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A **MedLey** with over ten years of (mostly) light-ion production measurements at The Svedberg Laboratory

Stephan Pomp
*Department of physics and astronomy
Uppsala University*



Outline

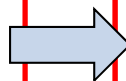
- Starting points
 - Fast neutron cancer therapy
 - Single event effects (and ADS)
- The 96 MeV campaign
 - The old TSL neutron beam
 - Description of Medley and the data analysis
 - Some results
- The 175 MeV campaign
 - The new neutron beam, spectrum measurements etc.
 - Preliminary results for Fe and Bi
- NFS next? Summary and outlook



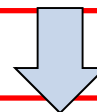
The starting point – cancer therapy

Why fast neutrons for cancer therapy:

- high **L**inear **E**nergy **T**ransfer
- high **R**elative **B**iological **E**ffect
- low **O**xxygen **E**nhancement **R**atio
- less pronounced cell cycle sensitivity



Requires good knowledge of delivered dose, i.e. better than 3.5 % (Mijnheer et al. 1987)

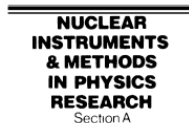


good ddx needed for all nuclei in the tissue



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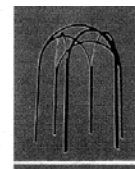
Nuclear Instruments and Methods in Physics Research A 452 (2000) 484–504



www.elsevier.nl/locate/nima



NUMBER 19 • FEBRUARY 2001



A facility for measurements of nuclear cross sections for fast neutron cancer therapy

S. Dangtip^a, A. Ataç^a, B. Bergenwall^a, J. Blomgren^a, K. Elmgren^a, C. Johansson^a,
J. Klug^a, N. Olsson^{a,*}, G. Alm Carlsson^b, J. Söderberg^b, O. Jonsson^c, L. Nilsson^c,
P.-U. Renberg^c, P. Nadel-Turonski^d, C. Le Brun^e, F.-R. Lecolley^e, J.-F. Lecolley^e,
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Received 29 March 2000; accepted 6 April 2000

Can you get cancer from flying?

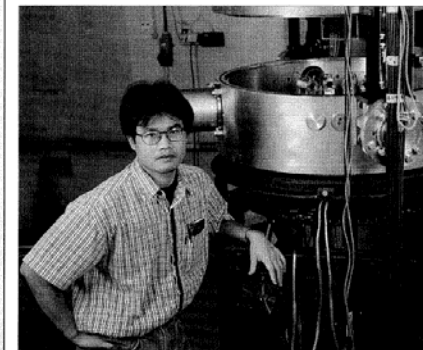


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The Svedberg Laboratory

Uppsala Accelerator News appears with irregular intervals. It gives news of scientific, technical or administrative nature from the The Svedberg Laboratory (TSL), the Department of Radiation Sciences (DS) and the Department of Neutron Research (DN) at Uppsala University. This newsletter will be sent to anyone interested. Inquiries and contributions should be sent to the Editor. Unsigned articles written by the Editor.

Uppsala Accelerator News

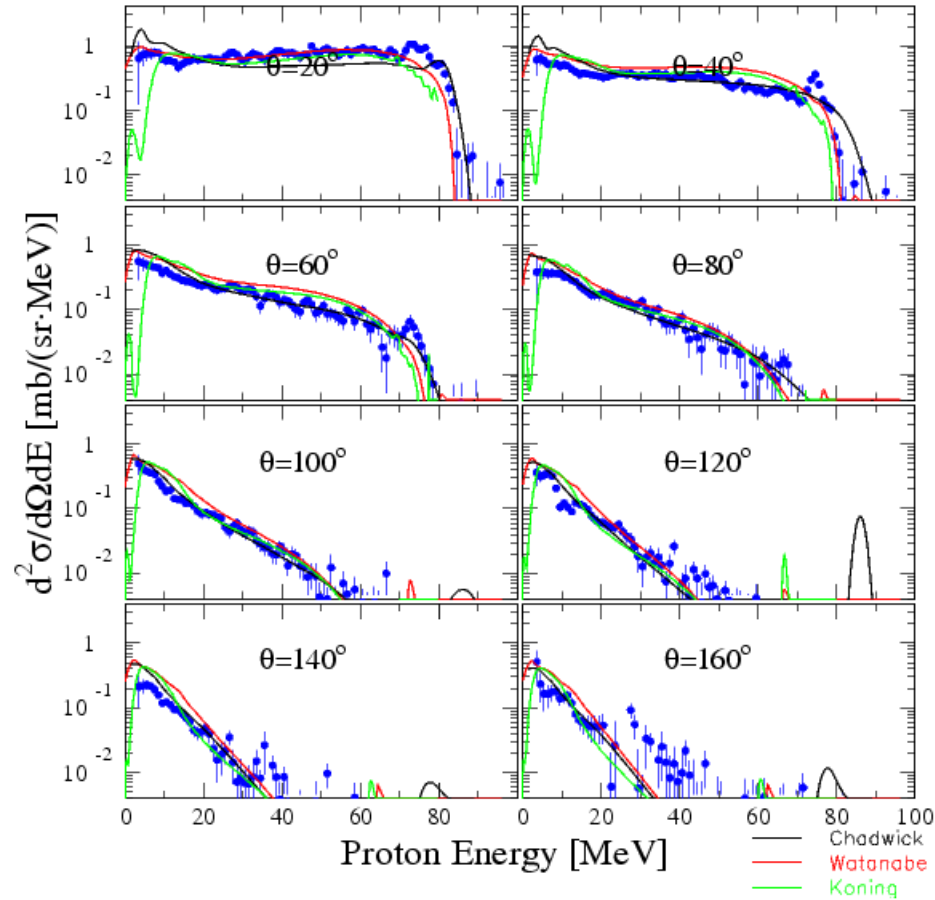
Editor: Gunnar Tibell
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Photographic: Teddy Thörnlund



Somsak Dangtip in front of the MEDLEY setup.



Results for C(n,px) @ 96 MeV



$$K = \Phi \cdot k_{\Phi}$$

Φ : fluence of uncharged particles at the same point
 k_{Φ} : **kerma coefficient**; unit: [J m² kg⁻¹] or [fGy m²]

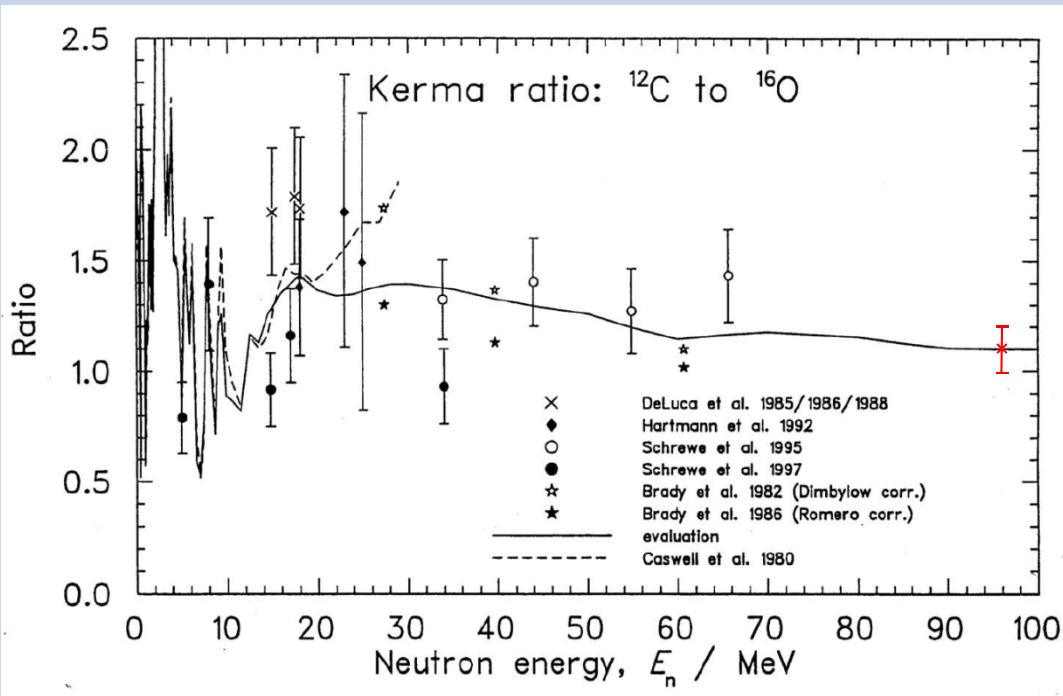
$$k_{\Phi}(E_n) = N \sum_i \int E \int \left(\frac{d^2 \sigma_i(E_n)}{d\Omega dE} \right) d\Omega dE$$

Kerma: Kinetic energy of the secondary charged particles **released** by the primary neutron per unit mass.

Dose: **Absorbed** energy per unit mass from the secondary charged particles.

- range of the secondary charged particles?
- their angular distribution?
- biological response?

U. Tippawan et al., PRC **79**, 064611 (2009)



ICRU 63:

$$k_\phi(\text{C@100 MeV}) = 7.07 \text{ fGy m}^2$$

$$k_\phi(\text{O@100 MeV}) = 6.44 \text{ fGy m}^2$$

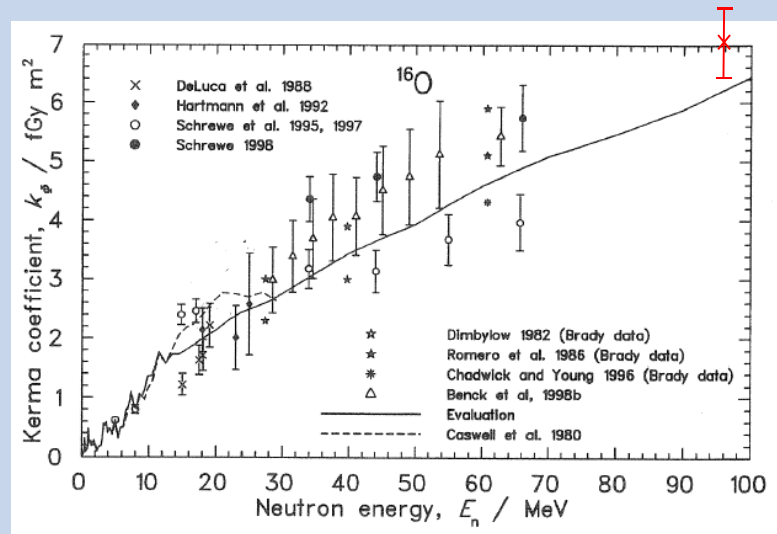
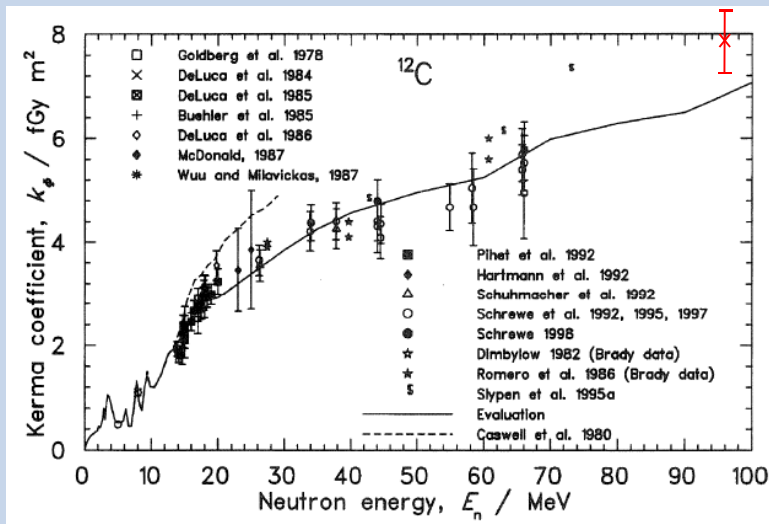
C/O Kerma ratio: 1.10

