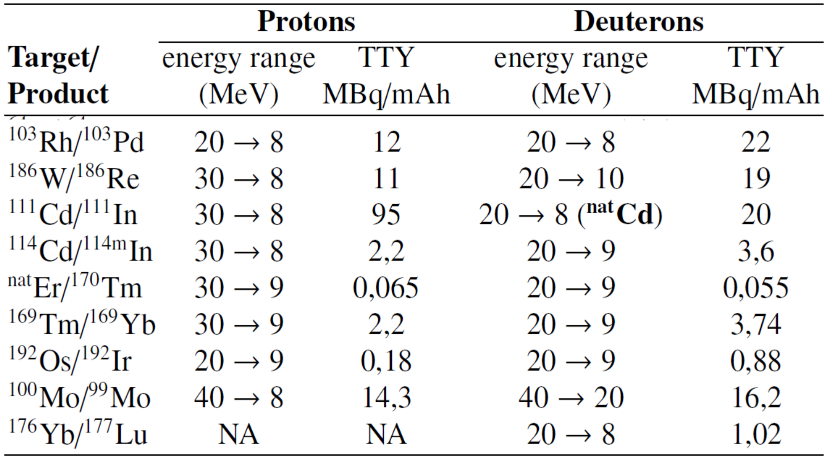


$$\frac{L}{D} = \left(\frac{L}{D}\right)_0 \times \sqrt{\left(\frac{T}{T_0} \times \frac{I}{I_0} \times \left(\frac{E}{E_0}\right)^{1.66}\right)}$$

Production of radiopharmaceutical isotopes

Production of radiopharmaceutical isotopes

- Today, most radiopharmaceutical isotopes are produced by protons up to 30 MeV
- Deuterons
  - Production of neutron-rich isotopes via the (d,p) reaction (equivalent to the (n,γ) reaction)
  - Typically, the (d,2n) cross section is significantly larger than the (p,n) reaction, for A>~100

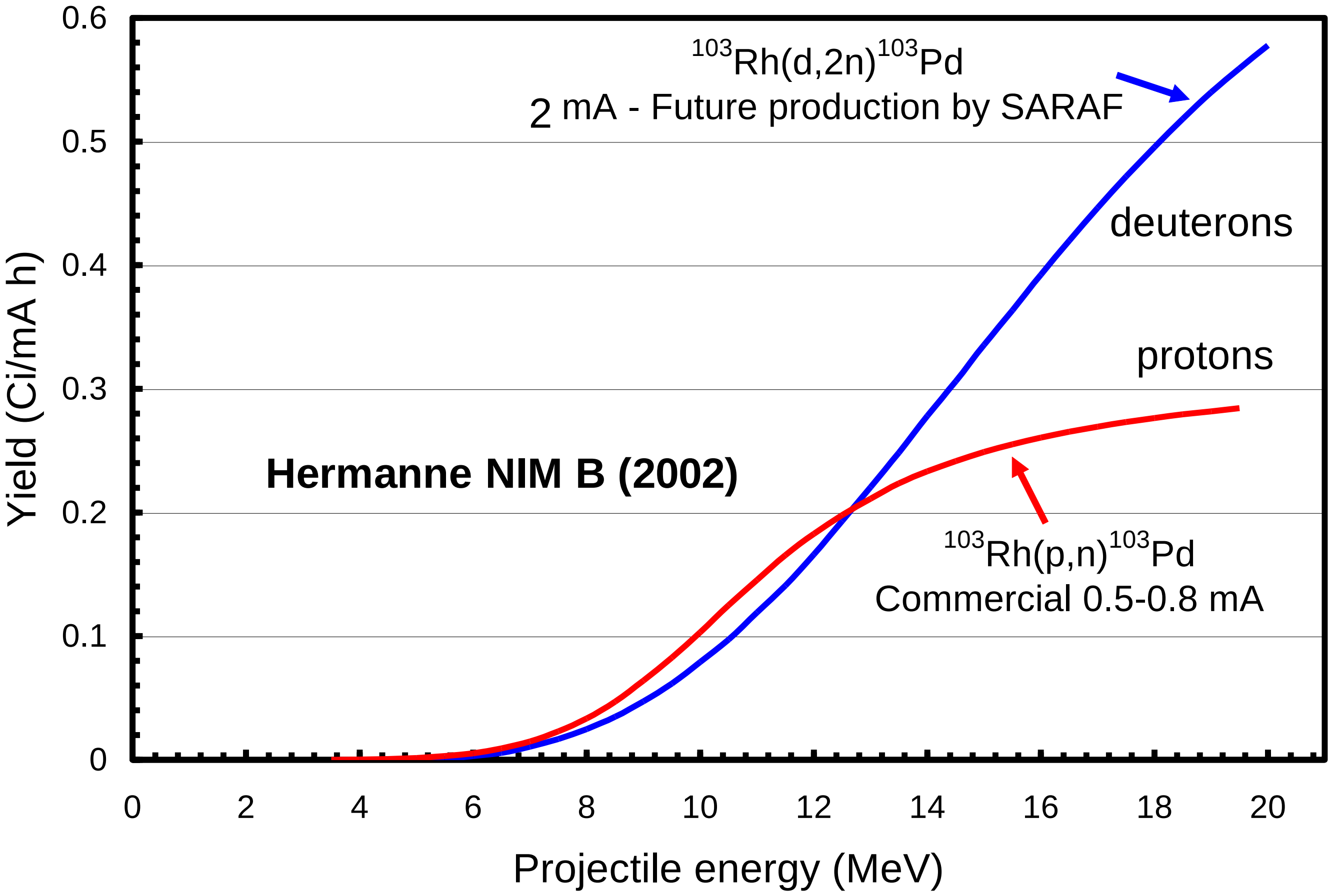


Target/ Product	**Protons**		**Deuterons**	
	energy range (MeV)	TTY MBq/mAh	energy range (MeV)	TTY MBq/mAh
^{103}Rh/^{103}Pd	20 → 8	12	20 → 8	22
^{186}W/^{186}Re	30 → 8	11	20 → 10	19
^{111}Cd/^{111}In	30 → 8	95	20 → 8 ($^{\mathrm{nat}}$**Cd**)	20
^{114}Cd/^{114m}In	30 → 8	2,2	20 → 9	3,6
$^{\mathrm{nat}}$Er/^{170}Tm	30 → 9	0,065	20 → 9	0,055
^{169}Tm/^{169}Yb	30 → 9	2,2	20 → 9	3,74
^{192}Os/^{192}Ir	20 → 9	0,18	20 → 9	0,88
^{100}Mo/^{99}Mo	40 → 8	14,3	40 → 20	16,2
^{176}Yb/^{177}Lu	NA	NA	20 → 8	1,02

Hermanne
Nucl. Data (2007)

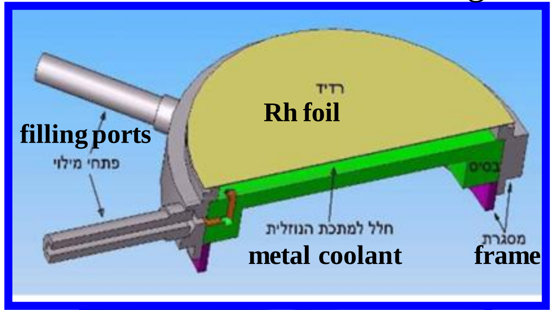
Production of ^{103}Pd

Radiopharmaceutical for prostate cancer therapy



Proton:
used today
plated target

Deuteron: demonstrated target



E. Lavie *et al.* INS23 (2006)

I. Silverman et al. NIM B (2007)

Currently Preferred Options at SARAF Phase-II

Medical Use	Radioisotopes
Diagnostics	^{64}Cu (β^+) ^{89}Zr (β^+) ^{111}In (γ) ^{124}I (β^+)
Diagnostics Generator	^{68}Ge (^{68}Ga – β^+) ^{99}Mo (^{99m}Tc – γ)
Therapy	^{67}Cu (β^-) ^{103}Pd (X-ray) ^{177}Lu (β^-) ^{186}Re (β^-) ^{211}At (α) ^{225}Ac (α)

A. Dahan, *et al.*, Center of Targeted Radiopharmaceuticals – CTR, SNRC and HADASA proposal 2011

Basic Physics

Nuclear Physics status in Israel

- Until a few years ago, there was a decrease of the number of nuclear physicists and students in Israel
- Senior researchers in Israeli academia formulated improvement recommendations, which include the construction of SARAF as a world-class domestic scientific infrastructure that will attract researchers and students
- In recent years we observe a trend reversal, which is attributed also to the expectations for the construction of SARAF

What should come first
the chicken or the egg?

SARAF Scientific Research Potential (1/2)

1. Search for physics beyond the Standard Model
   - Exploration of the ‘High Precision Frontier’, necessary in order to direct and focus the ‘High Energy Frontier’
2. Nuclear Astrophysics
   - Investigation of Stellar and Big-Bang Nucleosynthesis
3. Exploration of exotic nuclei
   - Studies of properties of nuclei away from the valley of stability, better understanding nuclear models that were developed for stable nuclei
4. High-energy neutron induced cross sections
   - Systematic studies of these processes

I. Mardor and D. Berkovits, Nuclear Physics News 25(2015)16-22

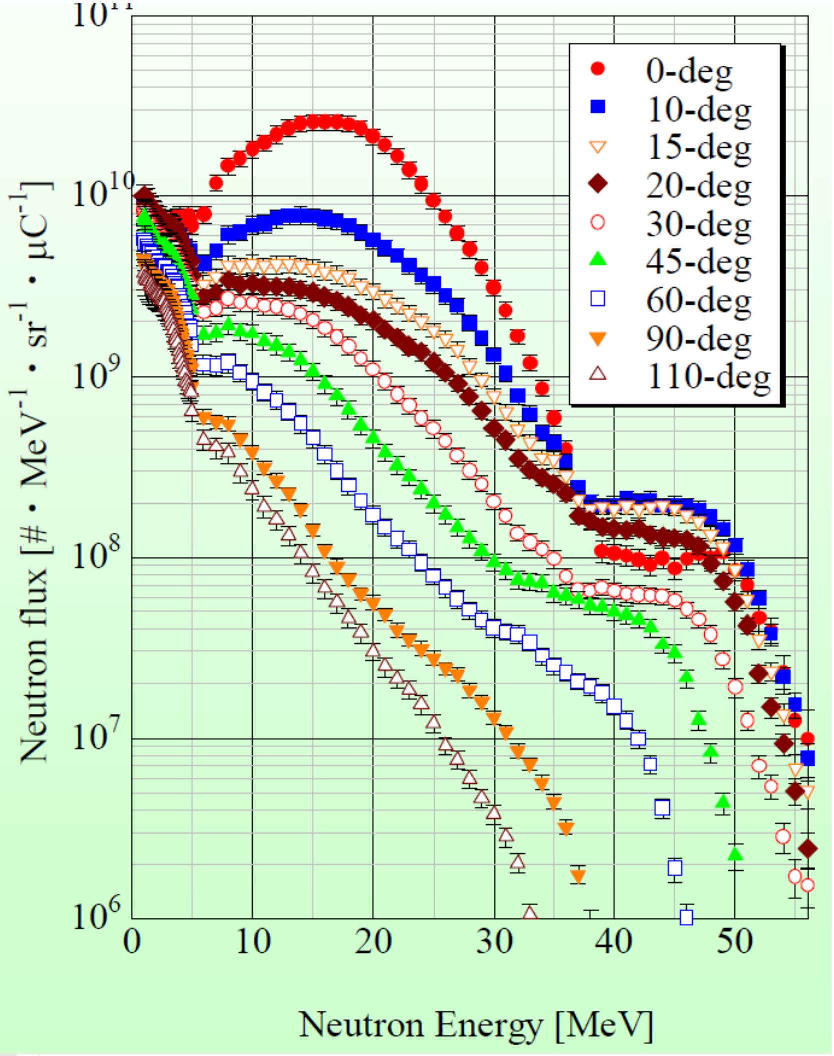
SARAF Scientific Research Potential (2/2)

5. Neutron based material research
   - Necessary for Accelerator Driven Systems (ADS) for nuclear waste transmutation, Generation IV fission reactors and fusion reactors
6. Neutron based therapy
   - Accelerator based Boron Neutron Capture Therapy (BNCT), more efficient and practical than reactor based BNCT
7. Development of new radiopharmaceuticals
   - R&D of new radiophmaceutical products, reachable only via irradiation by high power proton, deuteron and neutron beams
8. Accelerator based neutron imaging
   - R&D of thermal neutron imaging with medium energy deuteron accelerators, and fast neutron imaging for good contrast over broad densities and atomic numbers (e.g. coolant flow around fuel rods)

