Measurements of DN Yields and Time Spectra from p(1 GeV) + ^{nat}Pb & p(1 GeV) + ^{209}Bi

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Collaboration:
- PNPI, Russia
- IoP, Lithuania
- PSI, Switzerland

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- FR Ministry of Foreign Affairs
- GEDEPEON

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Introduction

- **high-energy high-power accelerators →**
  use of liquid metal targets (Hg, Pb, Pb-Bi, …)

- **long flowing metal loop →**
  activated metal close to electronics, in hot cells,
  heat exchanger, pumps, …

- **short transit time →**
  "moving" beta, photon and delayed neutron (DN) radioactivity

<u>Goal:</u>
Characterization of DNs from high-energy spallation-fission reactions

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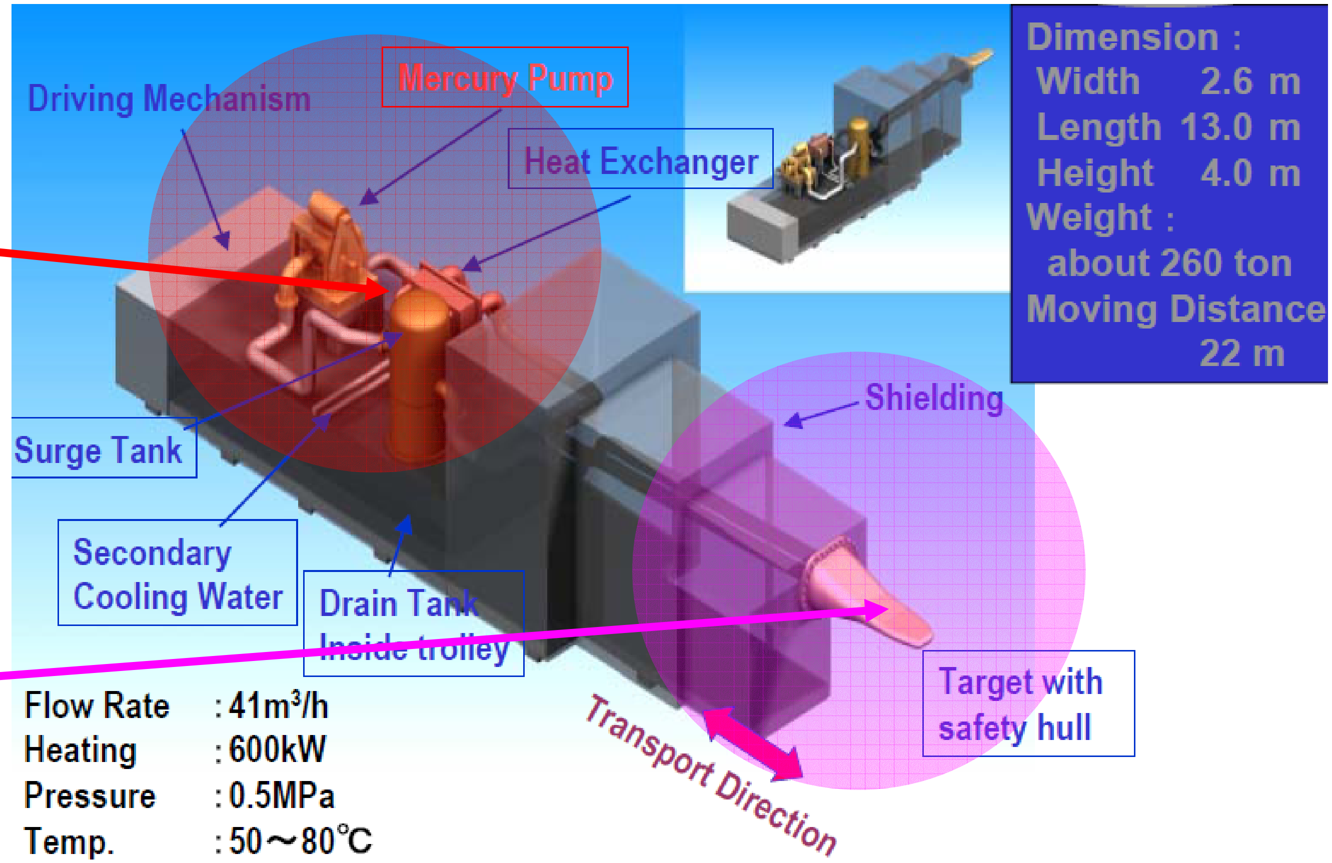
Examples (A)