Medley:

$$k_\phi(\text{C@96 MeV}) = 7.85 \pm 0.63 \text{ fGy m}^2$$

$$k_\phi(\text{O@96 MeV}) = 7.09 \pm 0.57 \text{ fGy m}^2$$

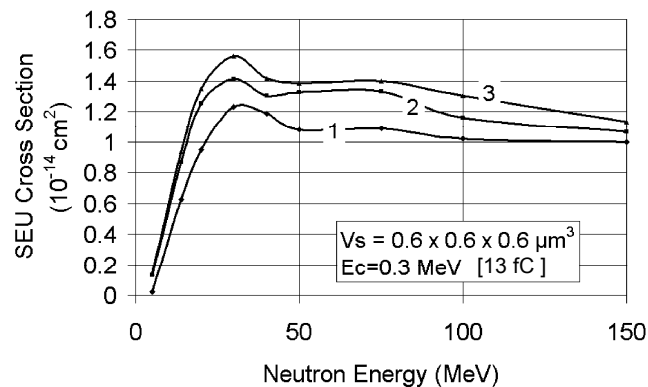
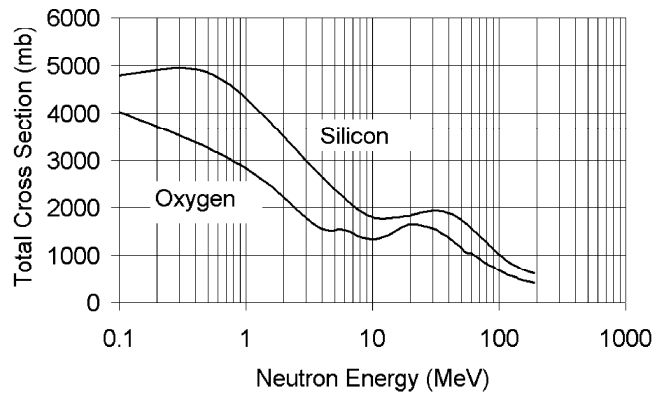
C/O Kerma ratio: 1.11 ± 0.13



S. Pomp, Neudos-11 (2009) and M. Götsche et al., Neudos-11 (2009)



Enter SEU and ADS (HINDAS)



- 1: only Si
- 2: SiO₂ on top
- 3: SiO₂ on both sides

F. Wrobel et al., IEEE Transactions Nuclear Science **50**, 2055 (2003).

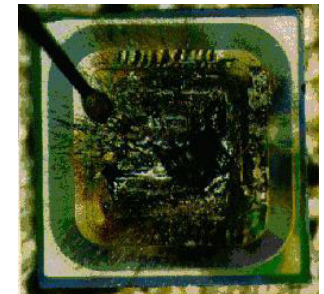
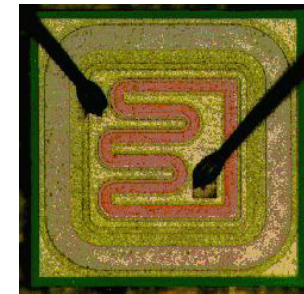
JEDEC STANDARD

Measurement and Reporting of
Alpha Particles and Terrestrial
Cosmic Ray-Induced Soft Errors in
Semiconductor Devices

JESD89

AUGUST 2001

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See, e.g., <http://holbert.faculty.asu.edu/eee560/see.html>



The old neutron beam @ TSL

- quasi monoenergetic neutron beam
- 20-180 MeV neutrons
- 10^6 neutrons/sec @ 100 MeV
- 10^5 neutrons/sec @ 180 MeV
- beam size: 7 to 25 cm in diameter

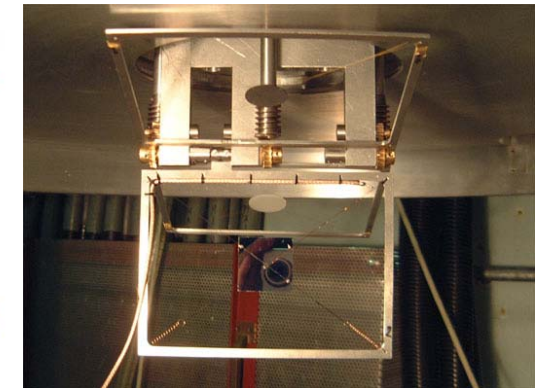
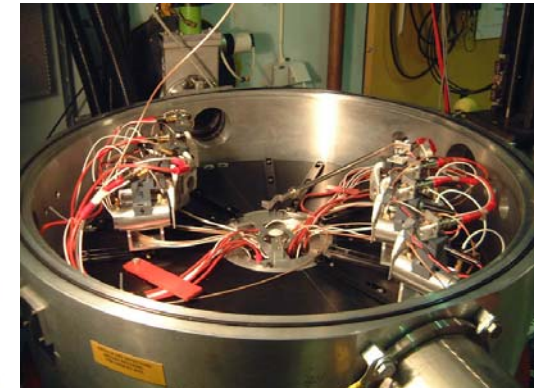
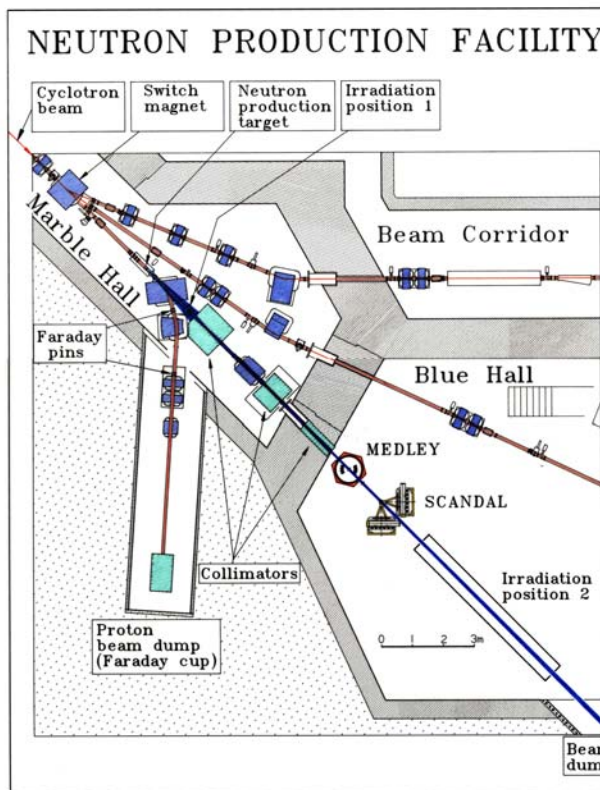
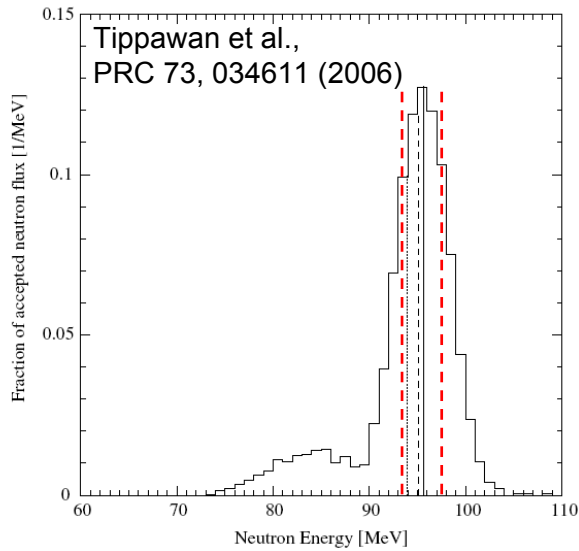
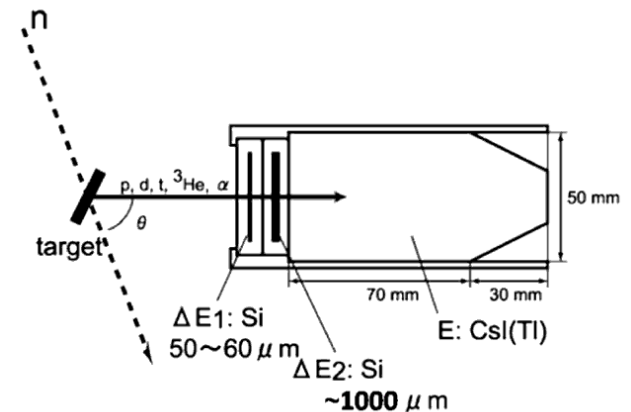


FIG. 1. Neutron energy distribution with TOF criterion applied derived from np scattering data at an angle of 20° . The peak (95.6 MeV), median (95.1 MeV), and average (94.0) are indicated by solid, dashed, and dotted vertical lines, respectively.