Fast neutron

Fast neutrons in Phase-II

40 MeV deuterons on lithium

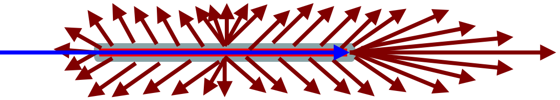


M. Hagiwara *et al. Fus. Sci. Tech.*, **48** (2005)

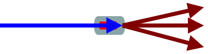
Spallation vs. stripping neutron spectra

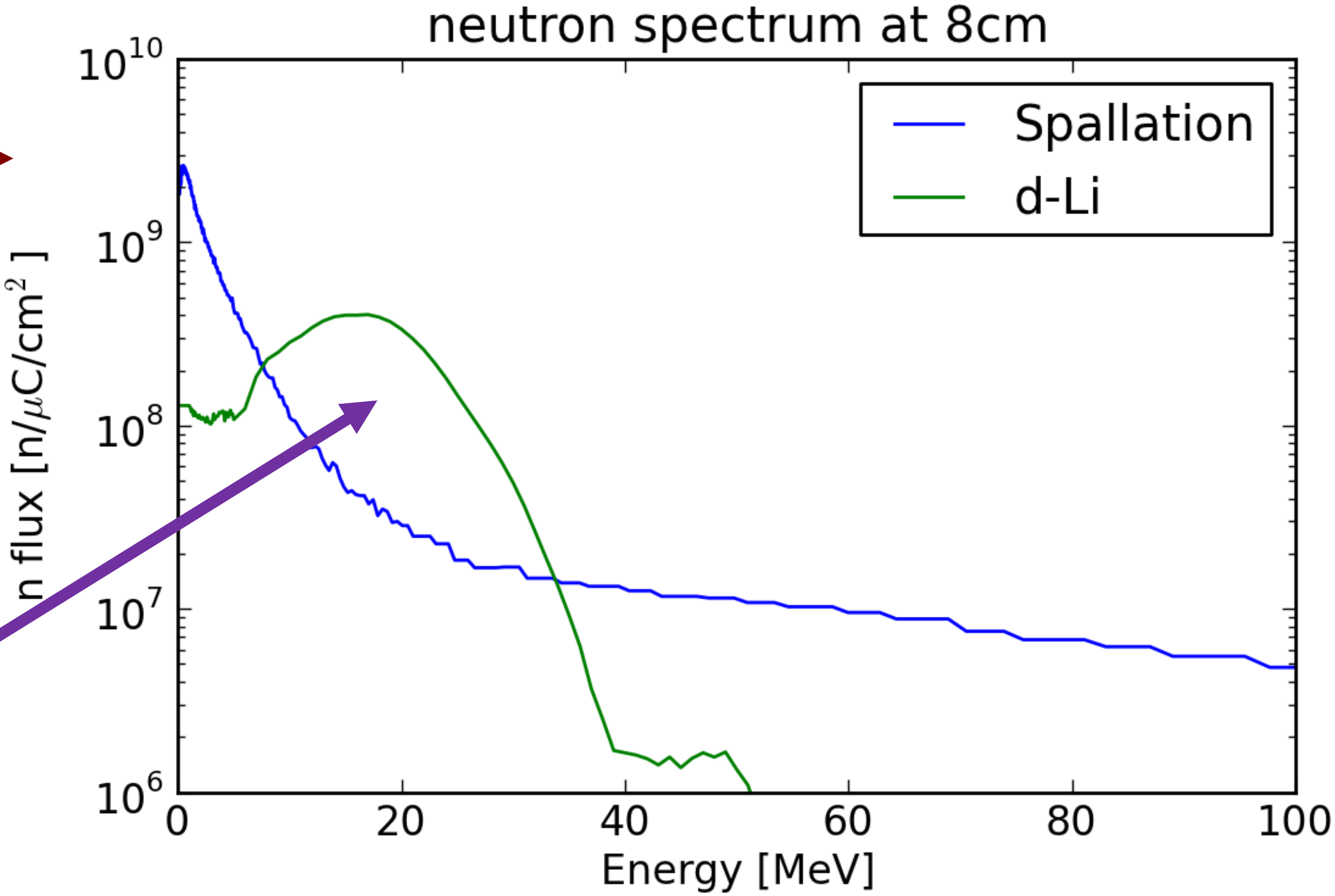
40 MeV d-Li vs. 1400 MeV p-W, 0 deg forward spectra, 8 cm downstream the primary target

Spallation



Direct+stripping





Area optimal for the (n,α) (n,p) (n,2n) (n,f)

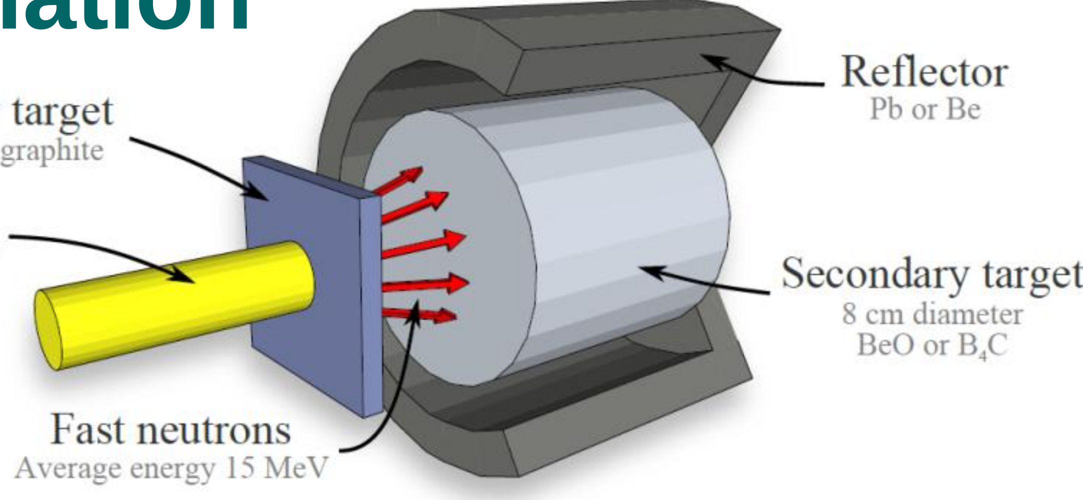
T. Hirsh PhD. WIS thesis 2012
D. Berkovits *et al.* LINAC 2012
I. Mardor *et al.*, NuPecc 2015

This fast neutron spectrum is ideal for

1. Radioisotopes generation in (n,p) (n,α) (n,2n) reactions for:
    1. β decay test of the standard model
    2. Nuclear astrophysics cross section measurements
    3. Neutrino source for neutrino oscillation study
    4. Material studies using β-NMR
2. Induced fission of ^{238}U [SPIRAL2]
3. Simulation of nuclear fusion reactor neutrons spectrum [IFMIF]

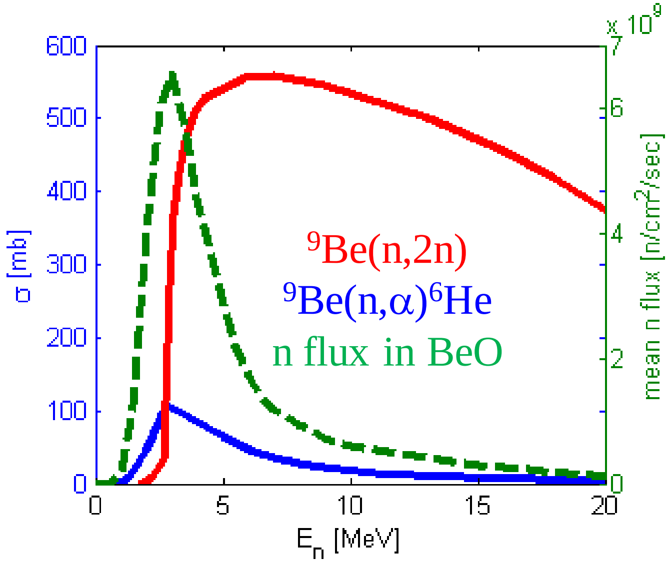
Production of light RIB
Two-stage irradiation

M. Hass (WIS)



Yield calculated for a 40 MeV, 1 mA deuteron beam and for a ~ 800 cm^3 cylindrical porous secondary target

Material	Reaction	half life $[msec]$	Yield $\left[\frac{10^{12}\ atoms}{mA\ sec}\right]$
BeO	$^{9}\mathrm{Be}(n,\alpha)^{\mathbf{6}}\mathbf{He}$	807	2.53
	$^{9}\mathrm{Be}(n,p)^{\mathbf{9}}\mathbf{Li}$	178	0.033
	$^{16}\mathrm{O}(n,p)^{\mathbf{16}}\mathbf{N}$	7130	0.9
B_4C	$^{11}\mathrm{B}(n,\alpha)^{\mathbf{8}}\mathbf{Li}$	838	0.87
	$^{11}\mathrm{B}(n,p)^{\mathbf{11}}\mathbf{Be}$	13810	0.14
	$^{12}\mathrm{C}(n,p)^{\mathbf{12}}\mathbf{B}$	20	0.24
	$^{13}\mathrm{C}(n,p)^{\mathbf{13}}\mathbf{B}$	17	$6.63\cdot 10^{-4}$

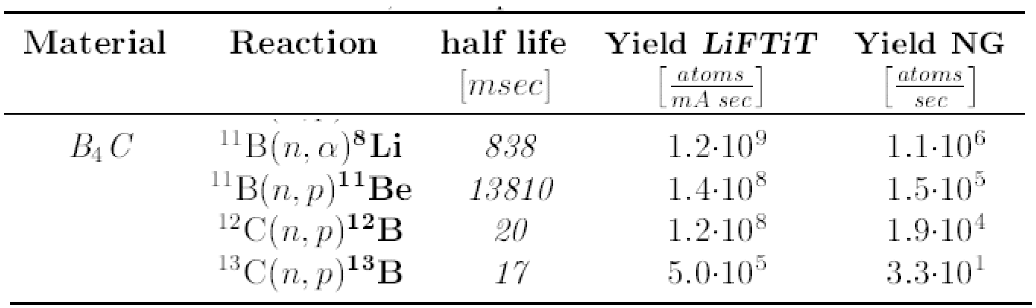


M. Hass *et al.*, J. Phys. G. 35 (2008), T. Hirsh *et al.*, J. Phys. NPA 337 (2012), Stora et al., EPL, 98, 32001 (2012)

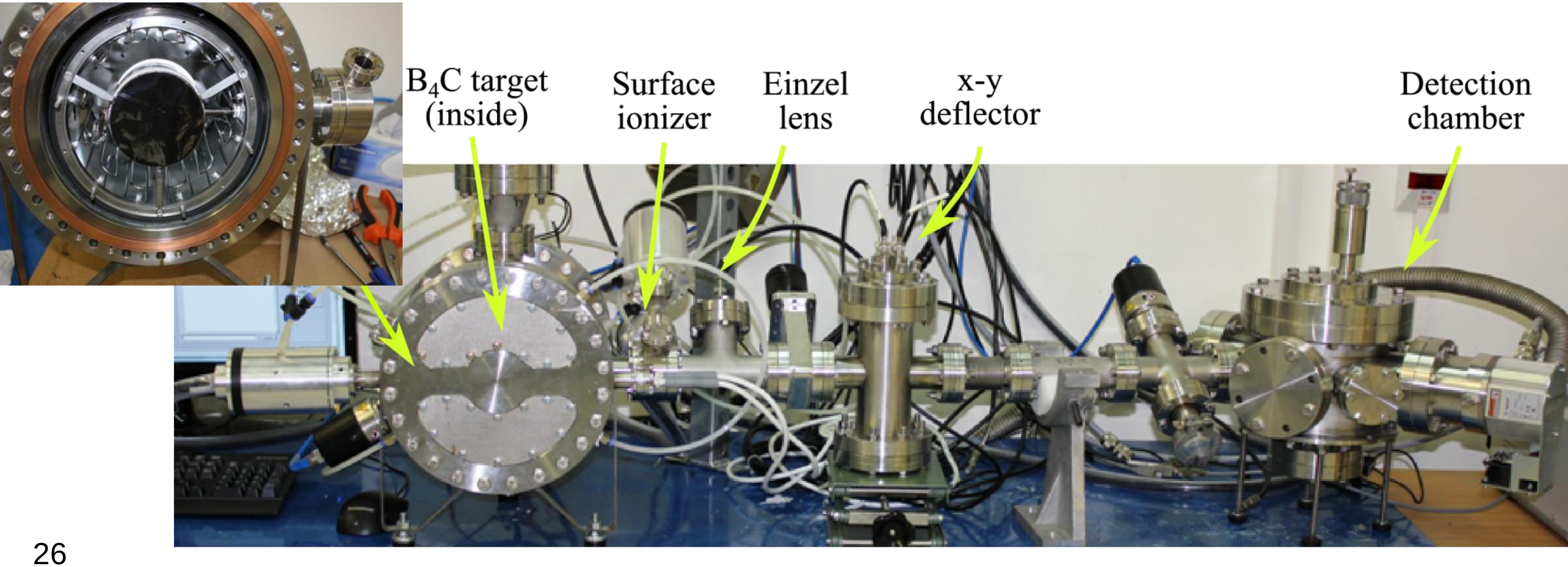
^{8}Li RIB test bench at SARAF

- Off-line apparatus that would be later be transferred to a beam line at SARAF, or as a preliminary test, a *d-t* neutron generator (NG)
- Calculated yields of 10^9 ^{8}Li/sec/mA already at phase 1