J-PARC/JAEA - thanks to H. Nakashima

Delayed neutrons

Prompt neutrons



short Hg transit time → delayed neutron (DN) activity

Examples (B)

MegaPie/PSI - thanks to F. Groeschel

<u>Beam on the target from</u>
14 August to 23 December!

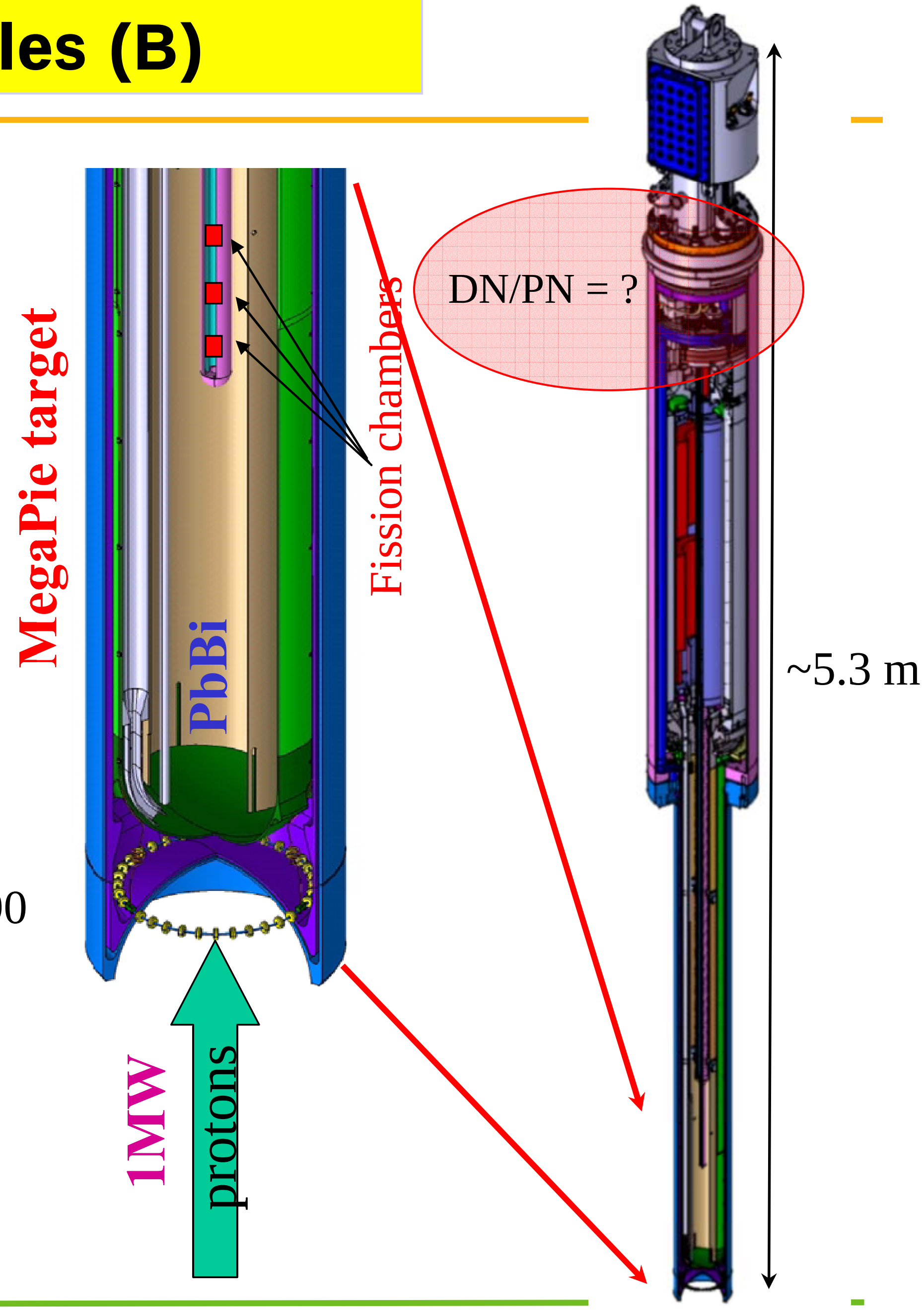
E_p I_p W	570 MeV 1.2 mA (1.8) 0.7MW (1.0)
V_{PbBi}	~ 82 liters
Main pump	~4.00 l/s
$T_{transit}$	~20 s