Medley = $\Delta E - \Delta E - E \dots$

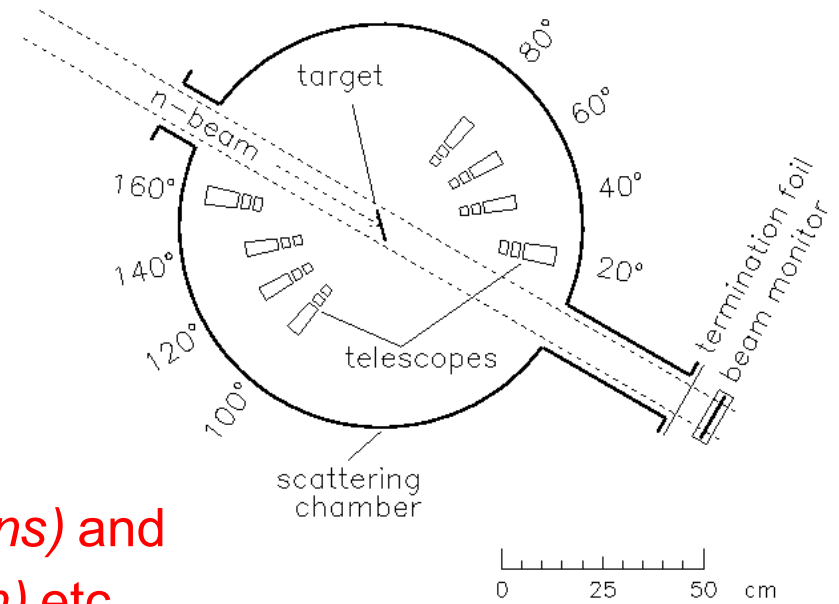
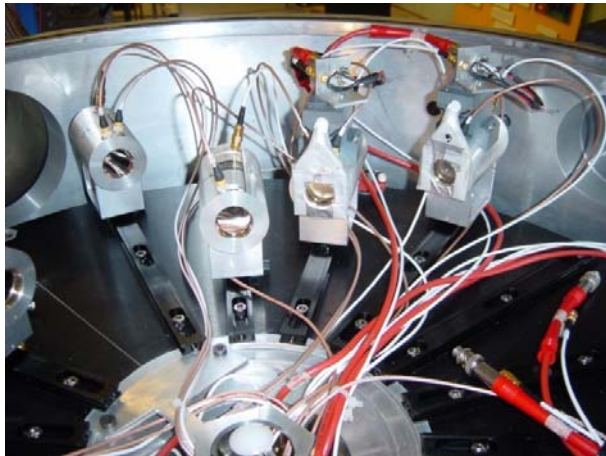
- detect and identify light ions: p , d , t , ${}^3\text{He}$ and α
 - but may also detect heavier ions and even fission products
- use the ΔE - ΔE - E technique – wide dynamic range
 - 8 Si detectors (Ortec) with thickness 50-60 μm , area 450 mm^2
 - 8 Si detectors with thickness 400-550 μm , dito
 - 8 Si detectors with thickness $\sim 1000 \mu\text{m}$, dito
 - 8 small CsI(Tl) with total length 5 cm, readout by photodiode
 - 8 large CsI(Tl) with diameter 5 cm and total length 10 cm, dito
- low threshold for **PID**:
 - 2,5 MeV for protons
(if we need to identify!)
 - 4 MeV for alpha particles
(without He-3 separation)





... + angles → ddx

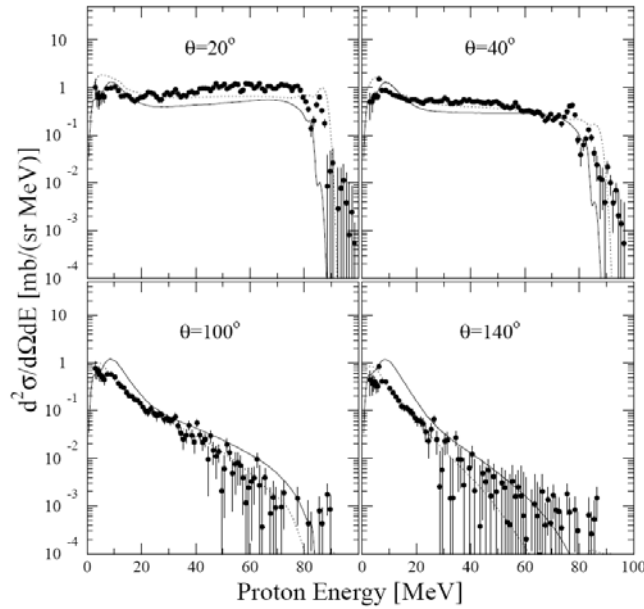
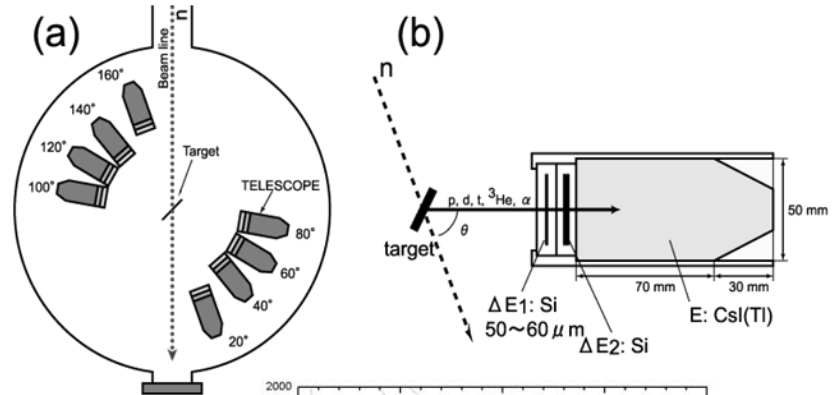
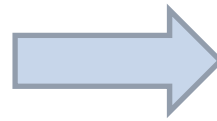
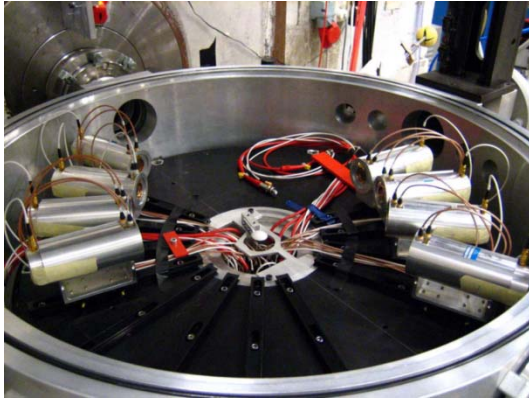
- use of thin targets (now well established correction procedure for target thickness)
 - ~100 - 200 mg/cm² (light ions); ~1 mg/cm² (fission)
- 8 telescopes, typically in 20 degree intervall
 - e.g. -70, -50, -30, -10, +30, +50, +70 and +90 degrees



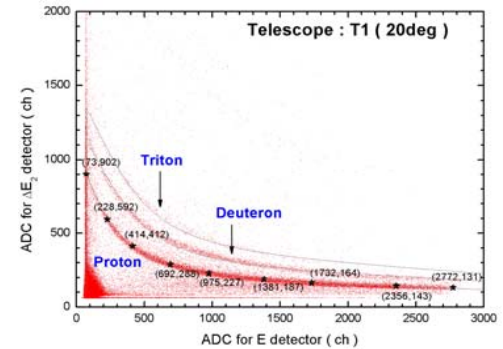
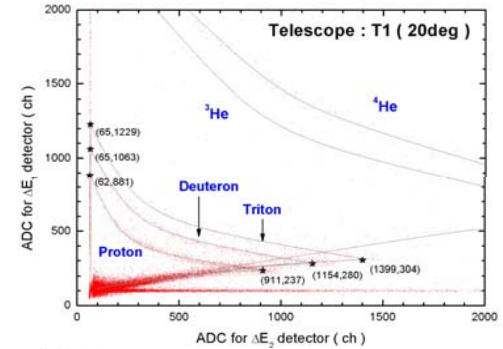
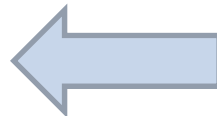
⇒ ddx data for $X(n, \text{light ions})$ and $\sigma, d\sigma/d\Omega$ for $X(n, \text{fission})$ etc.



So what we do is ...



$$\frac{d^2\sigma_i(E_n)}{d\Omega dE}$$





Main corrections

- Thick target
- CsI correction
- Wrap around



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Nuclear Instruments and Methods in Physics Research A 572 (2007) 893–898

**NUCLEAR
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Section A

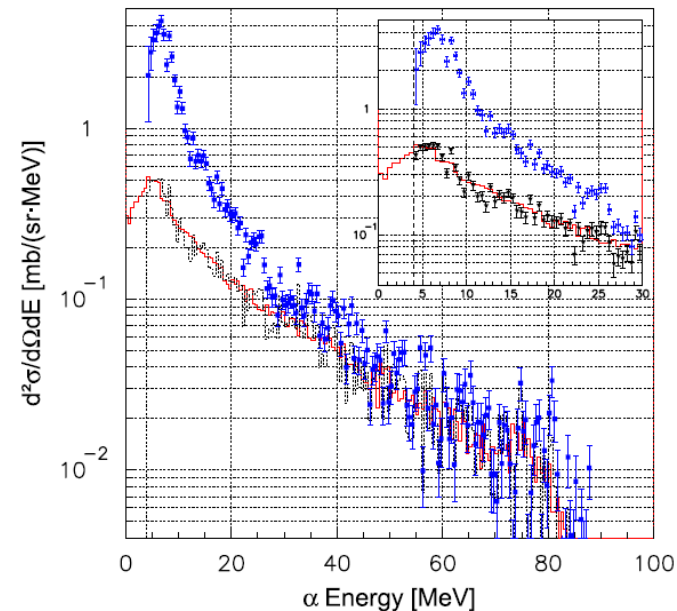
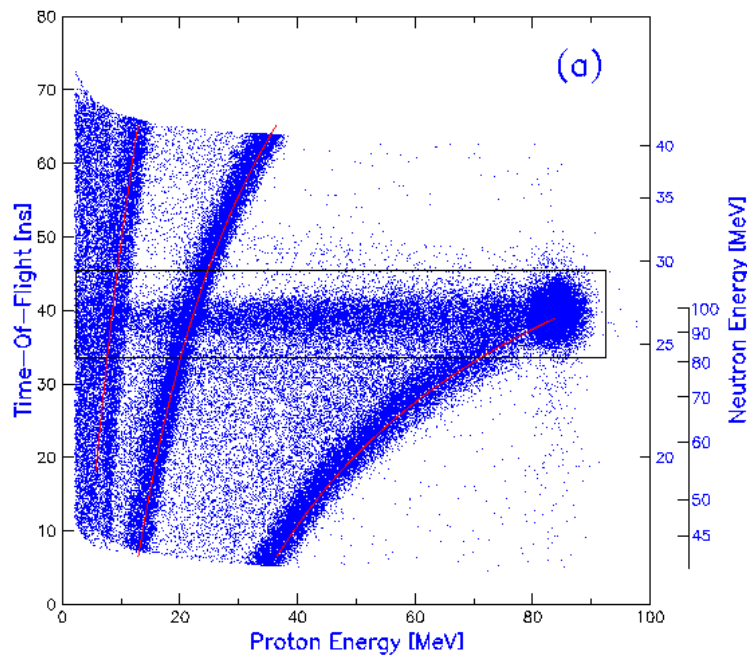
www.elsevier.com/locate/nima

An iterative procedure to obtain inverse response functions for thick-target correction of measured charged-particle spectra