Hirsh *et al.*, J. Phys, **337** (2012)



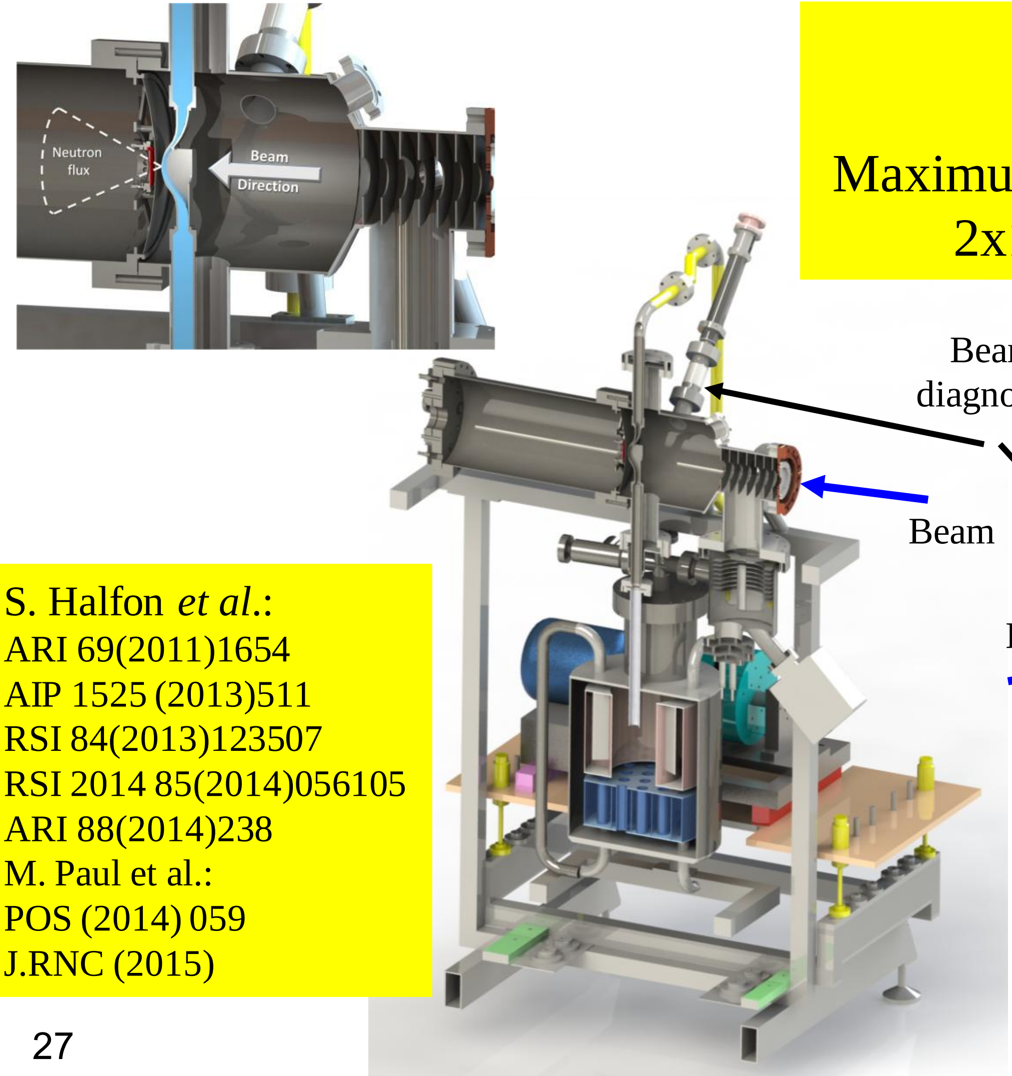
Material	Reaction	half life $[msec]$	Yield $\boldsymbol{LiFTiT}$ $\left[\frac{atoms}{mA\ sec}\right]$	Yield NG $\left[\frac{atoms}{sec}\right]$
B_4C	$^{11}B(n,\alpha)^{\mathbf{8}}\mathbf{Li}$	*838*	$1.2\cdot10^{9}$	$1.1\cdot10^{6}$
	$^{11}B(n,p)^{\mathbf{11}}\mathbf{Be}$	*13810*	$1.4\cdot10^{8}$	$1.5\cdot10^{5}$
	$^{12}C(n,p)^{\mathbf{12}}\mathbf{B}$	*20*	$1.2\cdot10^{8}$	$1.9\cdot10^{4}$
	$^{13}C(n,p)^{\mathbf{13}}\mathbf{B}$	*17*	$5.0\cdot10^{5}$	$3.3\cdot10^{1}$



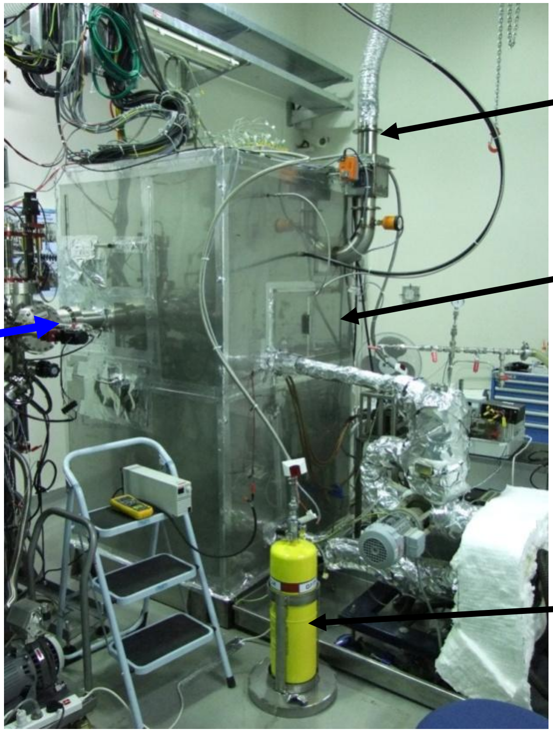
M. Paul (HUJI)

A liquid lithium jet target - LiLiT tested at SARAF beam corridor - 2013

Measured:
Li jet velocity 7 m/s
Maximum power density 2.0 MW/cm^3 @ 4 m/s
2x10^{10} n/s/mA @ 1.92 MeV protons



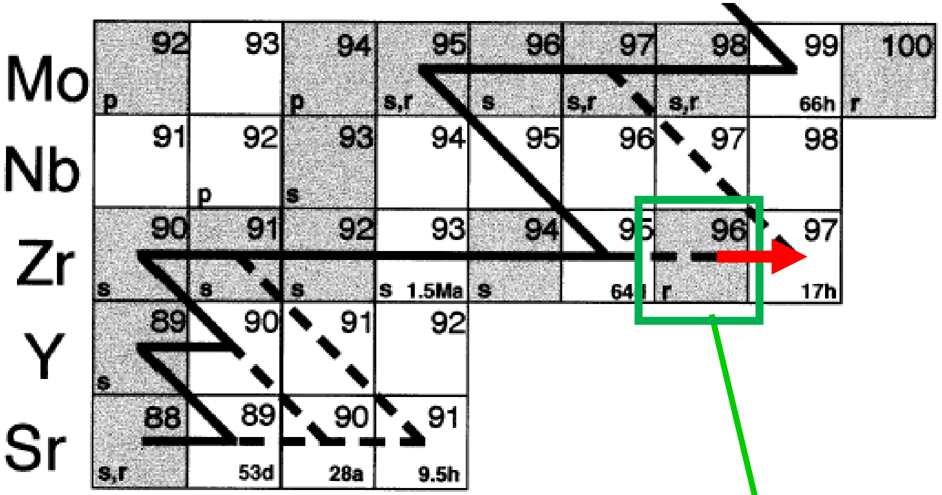
S. Halfon *et al.*:
ARI 69(2011)1654
AIP 1525 (2013)511
RSI 84(2013)123507
RSI 2014 85(2014)056105
ARI 88(2014)238
M. Paul et al.:
POS (2014) 059
J.RNC (2015)



LiLiT neutrons experiments

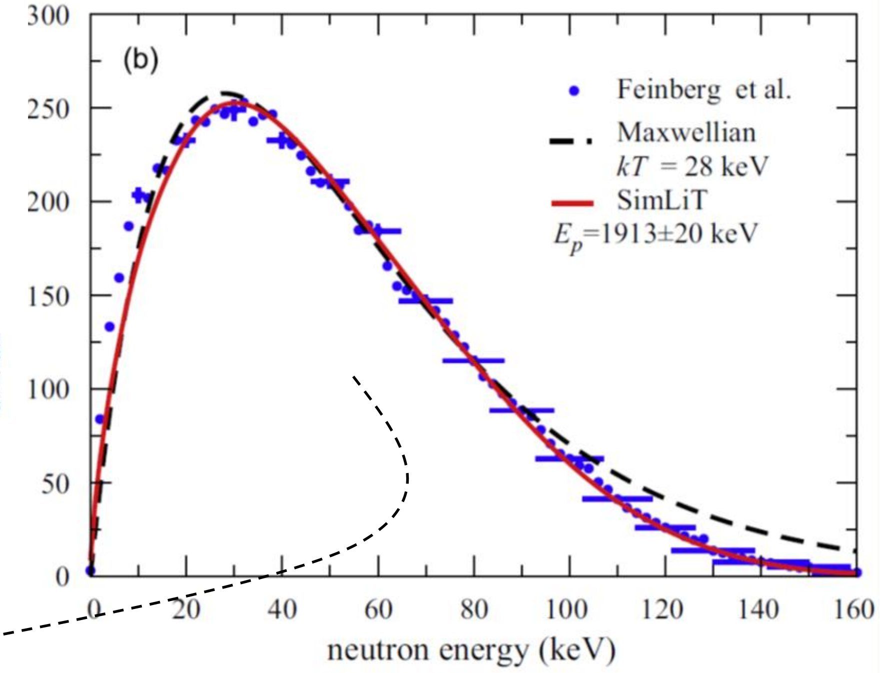
- Stellar nucleosynthesis neutrons induced reactions
- Short lived isotopes beta decay in tarp search of physics beyond standard model