DN and PN estimates using MCNPX+CINDER'90

Φ_n (DN)~ 10^6 n/(s cm^2)
Φ_n (PN)~ 10^6 n/(s cm^2)

Important: DN yields are very sensitive to the choice of physics models!

D. Ridikas et al., Proc. of PHYSOR2006, Vancouver, Canada



Model-dependence of DN yields

	INCL4 +ABLA model		CEM2k model	
Group	$T_{1/2}$, s	a_i, n/p times 10^6	$T_{1/2}$, s	a_i, n/p times 10^6
1	55.49	0.87	55.60	6.78
2	16.29	0.89	16.35	15.25
3	4.99	0.44	4.66	23.58
4	1.90	1.19	1.63	174.24
5	0.52	0.21	0.45	129.95
6	0.20	0.00	0.11	233.52
Total/average	18.70	3.59	1.90	583.35

Difference by 2 orders of magnitude!

D. Ridikas et al., Proc. of Fission2005, CEA Cadarache, France

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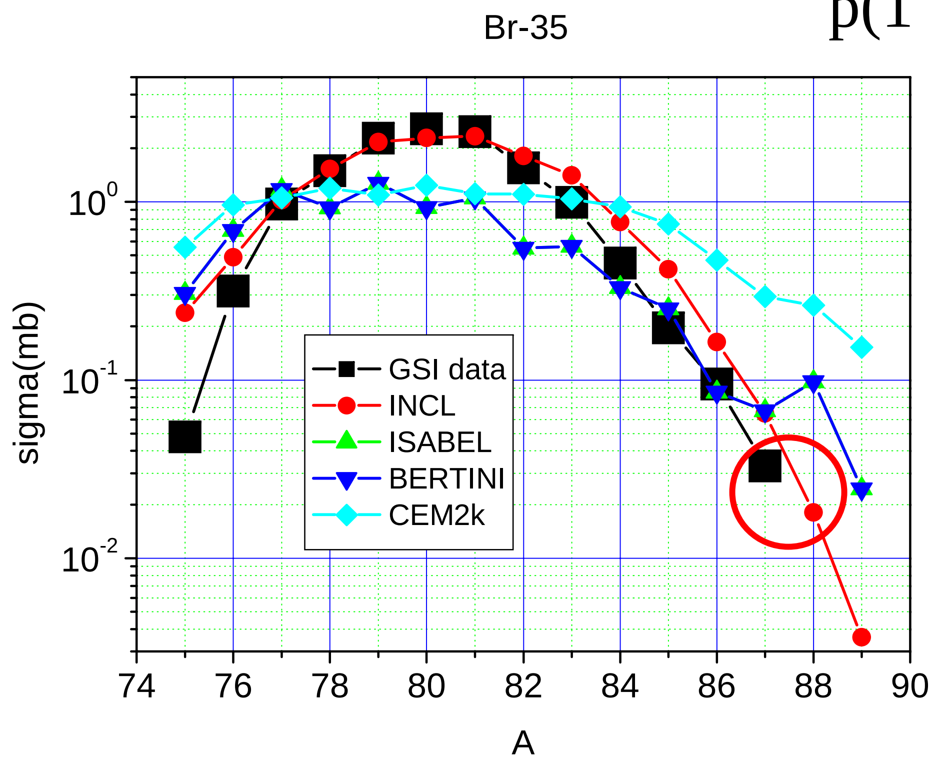
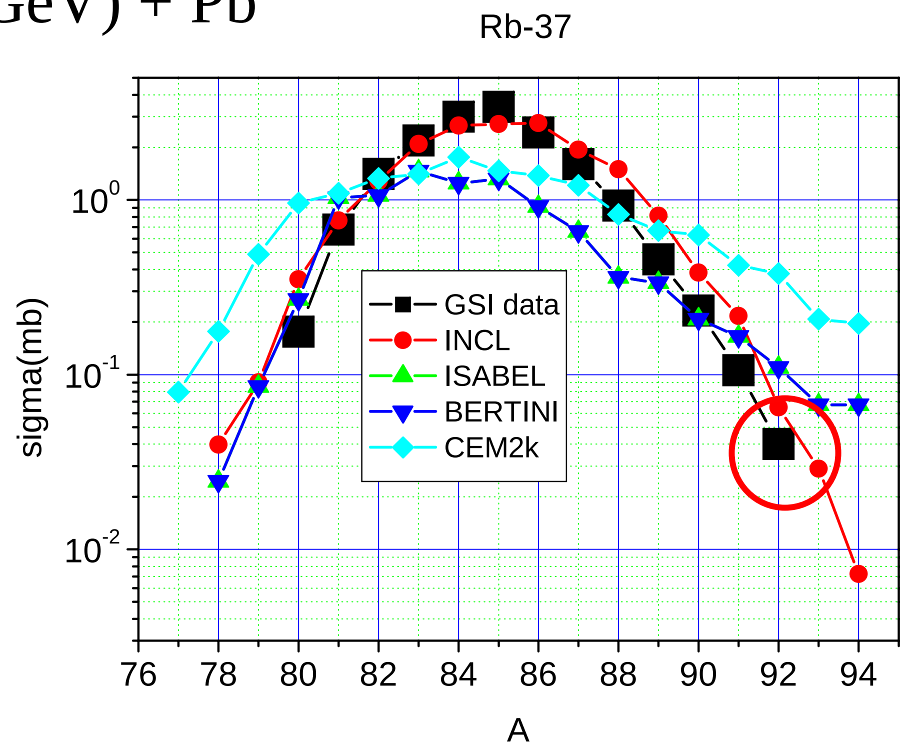
Model-dependence of $Y_{in}(A,Z)$ yields