S. Pomp^{a,*}, U. Tippawan^{a,b}

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Light ions from silicon and heavy metals

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PHYSICAL REVIEW C 69, 064609 (2004)

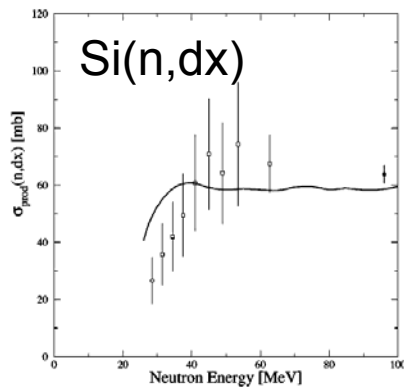
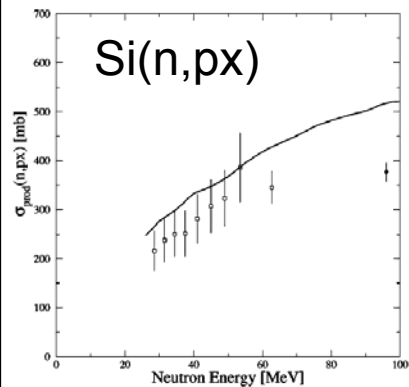
Light-ion production in the interaction of 96 MeV neutrons with silicon

U. Tippawan,^{1,2} S. Pomp,^{1,*} A. Ataç,¹
J. Klug,¹ P. Mermod,¹ L. Nilsson,^{1,4} M. Österlund,¹
P. Nadel-Turonski,¹⁰

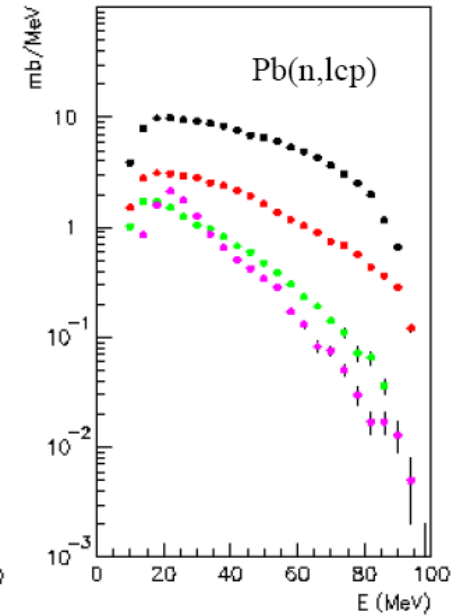
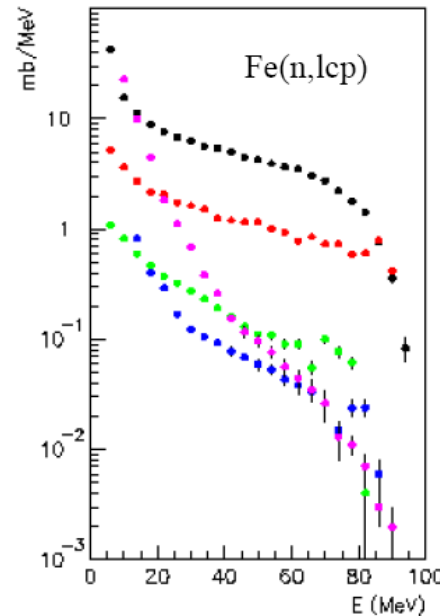
PHYSICAL REVIEW C 70, 014607 (2004)

Nucleon-induced reactions at intermediate energies: New data at 96 MeV and theoretical status

V. Blideanu,^{1,*} F. R. Lecolley,¹ J. F. Lecolley,¹ T. Lefort,¹ N. Marie,¹ A. Ataç,² G. Ban,¹ B. Bergenwall,² J. Blomgren,²
S. Dangtip,^{2,3} K. Elmgren,⁴ Ph. Eudes,⁵ Y. Foucher,⁶ A. Guertin,⁵ F. Haddad,⁵ A. Hildebrand,² C. Johansson,² O. Jonsson,⁷
M. Kerveno,⁸ T. Kirchner,⁵ J. Klug,² Ch. Le Brun,⁹ C. Lebrun,⁵ M. Louvel,¹ P. Nadel-Turonski,¹⁰ L. Nilsson,^{2,7}
N. Olsson,^{2,4} S. Pomp,² A. V. Prokofiev,⁷ P.-U. Renberg,⁷ G. Rivière,⁵ I. Slypen,¹¹ L. Stuttgé,⁸ U. Tippawan,^{2,3} and
M. Österlund²



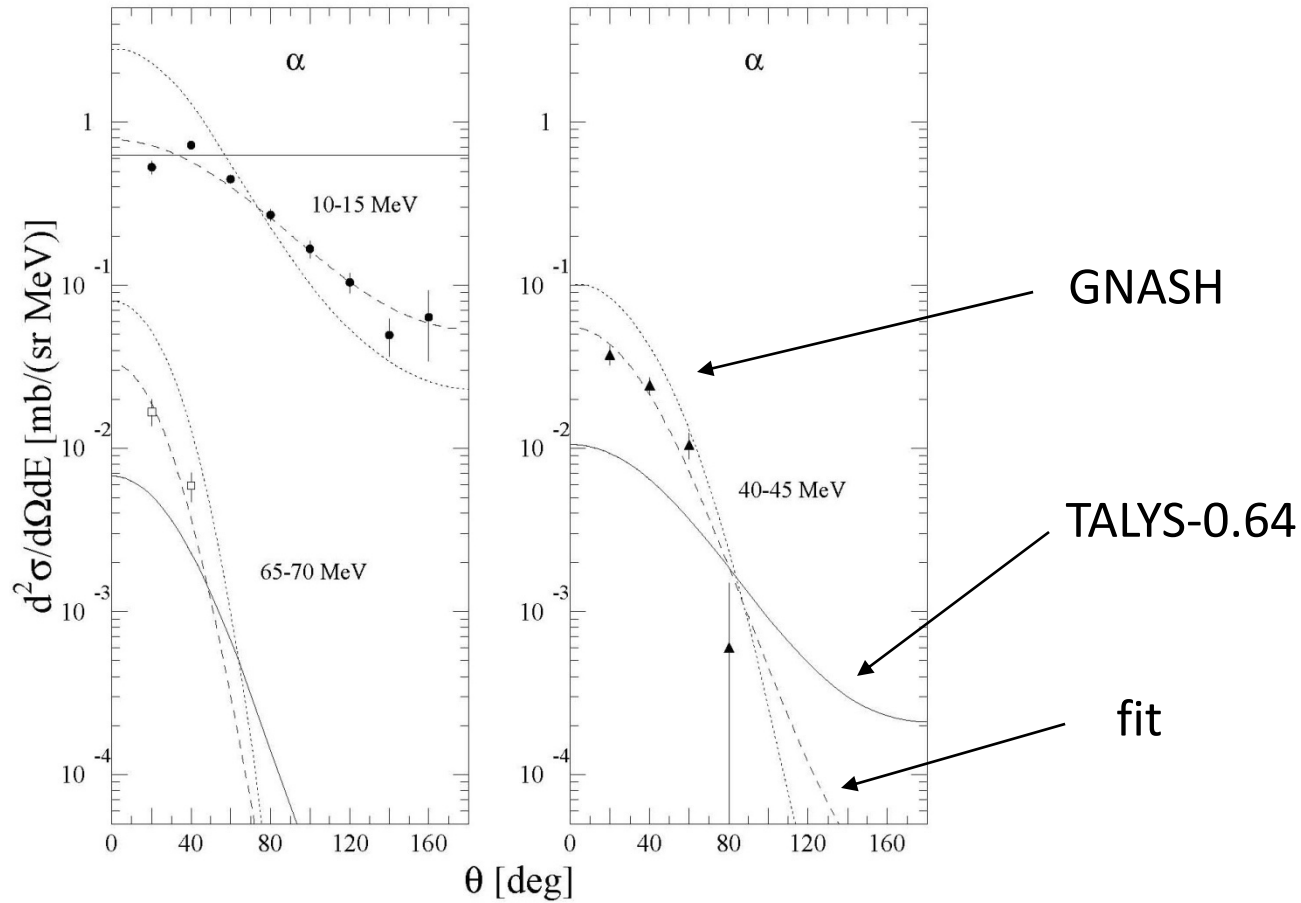
Production cross sections vs. GNASH
and data from LLN (Benck et al.)



protons
deuterons
tritons
He3
He4



Angular distributions for $O(n, \alpha x)$



Tippawan et al., Phys. Rev. C **73** (2006) 034611



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PHYSICS LETTERS B

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Physics Letters B 597 (2004) 243–248

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Search for three-body force effects in neutron–deuteron scattering at 95 MeV

P. Mermod^a, J. Blomgren^a, B. Bergenwall^a, A. Hildebrand^a, C. Johansson^a, J. Klug^a, L. Nilsson^{a,b}, N. Olsson^{a,c}, M. Österlund^a, S. Pomp^a, U. Tippawan^a, O. Jonsson^b, A. Prokofiev^b, P.-U. Renberg^b, P. Nadel-Turonski^d, Y. Maeda^e, H. Sakai^e, A. Tamii^e

RAPID COMMUNICATIONS

PHYSICAL REVIEW C 72, 061002(R) (2005)