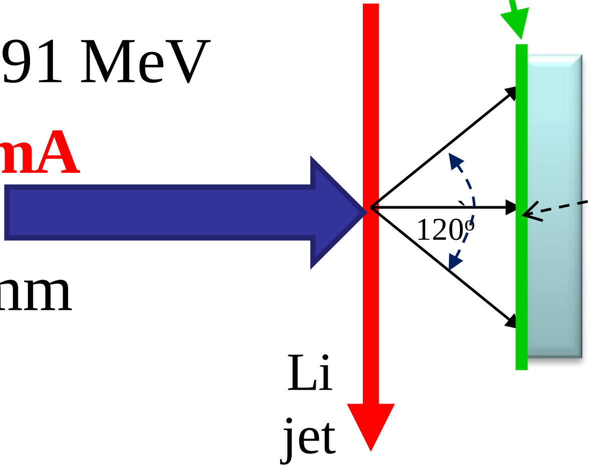
Astrophysics Nucleo-synthesis



W. Ratynski and F. Kaeppeler, PR C (1988), Karlsruhe, I~50 μA

simulation of a 300 MK stellar flux





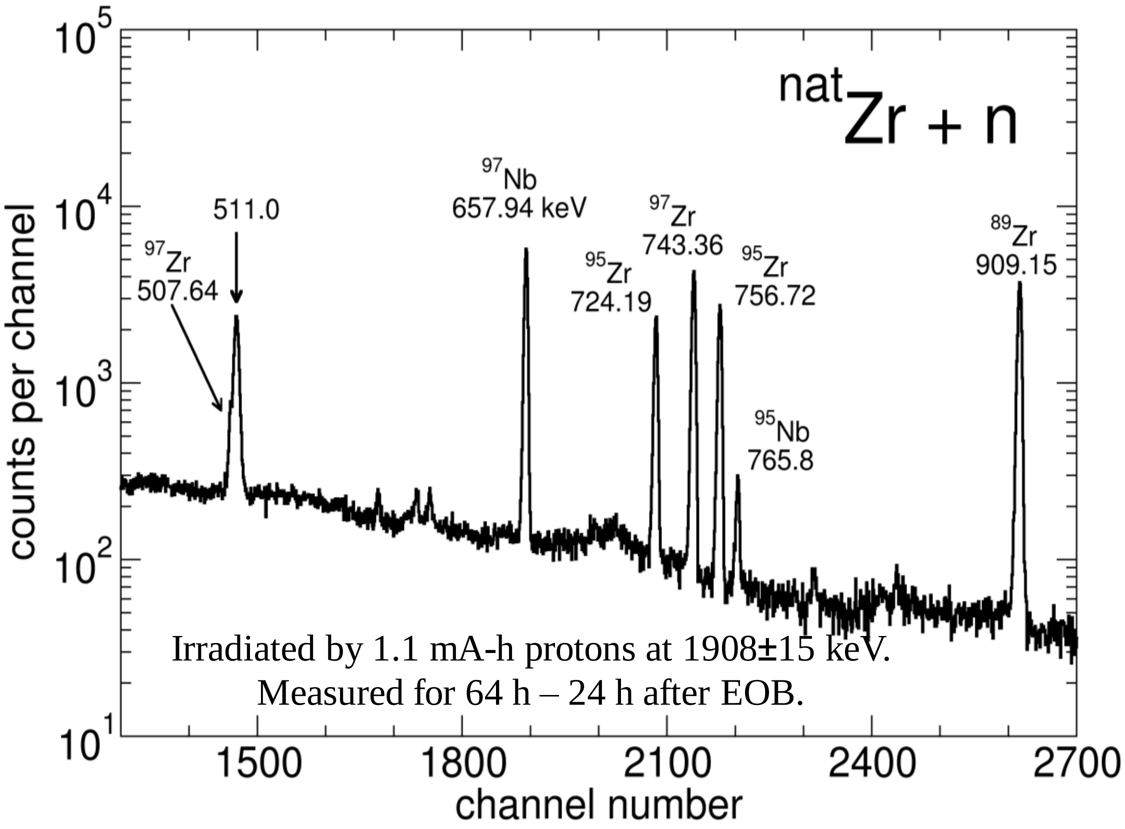
p @ 1.91 MeV

I ~ 2 mA

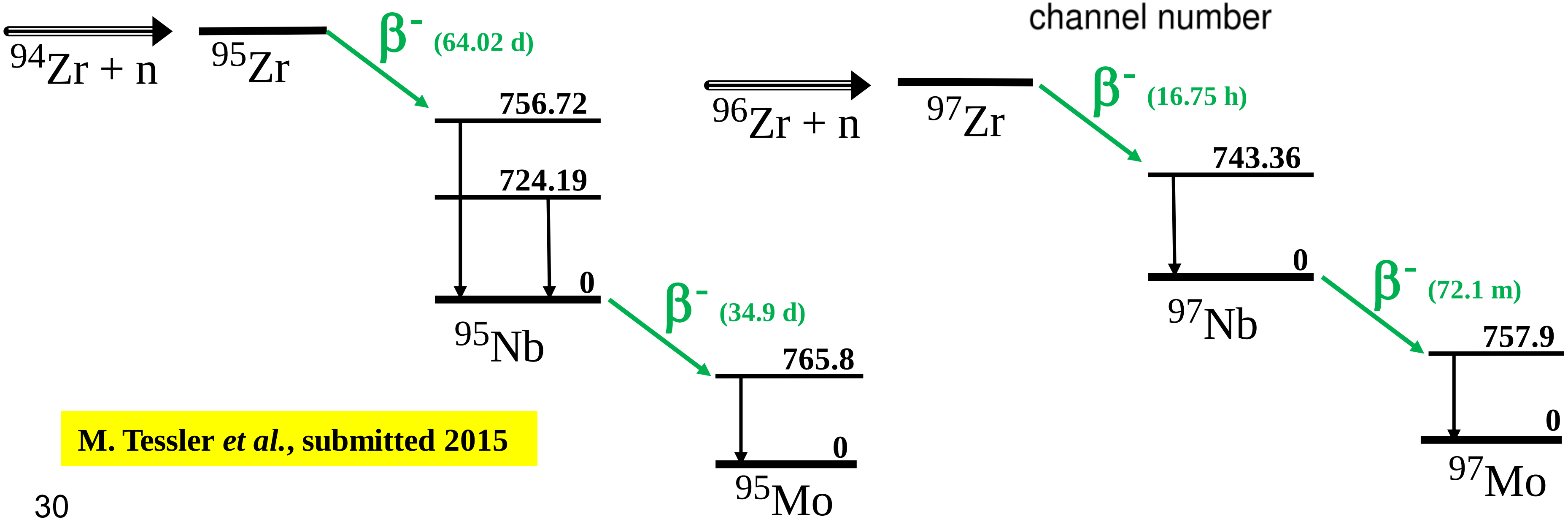
σ = 2 mm

G. Feinberg *et. al.*, Nucl. Phys. A 2009, Nucl. Phys. A 2012, Phys. Rev. C 2012
M. Friedman *et. al.*, NIM A 2013
M. Paul *et al.*, NIC *PoS* 2014
M. Tessler *et al.*, submitted 2015

^{nat}Zr+n measured γ



Irradiated by 1.1 mA-h protons at 1908±15 keV.
Measured for 64 h – 24 h after EOB.



M. Tessler *et al.*, submitted 2015

^{94,96}Zr(n,γ)^{95,97} cross section measurements

M. Paul (HUJI) et al. irradiation @ SARAF+LiLiT

XIII Nuclei in the Cosmos 7-11 July, 2014 Debrecen, Hungary, Proceedings of Science, http://pos.sissa.it, PoS (NIC XIII)059

M. Tessler et al., submitted 2015.

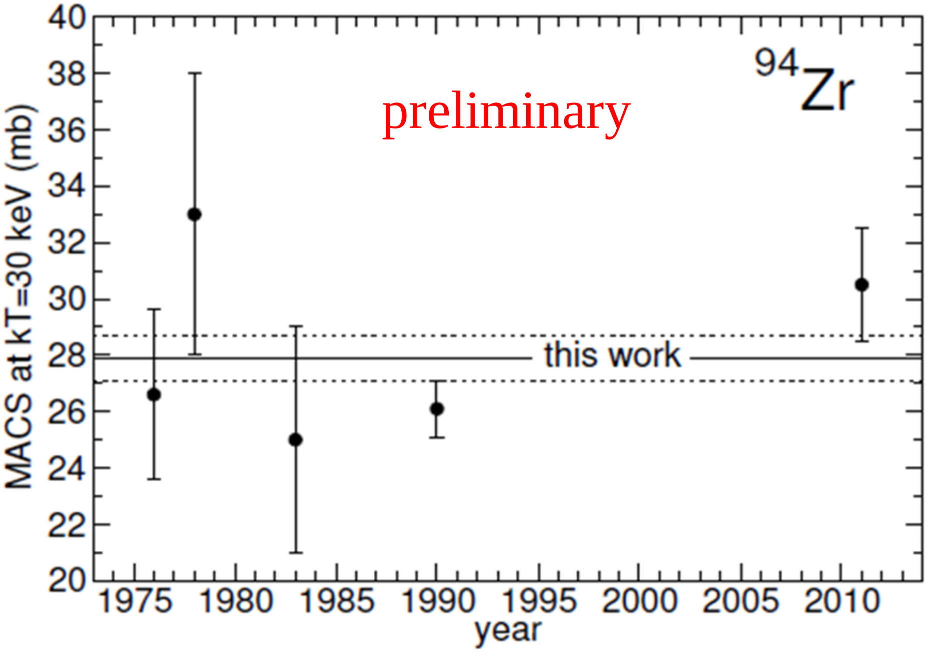


FIG. 10. Comparison of this work to previously measured MACS at $kT = 30$ keV for ^{94}Zr.

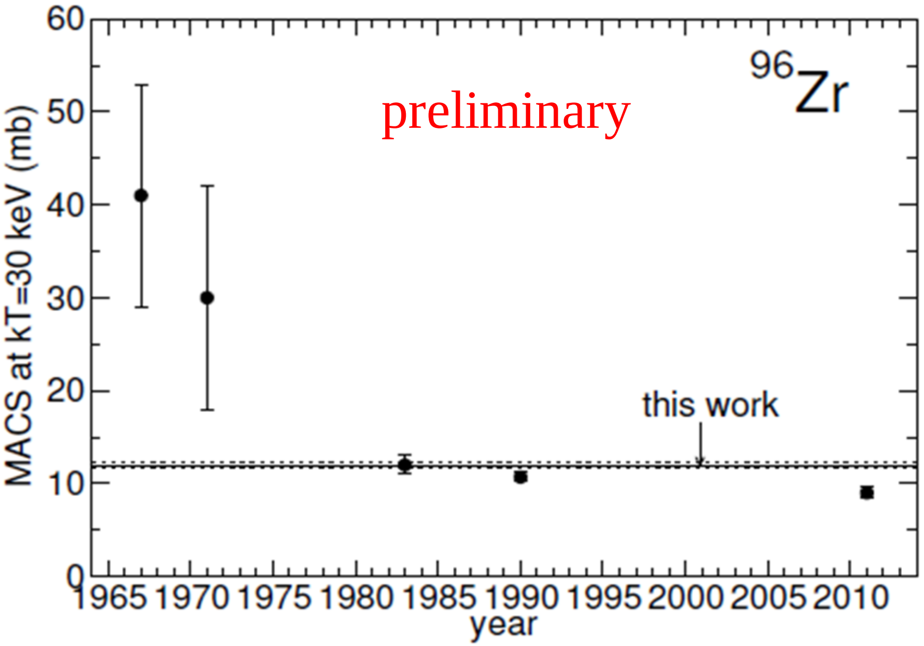
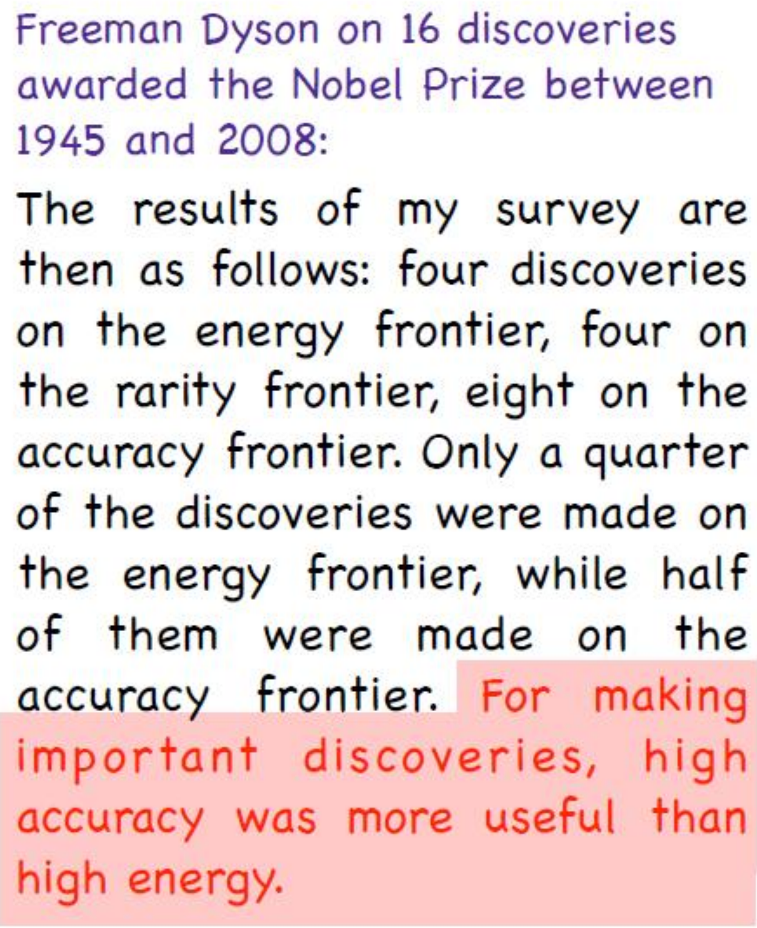


FIG. 11. Comparison of this work to previously measured MACS at $kT = 30$ keV for ^{96}Zr.