Evidence of three-body force effects in neutron-deuteron scattering at 95 MeV

P. Mermod, J. Blomgren,^{*} A. Hildebrand, C. Johansson, J. Klug, M. Österlund, S. Pomp, and U. Tippawan
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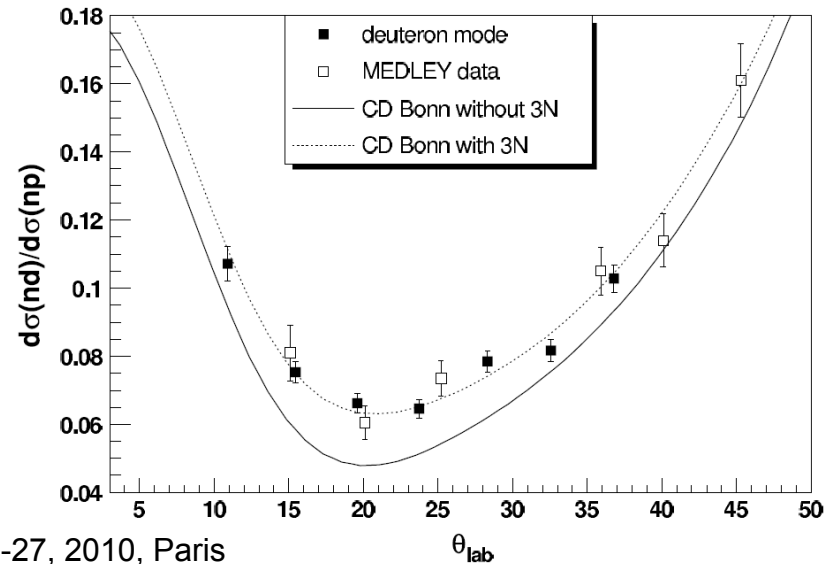
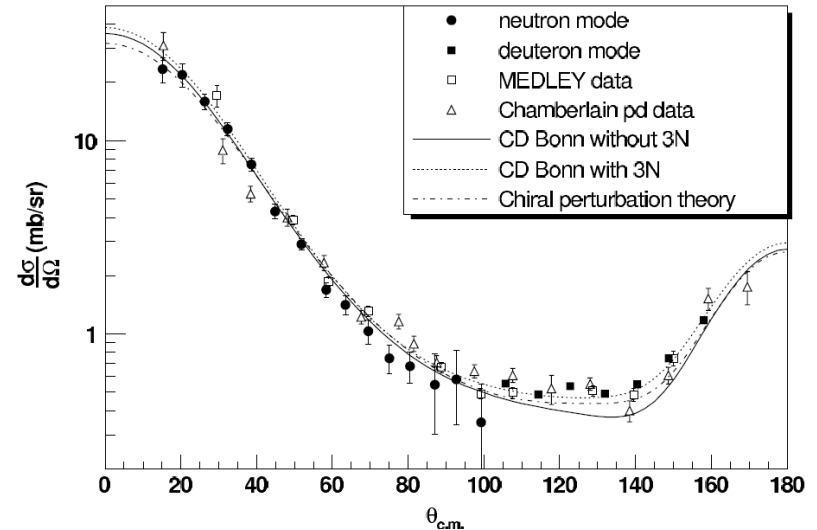
L. Nilsson
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P. Nadel-Turonski
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Y. Maeda, H. Sakai, and A. Tamii
Department of Physics, University of Tokyo, Japan
(Received 17 June 2005; published 30 December 2005)





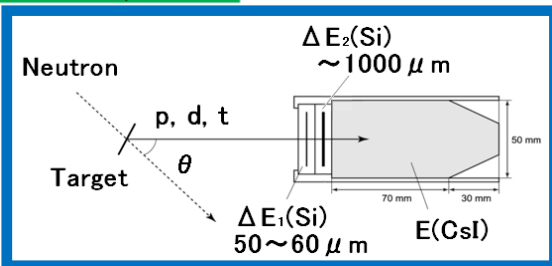
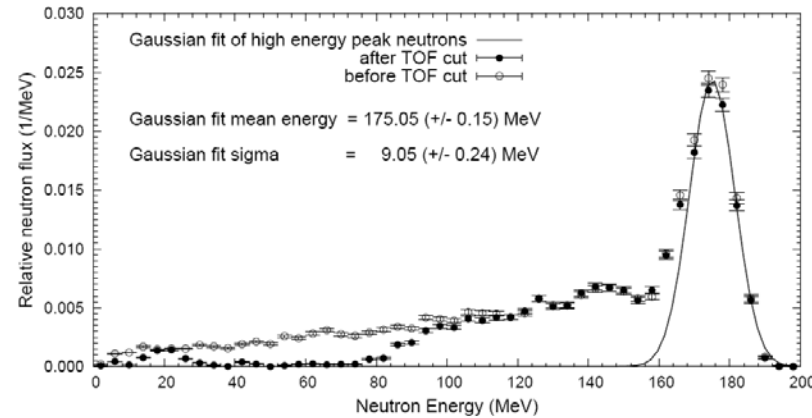
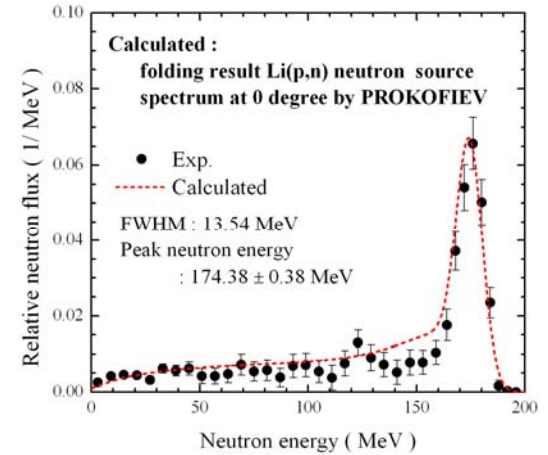
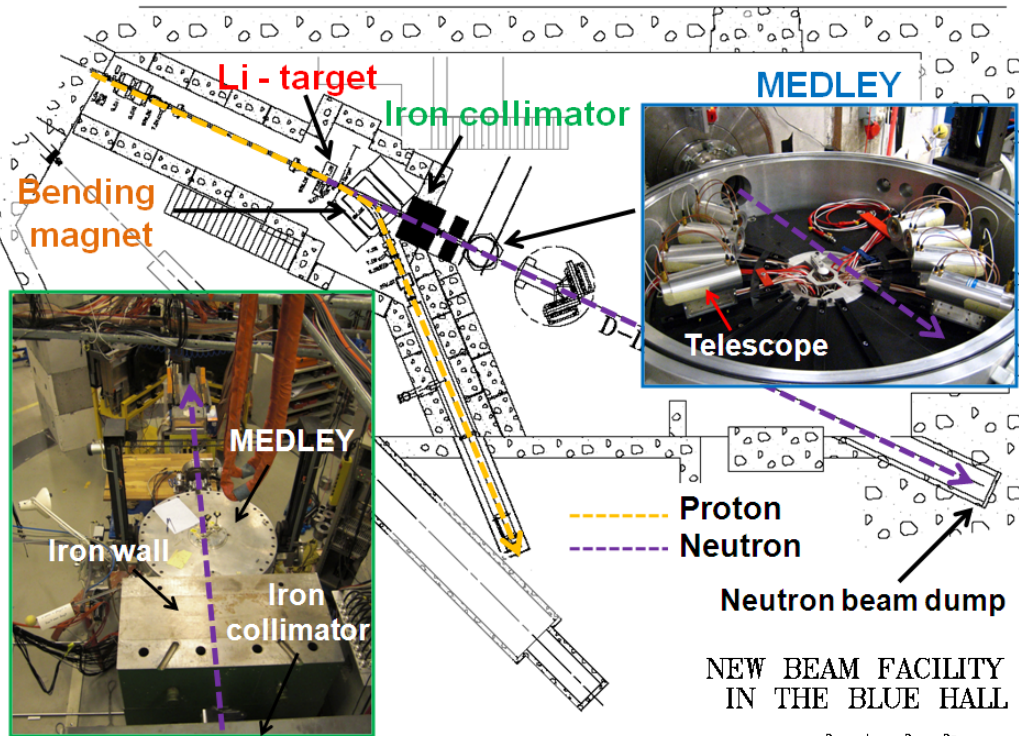
Summary for 96 MeV campaign

- **medicine** (cancer therapy, dosimetry)
 - C: Phys. Rev. C **79**, 064611 (2009)
 - O: Phys. Rev. C **73**, 034611 (2006)
 - Ca: “data under analysis”
- **electronics** (SEU effects)
 - Si: Phys. Rev. C **69**, 064609 (2004)
 - O: see above
- **energy applications** (transmutation)
 - Fe, Pb, U: Phys. Rev. C **70**, 014607 (2004)
- **3 body forces**
 - *nd* scattering : Phys. Rev. C **72**, 06002(R) (2005)



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Towards 175 MeV

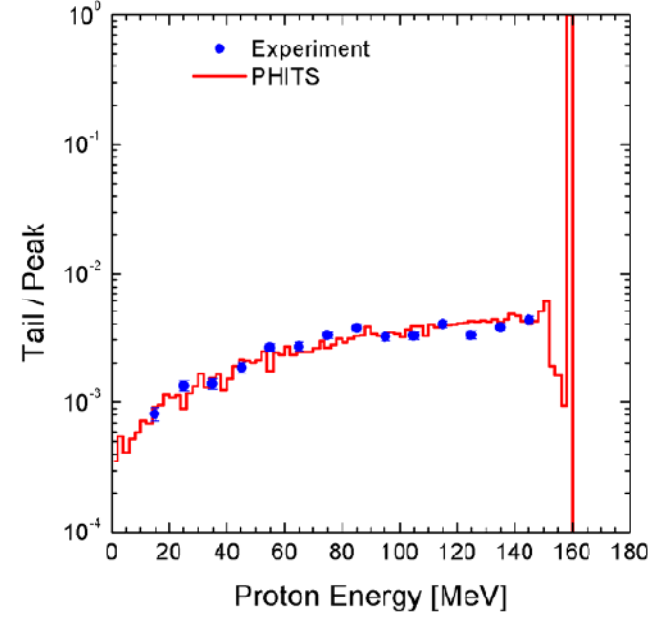
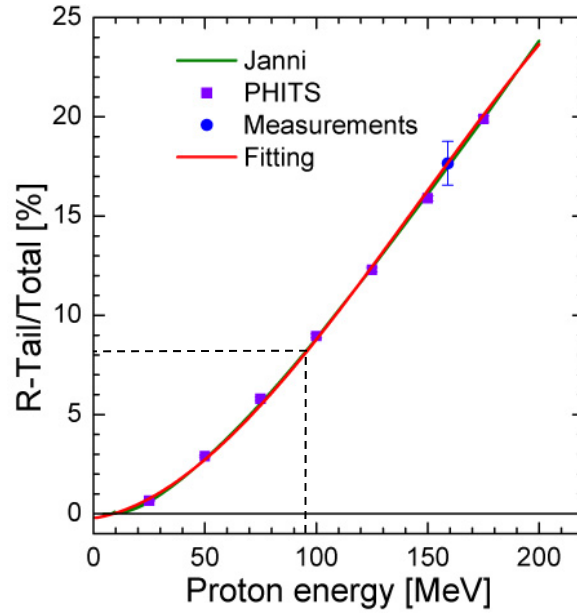
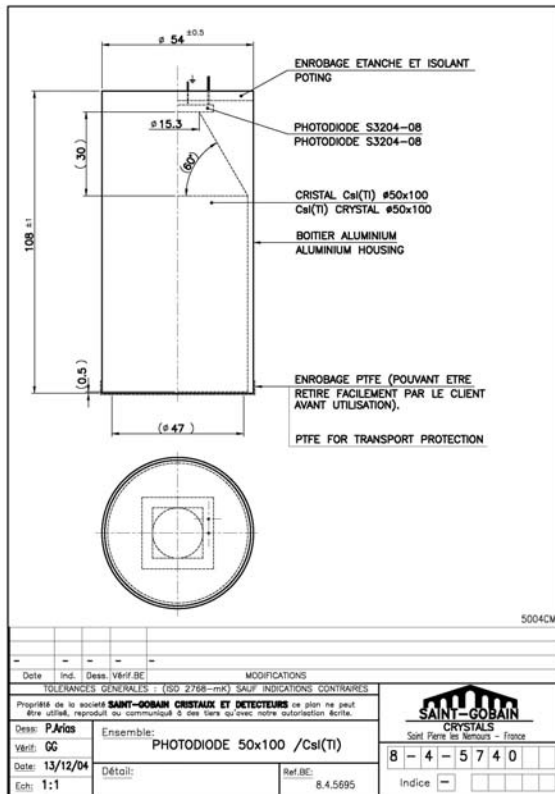