Measurements at SARAF with LiLiT

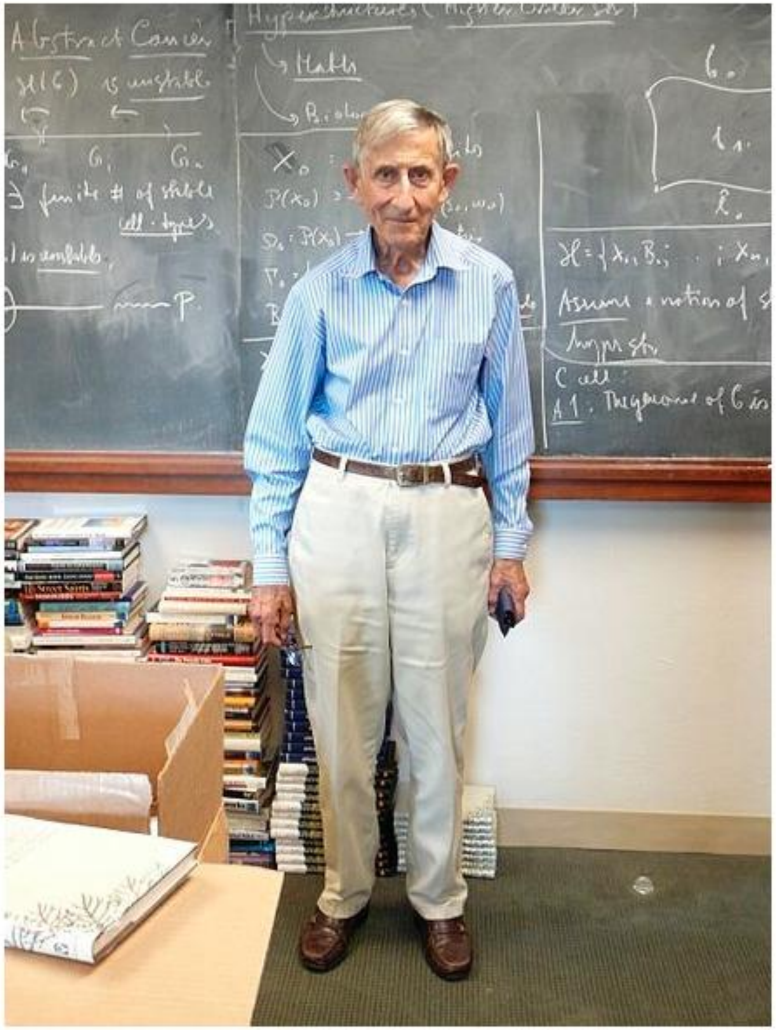
Target (reaction)	Product radioisotope measurement technique	2014-2015
^{nat}Zr(n,γ)	γ spec	✓
^{nat}Ce(n,γ)	γ spec	✓
^{23}Na, ^{35,37}Cl (n,γ)	γ spec + AMS	✓
^{92}Zr(n,γ)	AMS	
^{nat}Kr(n,γ)	γ spec + AMS + Atom trap	✓
^{36}Ar, ^{38}Ar, ^{40}Ar (n,γ)	AMS + γ spec	
^{209}Bi(n,γ)	α spec + β spec + γ spec	√
^{7}Be(n,α)	CR-39	
^{nat}Zr(γ,n)	γ spec	✓
^{nat}Co(γ,n)	γ spec	✓
^{nat}Mo(γ,n)	γ spec	✓
^{nat}Cu(γ,n)	γ spec	✓

New physics beyond the Standard Model

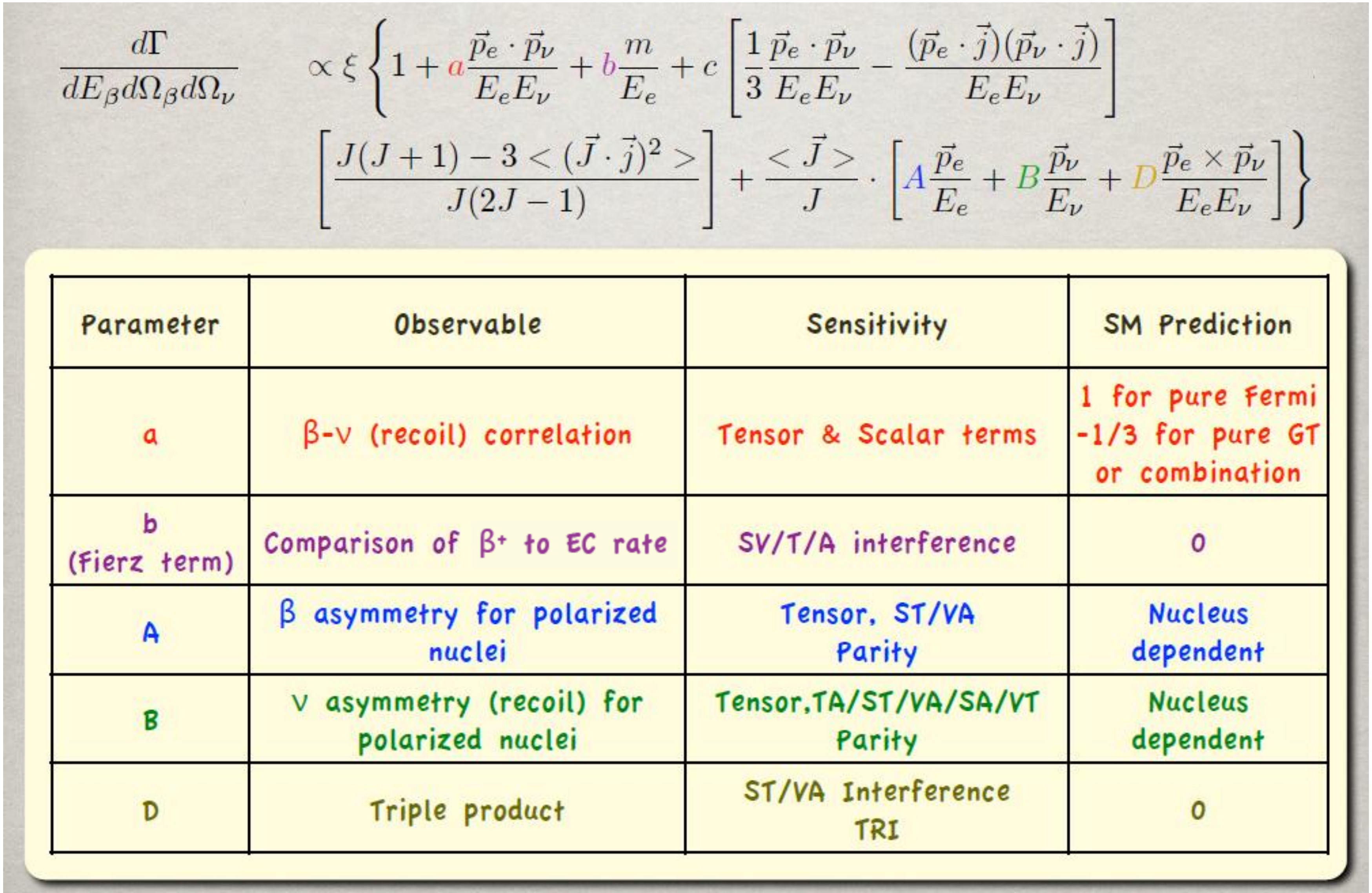


Freeman Dyson on 16 discoveries awarded the Nobel Prize between 1945 and 2008:

The results of my survey are then as follows: four discoveries on the energy frontier, four on the rarity frontier, eight on the accuracy frontier. Only a quarter of the discoveries were made on the energy frontier, while half of them were made on the accuracy frontier. For making important discoveries, high accuracy was more useful than high energy.



β-decay possible observable in nuclei



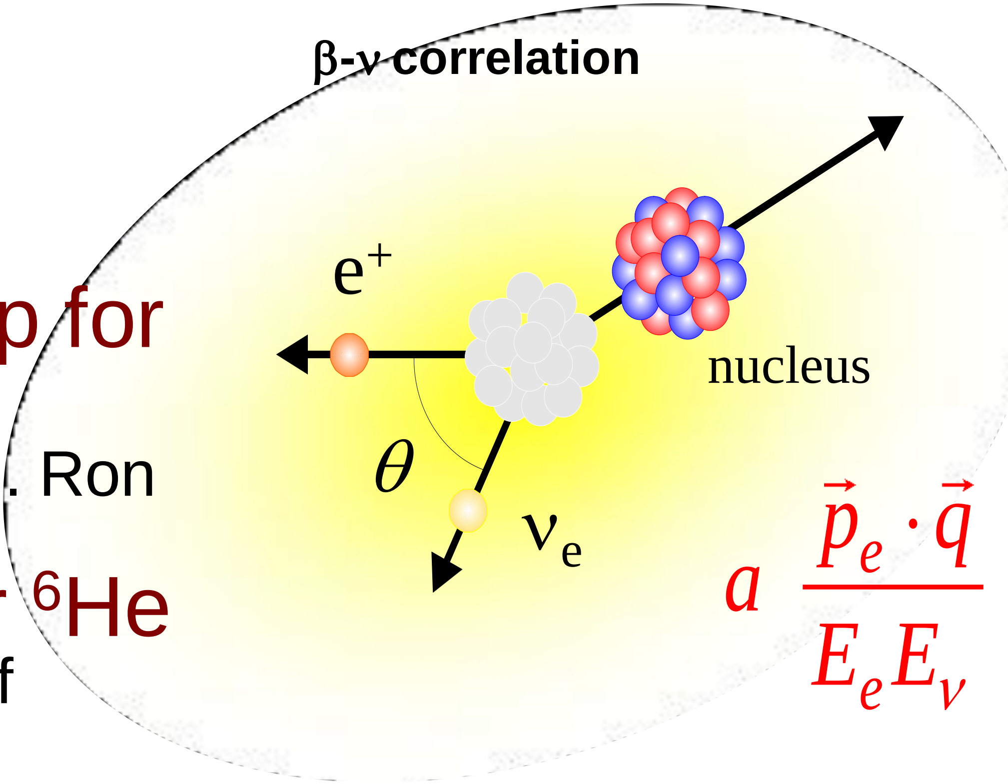
$$\frac{d\Gamma}{dE_\beta d\Omega_\beta d\Omega_\nu} \propto \xi \left\{1 + a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu} + b\frac{m}{E_e} + c\left[\frac{1}{3}\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu} - \frac{(\vec{p}_e\cdot\vec{j})(\vec{p}_\nu\cdot\vec{j})}{E_eE_\nu}\right]\left[\frac{J(J+1)-3<(\vec{J}\cdot\vec{j})^2>}{J(2J-1)}\right] + \frac{<\vec{J}>}{J}\cdot\left[A\frac{\vec{p}_e}{E_e}+B\frac{\vec{p}_\nu}{E_\nu}+D\frac{\vec{p}_e\times\vec{p}_\nu}{E_eE_\nu}\right]\right\}$$

Parameter	Observable	Sensitivity	SM Prediction
a	β-ν (recoil) correlation	Tensor & Scalar terms	1 for pure Fermi -1/3 for pure GT or combination
b (Fierz term)	Comparison of β^+ to EC rate	SV/T/A interference	0
A	β asymmetry for polarized nuclei	Tensor, ST/VA Parity	Nucleus dependent
B	ν asymmetry (recoil) for polarized nuclei	Tensor,TA/ST/VA/SA/VT Parity	Nucleus dependent
D	Triple product	ST/VA Interference TRI	0

Precise β-decay in ion traps

1. Magento Optical Trap for ^{18,19,23}Ne
   at the Hebrew University, G. Ron
2. Electrostatic Trap for ^{6}He
   at the Weizmann Institute of Science, M. Hass

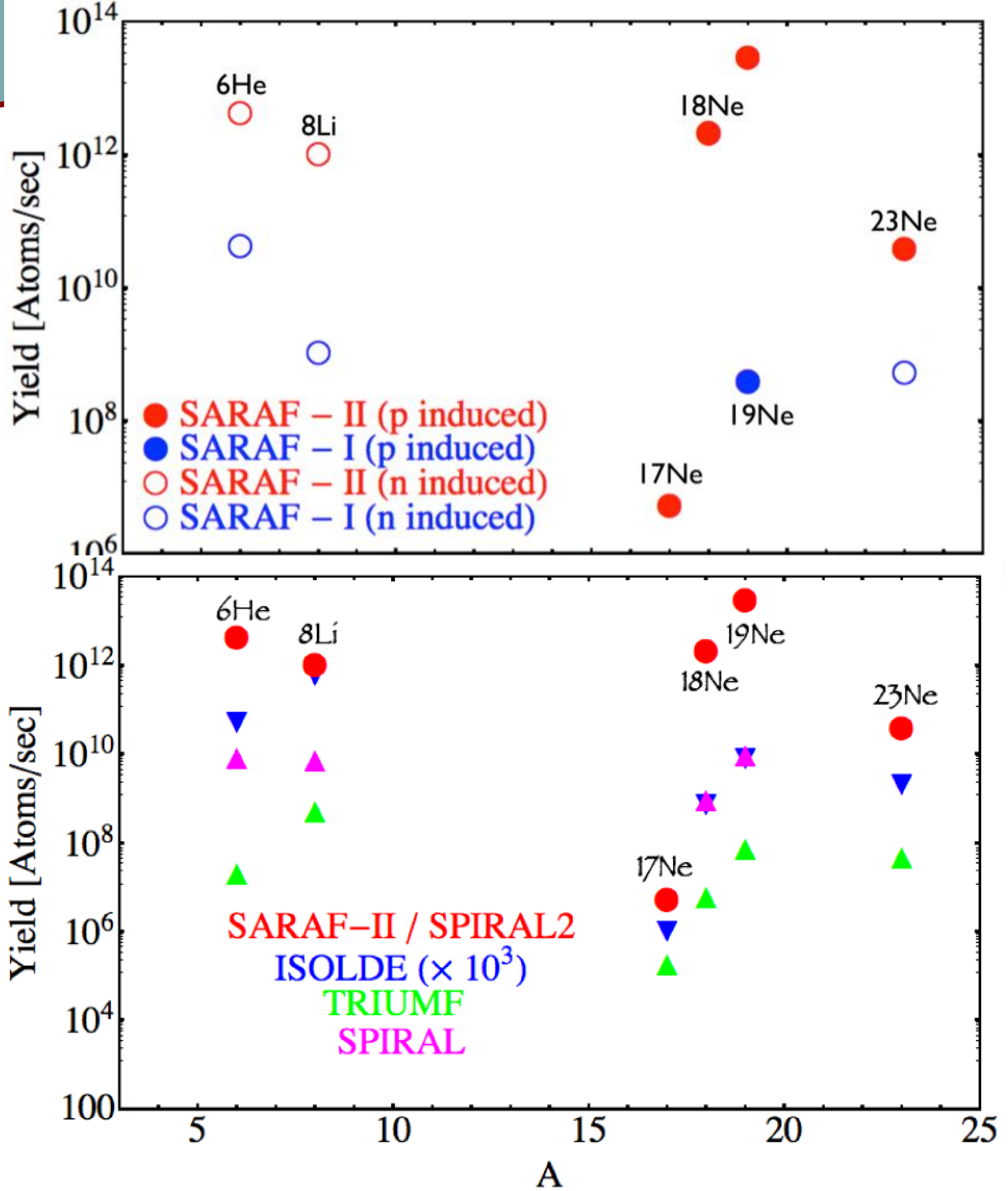
β-ν correlation



$$a\,\frac{\vec{p}_e\cdot\vec{q}}{E_e E_\nu}$$

Both apparatuses have been built and tested with stable isotopes

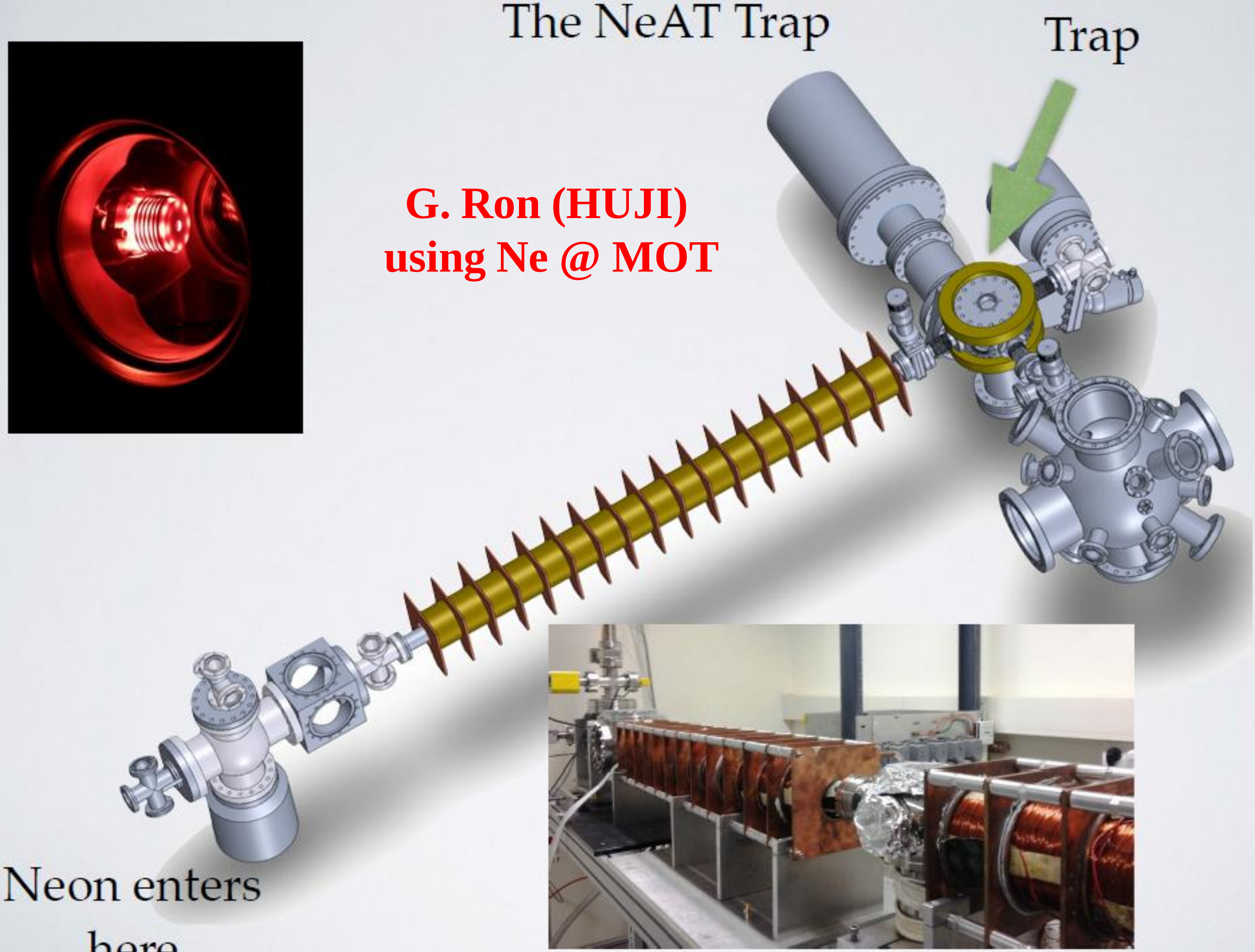
SARAF expected yields



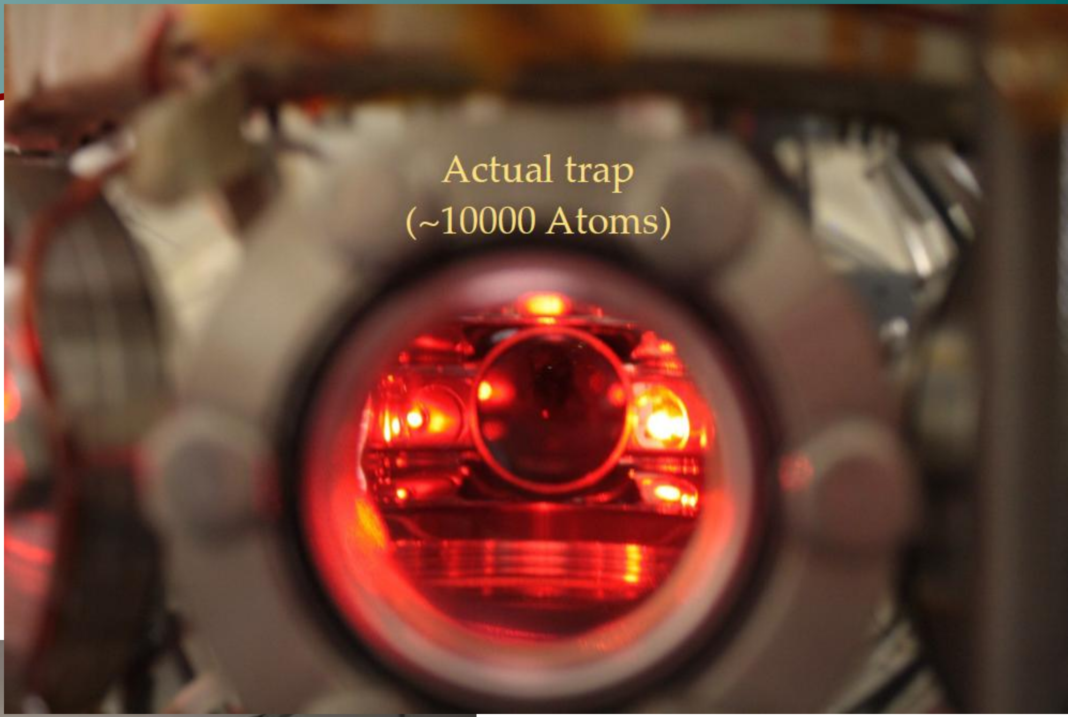
G. Ron at the Israeli joint nuclear seminar
June 22nd 2015