S. Hirayama et al. and R. Bevilacqua et al., ND2010



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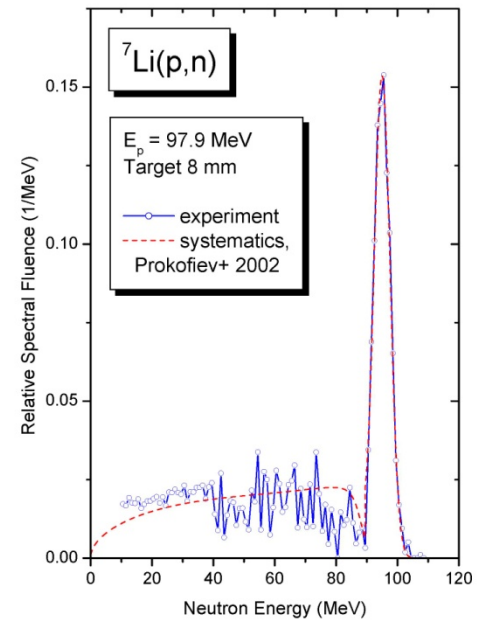
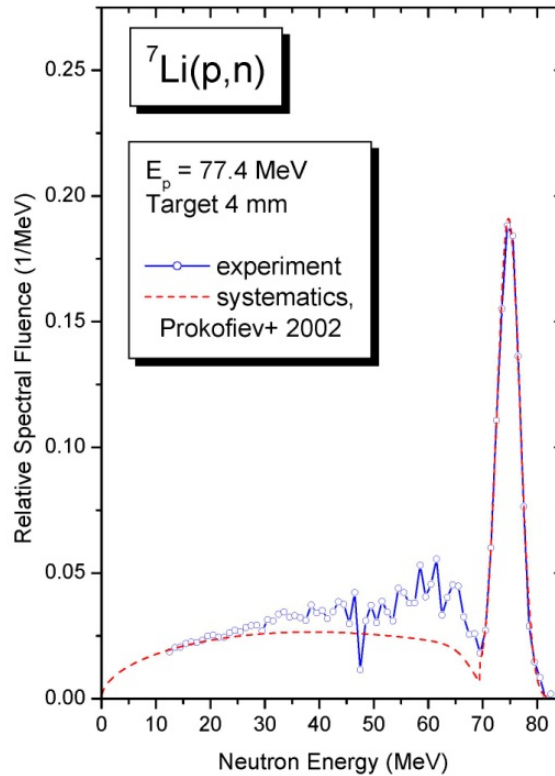
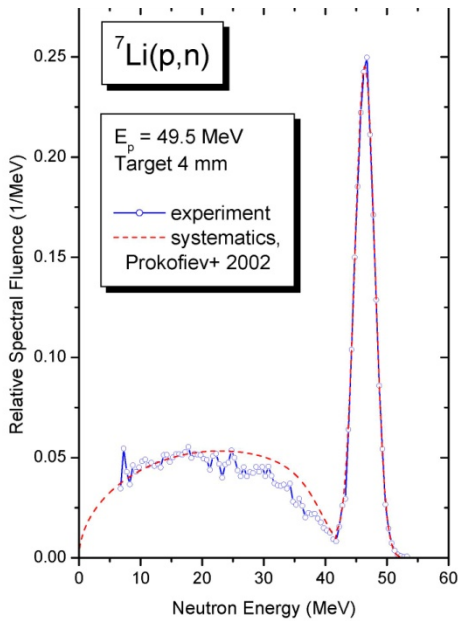
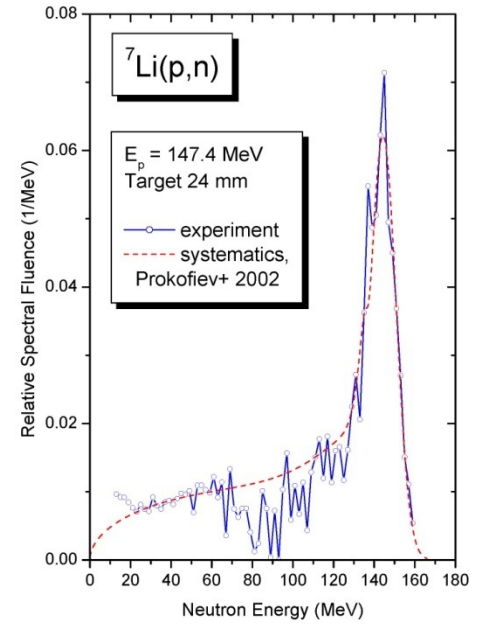
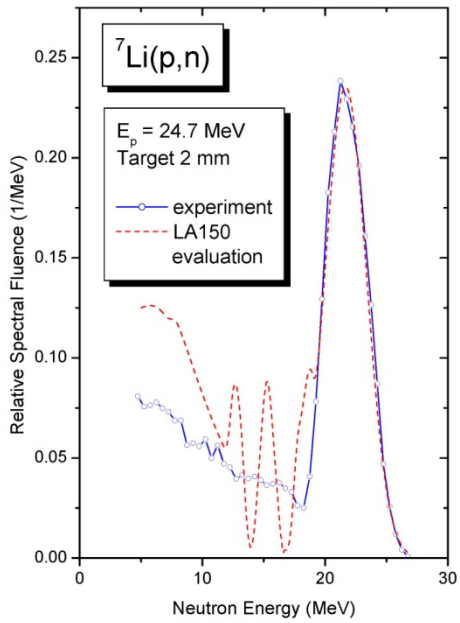
CsI response measurements



measured with 160 MeV protons at TSL

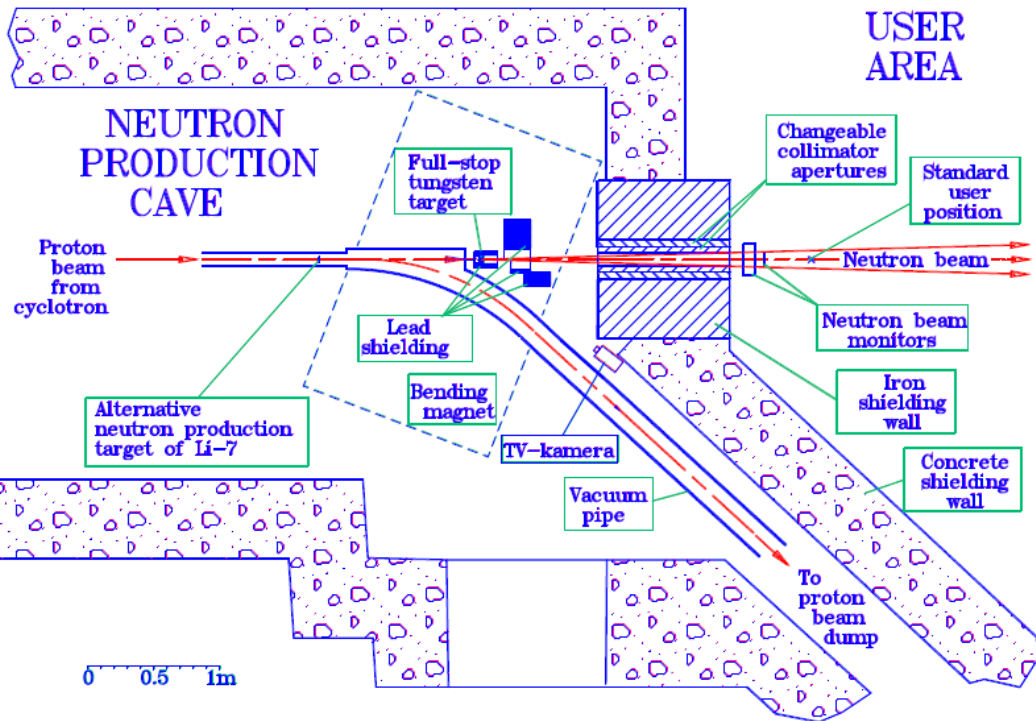
Analysis by M. Hayashi

neutron spectra as
measured with MEDLEY



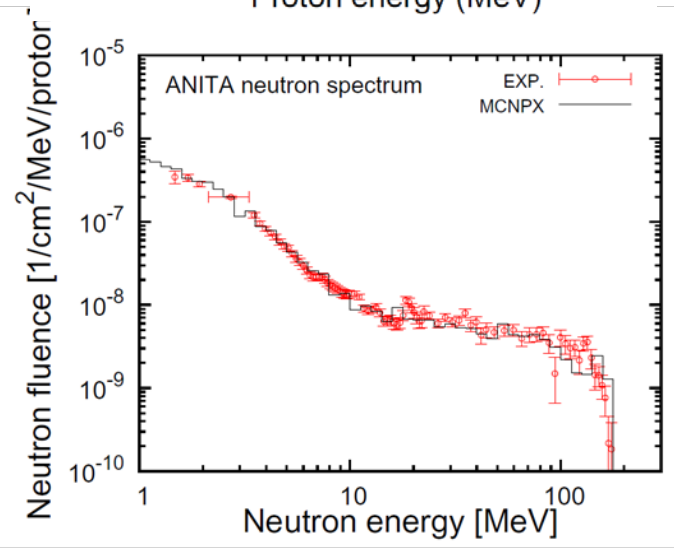
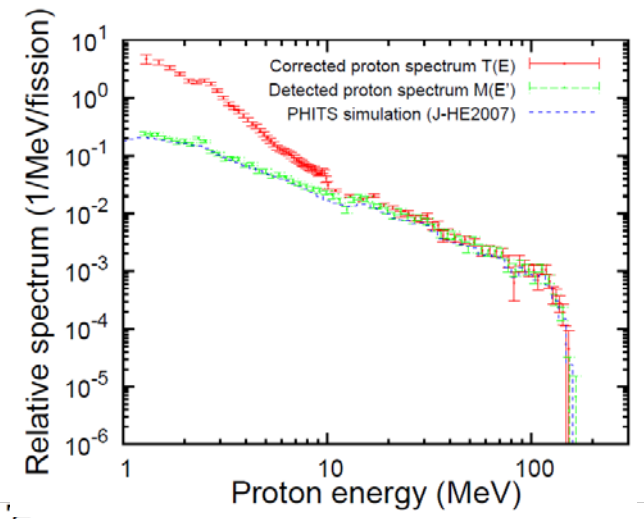