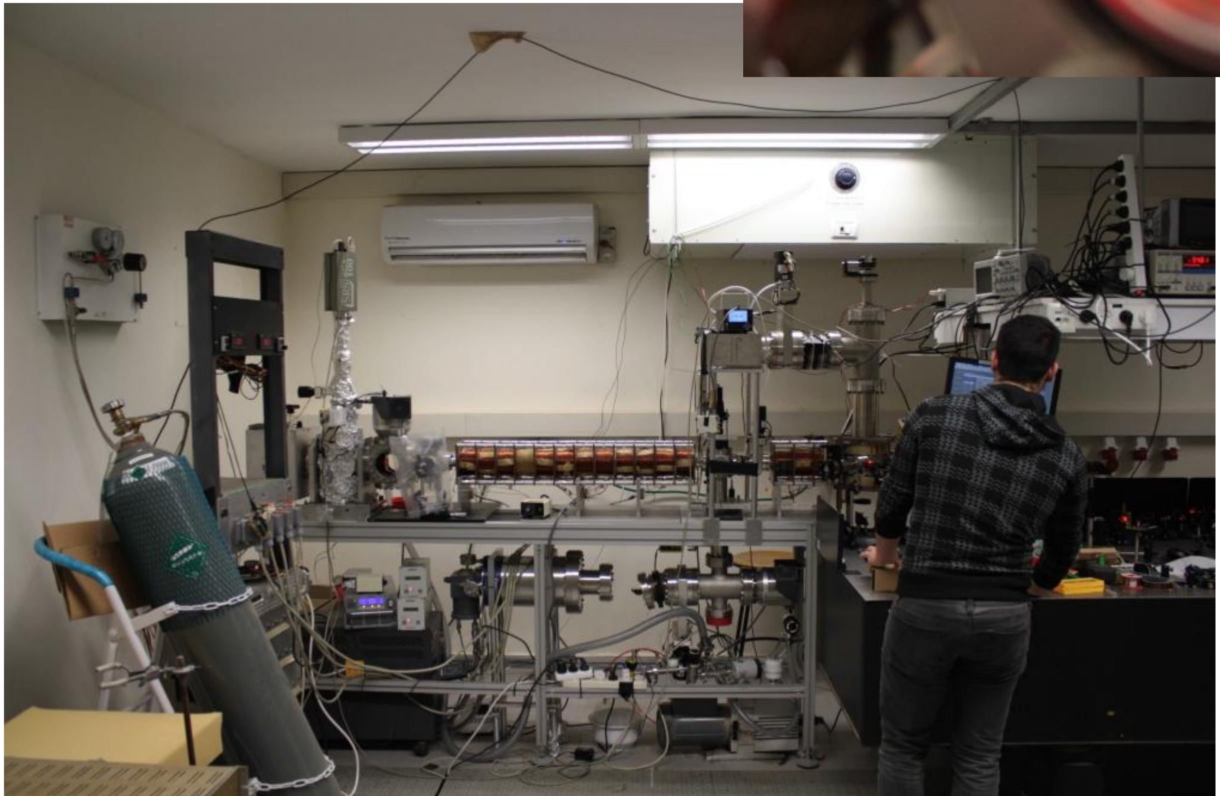
The NeAT Trap

G. Ron (HUJI)
using Ne @ MOT



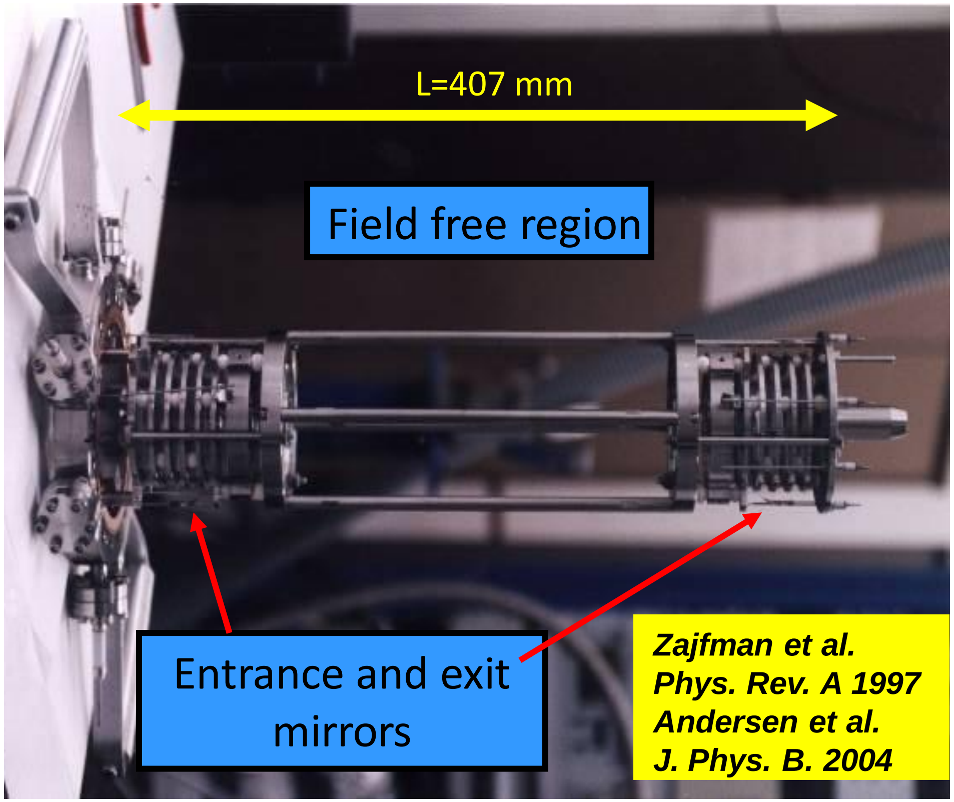
Ne MOT at the Hebrew University



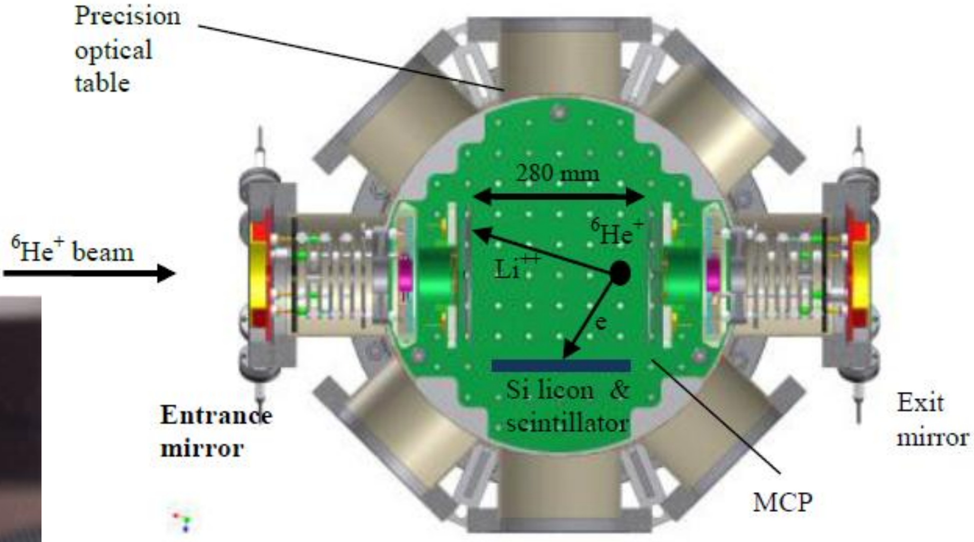


^{6}He β-decay in electrostatic trap @ WIS

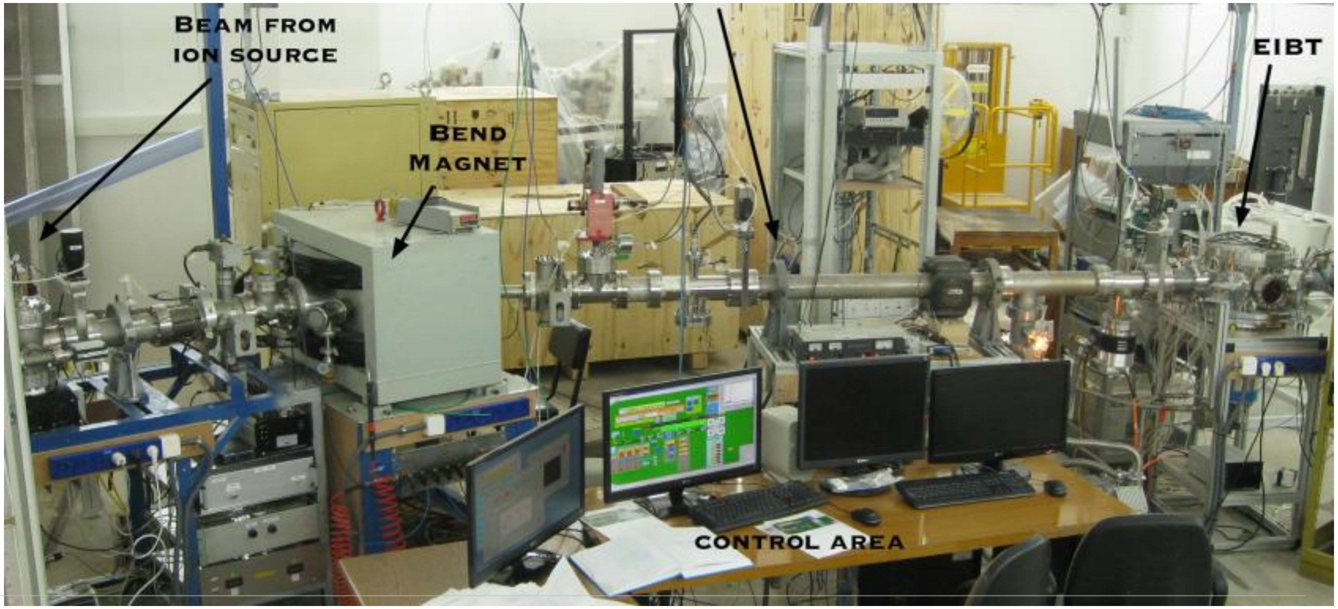
O. Aviv *et al.* J. of Physics 337 (2012)

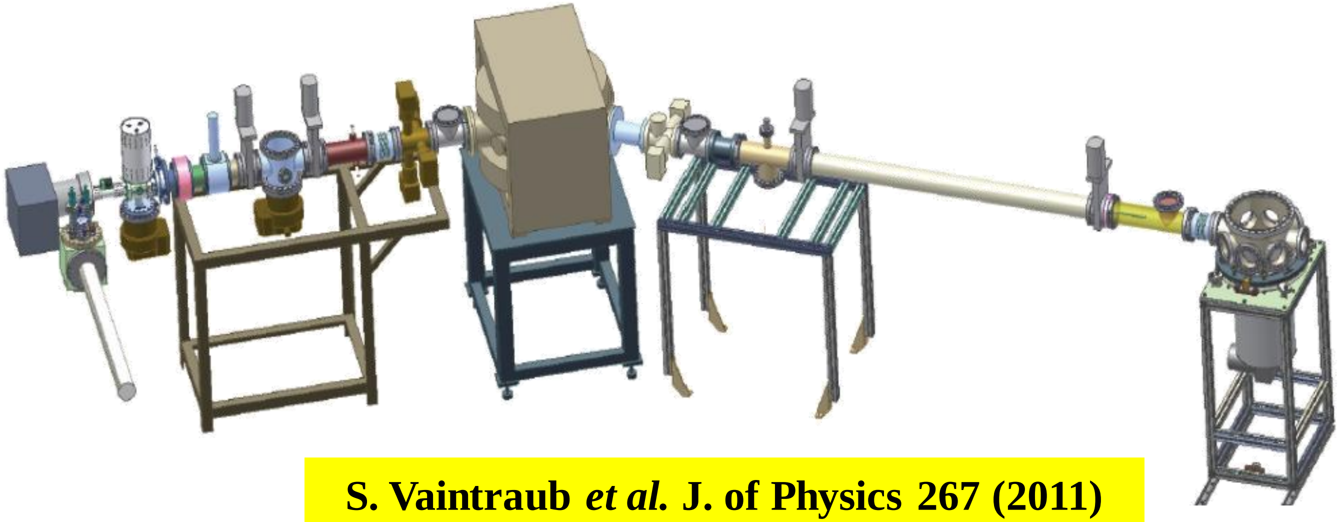


Zajfman et al. Phys. Rev. A 1997
Andersen et al. J. Phys. B. 2004



Electrostatic Ion Beam Trap

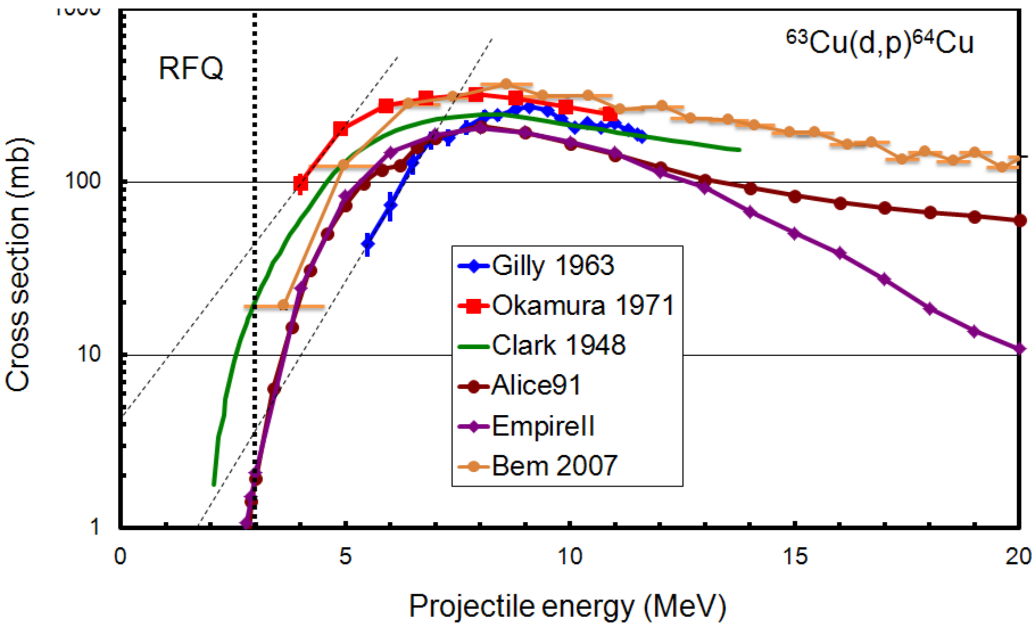




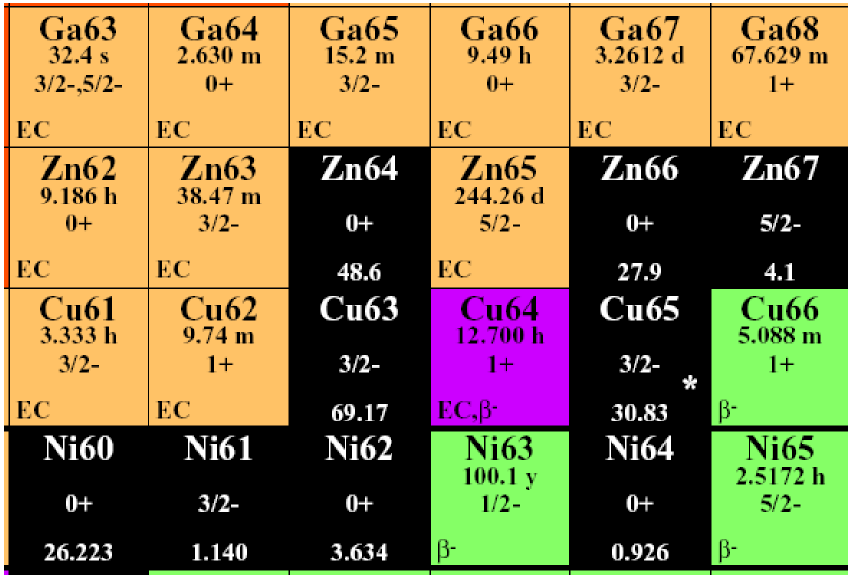
S. Vaintraub *et al.* J. of Physics 267 (2011)