ANITA – the white neutron source



- Neutron spectrum via $H(n,p)$ @ 20 degree
- Measurement extends to $E_n \approx 1.5$ MeV

Y. Naitou et al., SND2009

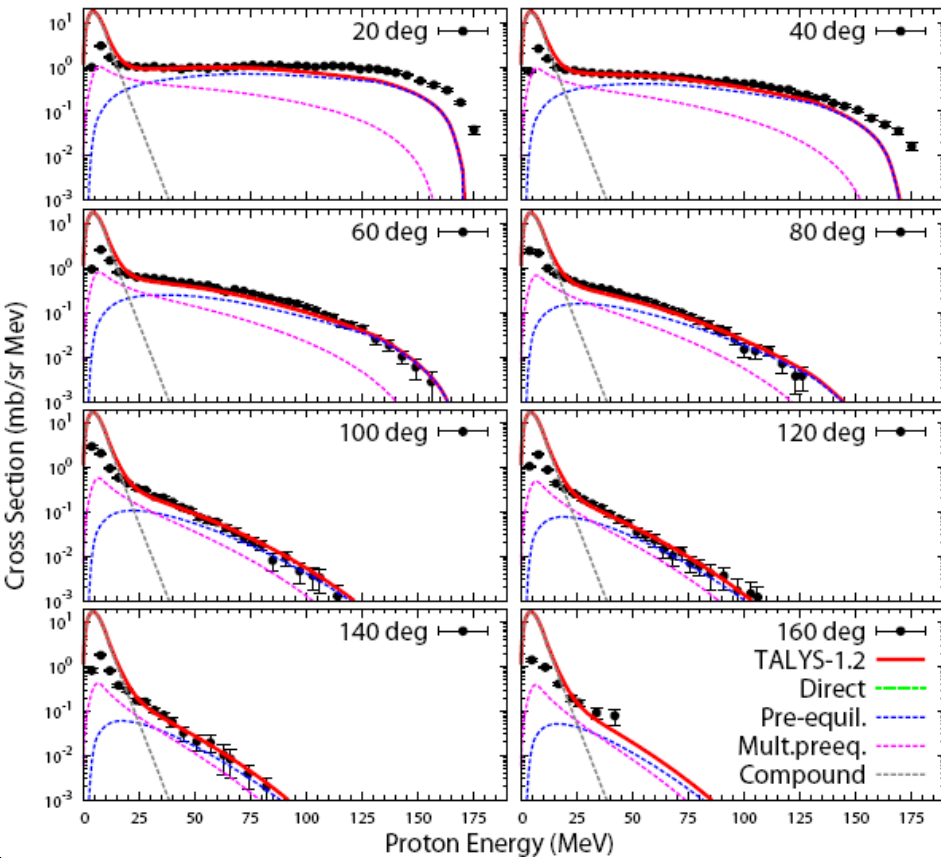




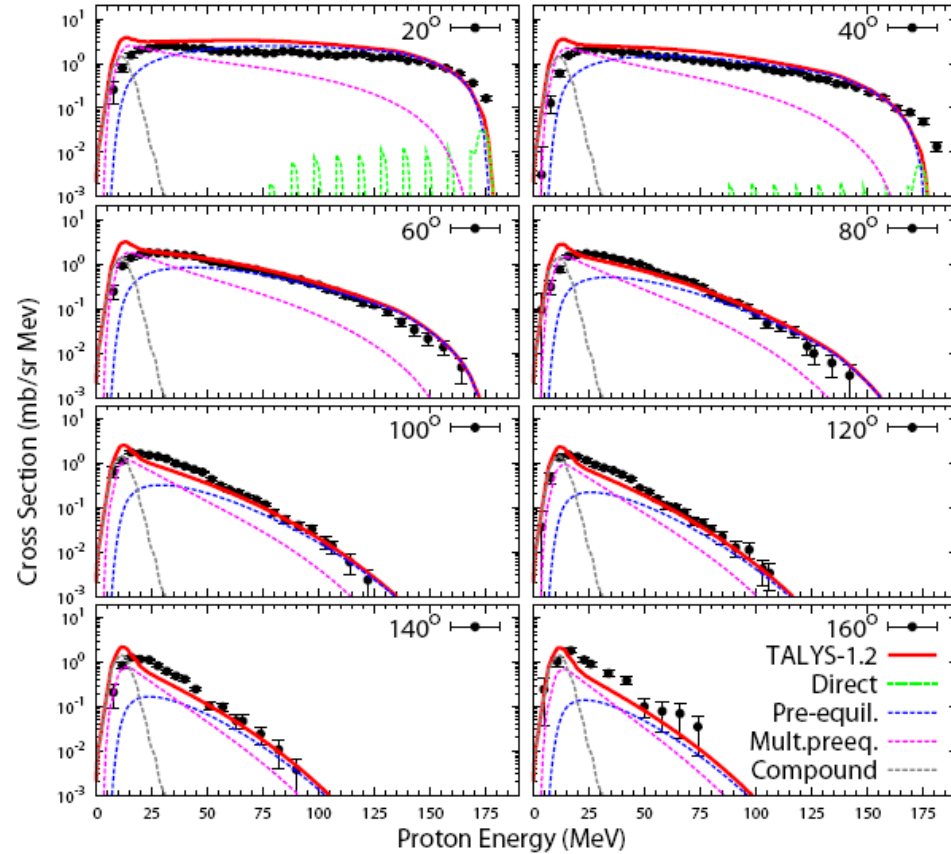
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(n,px) from Fe and Bi @ 175 MeV