Phase-I low energy deuterons cross section measurements

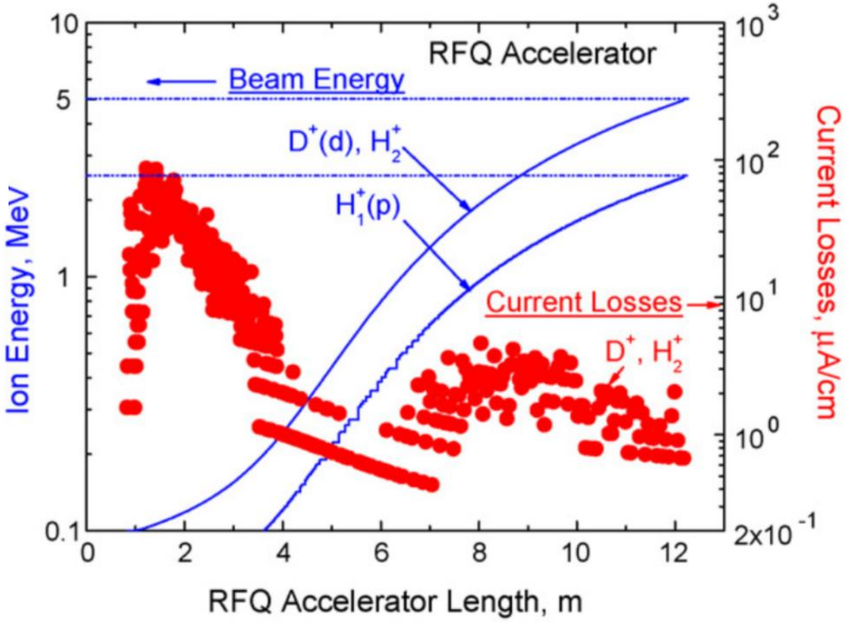
RFQ Cu activation



Status at 2007:
Unknown residual activation of 3-5 MeV deuteron beam on copper target due to unknown cross section



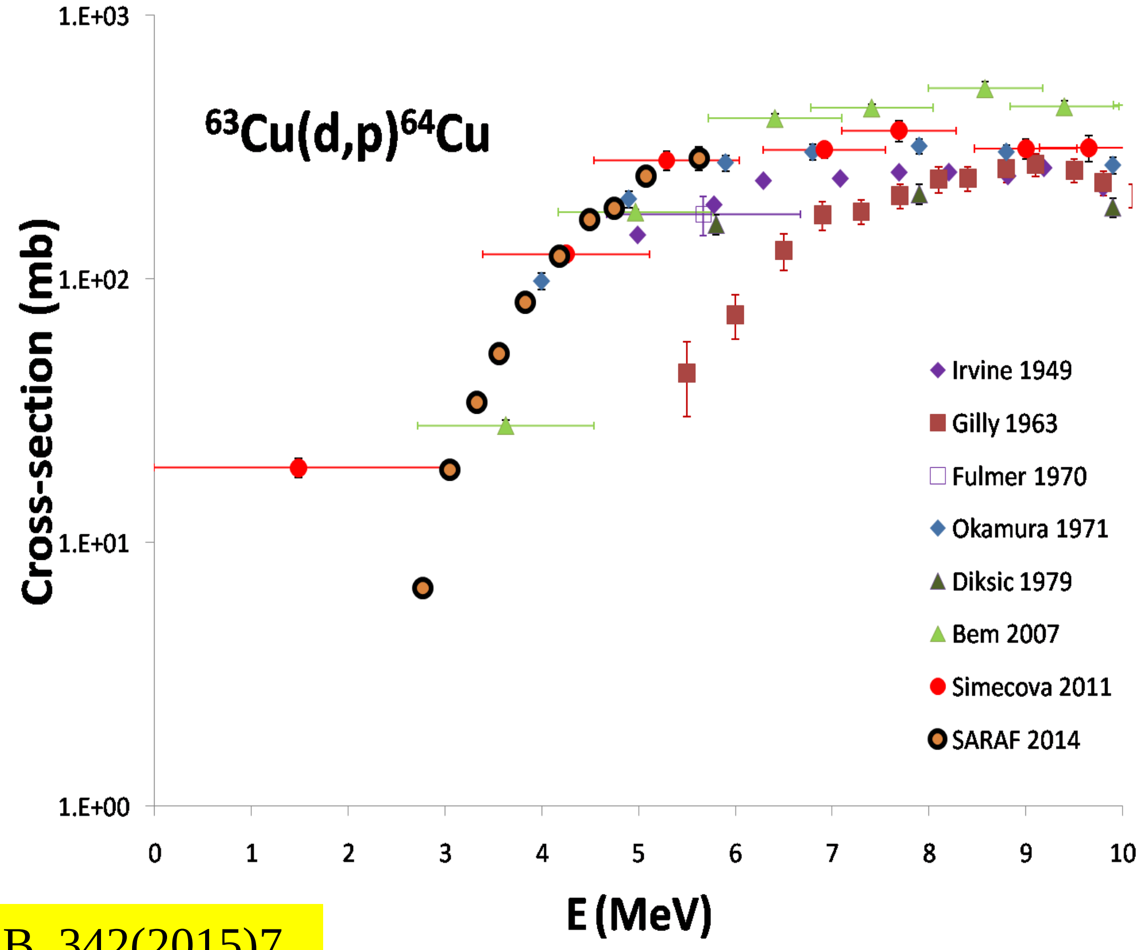
Ga63 32.4 s 3/2-,5/2- EC	Ga64 2.630 m 0+ EC	Ga65 15.2 m 3/2- EC	Ga66 9.49 h 0+ EC	Ga67 3.2612 d 3/2- EC	Ga68 67.629 m 1+ EC
Zn62 9.186 h 0+ EC	Zn63 38.47 m 3/2- EC	Zn64 0+ 48.6	Zn65 244.26 d 5/2- EC	Zn66 0+ 27.9	Zn67 5/2- 4.1
Cu61 3.333 h 3/2- EC	Cu62 9.74 m 1+ EC	Cu63 3/2- 69.17	Cu64 12.700 h 1+ EC,β-	Cu65 3/2- 30.83 *	Cu66 5.088 m 1+ β-
Ni60 0+ 26.223	Ni61 3/2- 1.140	Ni62 0+ 3.634	Ni63 100.1 y 1/2- β-	Ni64 0+ 0.926	Ni65 2.5172 h 5/2- β-



S.P. Simakov et al., Fus. Eng. and Des. 83 (2008) 1543-1547

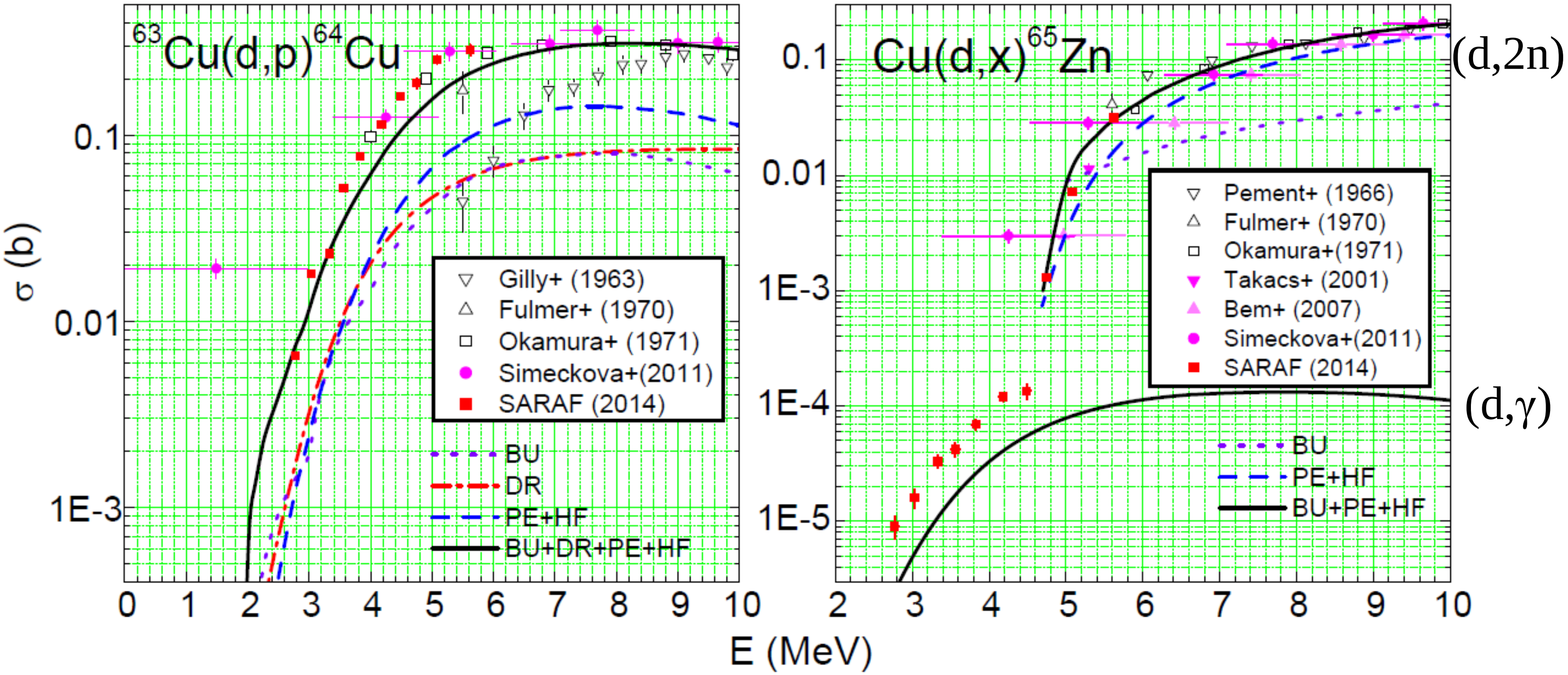
^{63}Cu(d,p)^{64}Cu accurate measurement @SARAF Phase-I

Measurements at linacs are more accurate due to the linac fine variable energy



L. Weissman et al. NIM B, 342(2015)7

Deuteron induced reaction calculation



Simeckova analysis (thick solid) using the DR (dash-dotted) for the (d; p) reaction and deuteron breakup (thin solid) for the (d; xn) and (d; 2p) reactions, and PE + HF components (dotted).

Direct reaction (DR)
inelastic breakup or breakup fusion (BF)
pre-equilibrium (PE)
compound-nucleus Hauser-Feshbach (HF)

M. Avrigeanu 2015, Phys. Rev. C 84 (2011) 014605 and Journal of the Korean Physical Society, 59 (2011) 1928-1931
L. Weissman et al. NIM B, 342(2015)7

Summary

- SARAF Phase-I accelerator proved the needed novel acceleration technologies
- High intensity targets were developed and demonstrated
- Industrial, medical and scientific applications were designed. Some basic physics apparatuses have been built and tested
- SARAF Phase-I is used for basic research
- Phase-II detailed design was recently started