Iron - Neutron Induced Proton Production Cross Sections



Bismuth - Neutron Induced Proton Production Cross Sections

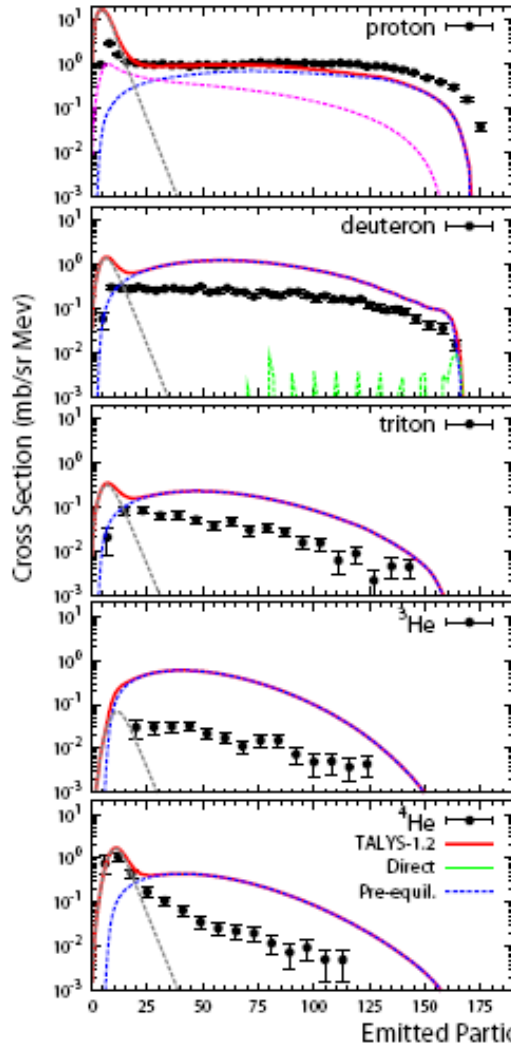


R. Bevilacqua et al., ND2010

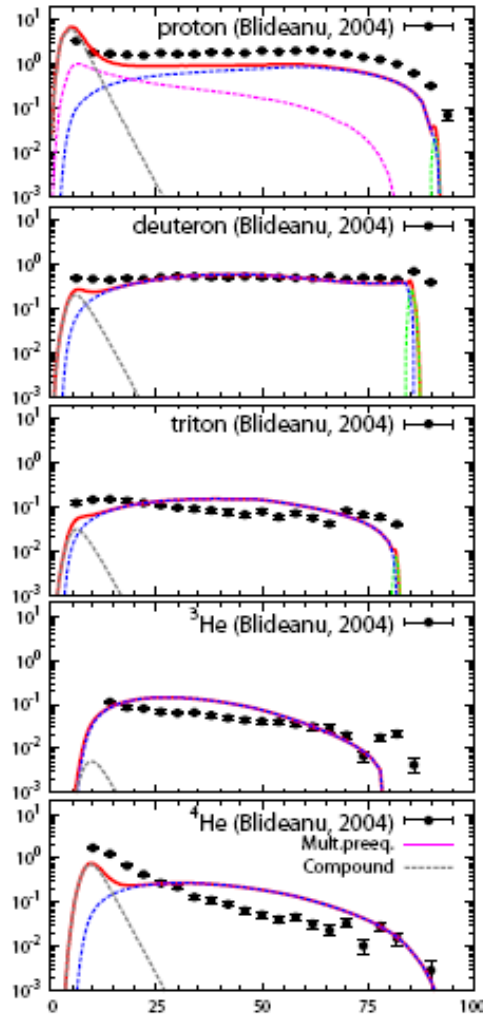


Fe @ 175 MeV vs. 96 MeV

Light-ion production from Iron at 20°
175 MeV QMN



96 MeV

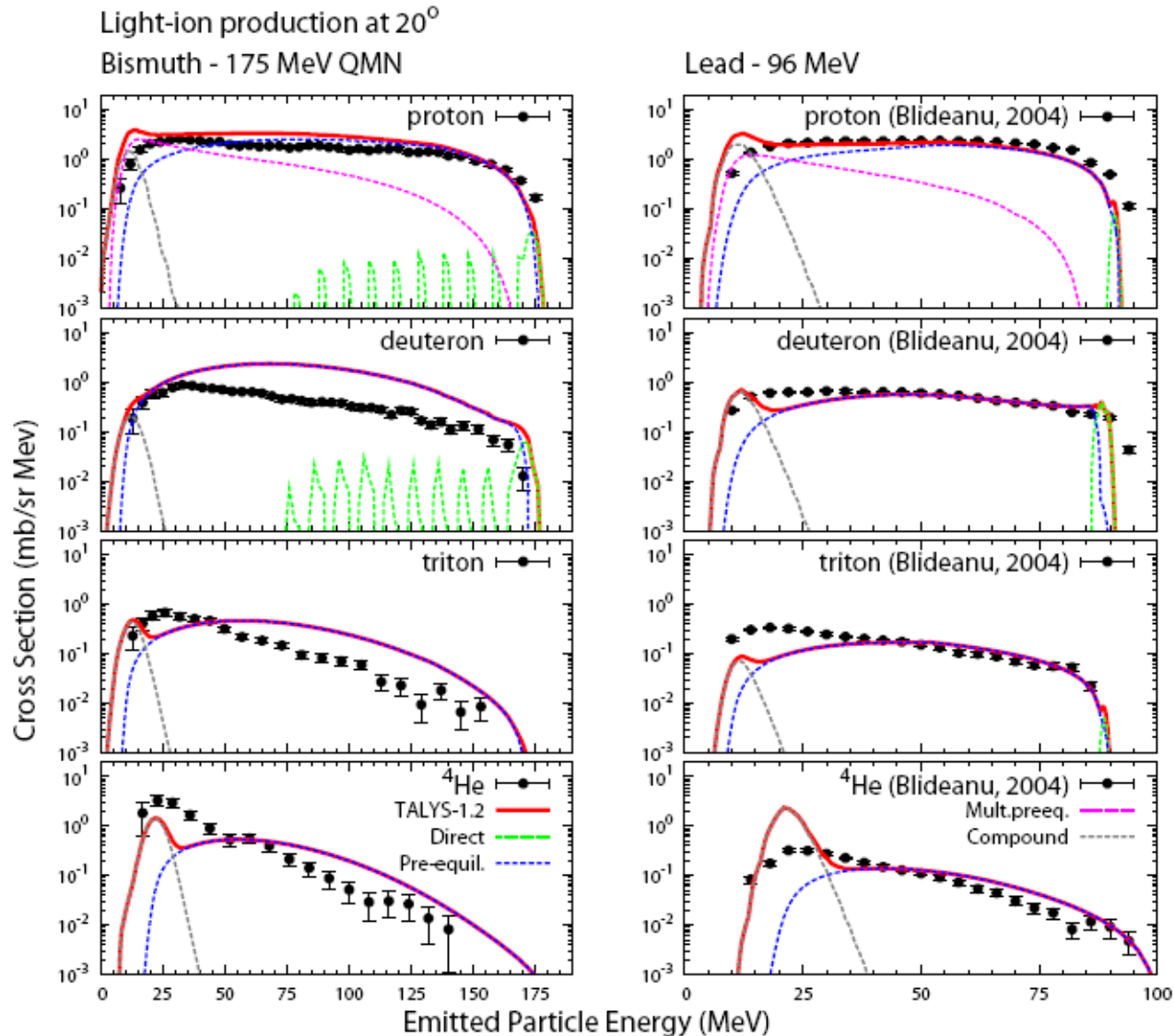


- still preliminary data at 20 deg from R. Bevilacqua et al.
- neutron tail included in Talys calculations
- 96 MeV data are from V. Blideanu et al., PRC **70**, 014607 (2004)

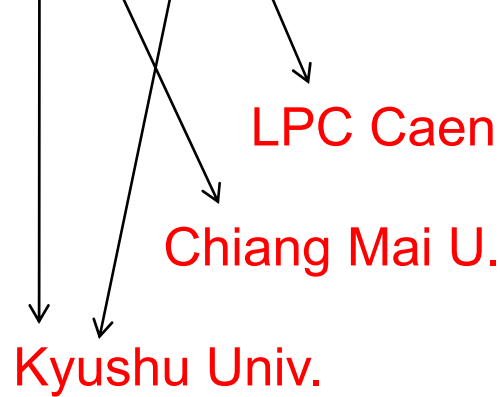


Dito for Bi/Pb @ 175 MeV vs. 96 MeV

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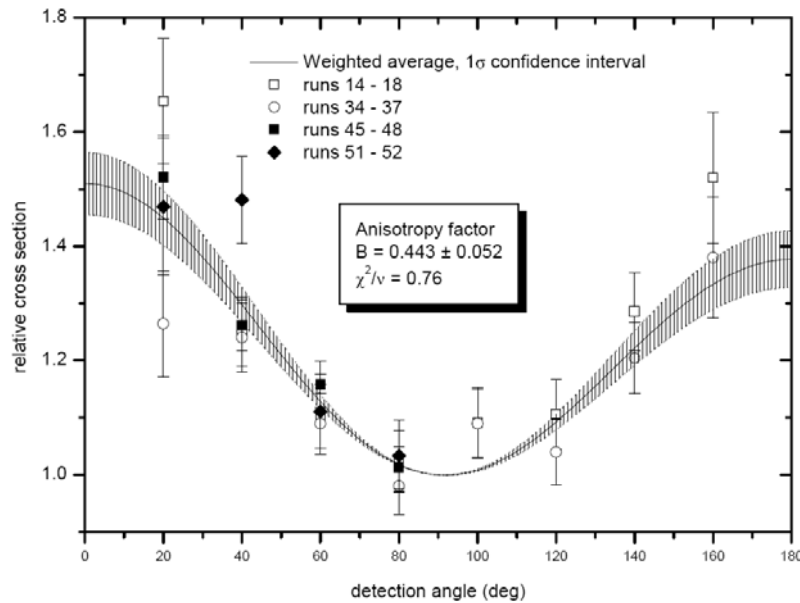


Other targets
measured so far:
C, O, Si, U

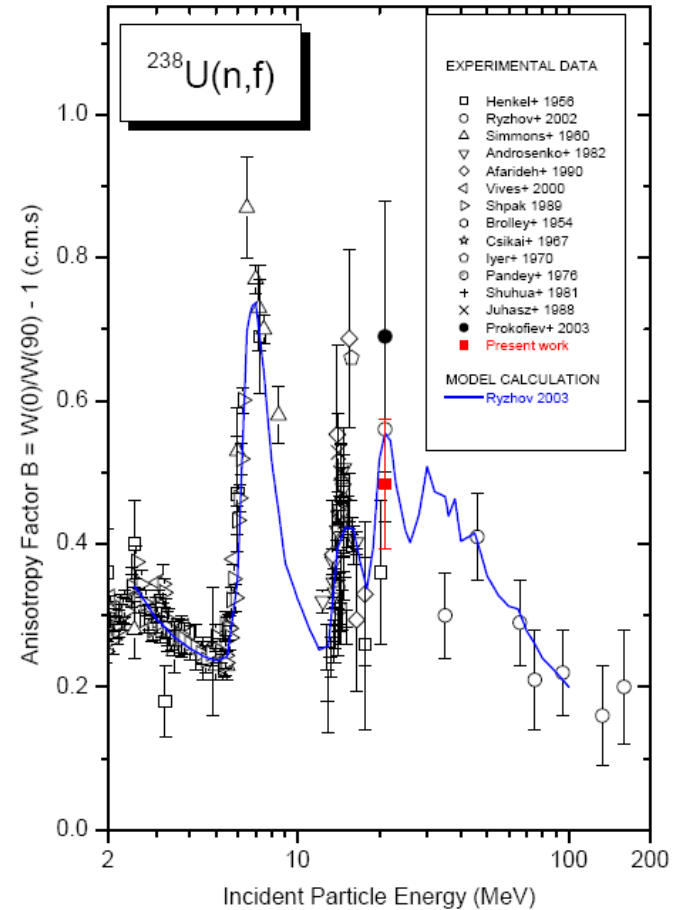




Medley for fission: anisotropy of U(n,f) @ 21 MeV



- Special option: **normalisation** procedure!
 - Simultaneous detection of fission and **np** scattering events
 - count particles from alpha decay

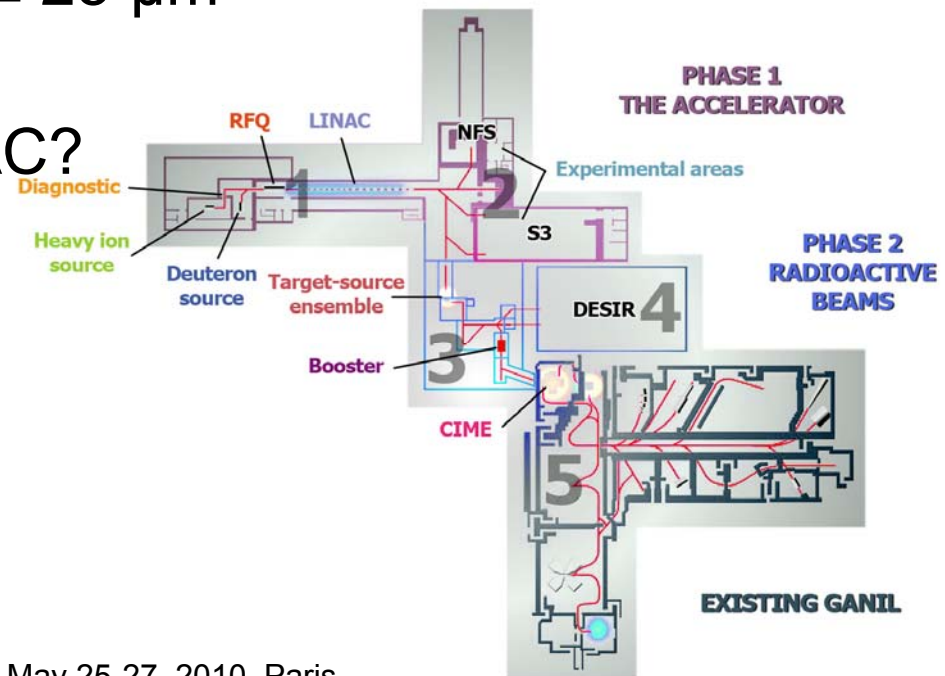


Prokofiev et al., ND2004, Santa Fe



Medley applying for french citizenship?

- We plan to move Medley to NFS
- Several upgrades necessary/useful:
 - New digital DAQ
 - New Si1 with thickness $\leq 25 \mu\text{m}$
 - $A > 5$, fission
 - Detector for timing: PPAC?
 - E_{η} , PID, ...





Summary + Outlook

- A lot has been done and the energy range for available ddx data on light-ion production has been tripled
- But more is possible @ NFS
 - (n,lcp) at 10-40 MeV
 - Cancer Therapy, Dosimetry, SEU, GenIV, Fusion/IFMIF, ...
 - Fission: angular dist., standards, ...
 - H(n,p) – tagging?
 - Coincidence measurements
 - Commissioning (spectra)



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(incomplete list ...)

- the Swedish Research Council
- the Swedish Cancer Foundation
- Swedish Nuclear Fuel and Waste Management Company
- Swedish Nuclear Power Inspectorate
- Swedish Nuclear Safety Authority
- Vattenfall AB
- Barsebäck Power AB
- the Swedish Defence Research Agency
- the Thailand Research Fund
- the EU Council through HINDAS ...
- ... and (last not least) EFNUDAT