p(1 GeV) + Pb



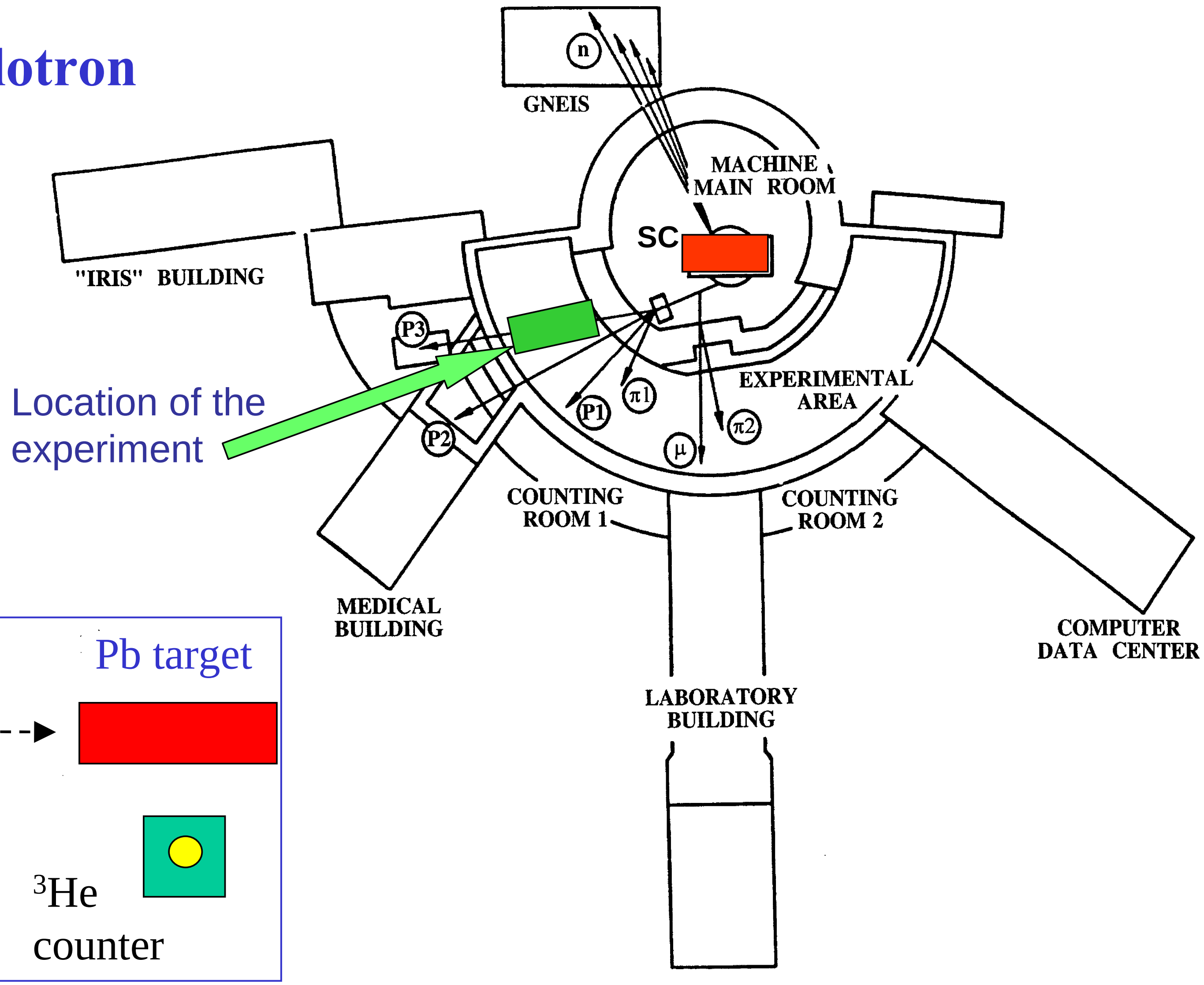


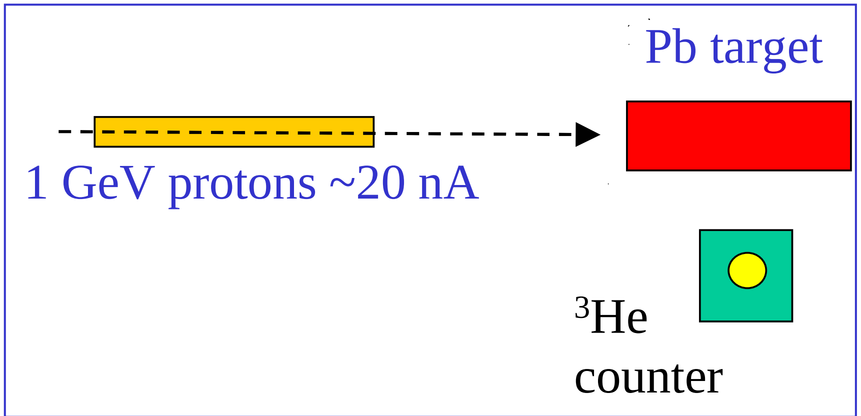
- INCL4-ABLA gives “reasonable” predictions
- other models overestimate significantly the neutron-rich side

1. **Fission yields on the very neutron-rich side are difficult to reach**
2. **No available data on DN yields from high energy fission-spallation**

DN measurements from p (1GeV)+Pb at PNPI Gatchina (Russia)

PNPI synchrocyclotron





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Experimental strategy

He-3 counter calibration:

^{252}Cf neutron source + Monte Carlo

Proton beam monitoring:

^{27}Al foils and gamma spectroscopy from ^{22}Na, ^{24}Na and ^{7}Be

Measurement strategy:

a) No target at all – long irradiations
b) Concrete block – long irradiation
c) Iron thick target – long irradiations

d) Lead target of variable thickness;
short (350 μs), intermediate (20 s) and long (300 s) irradiations

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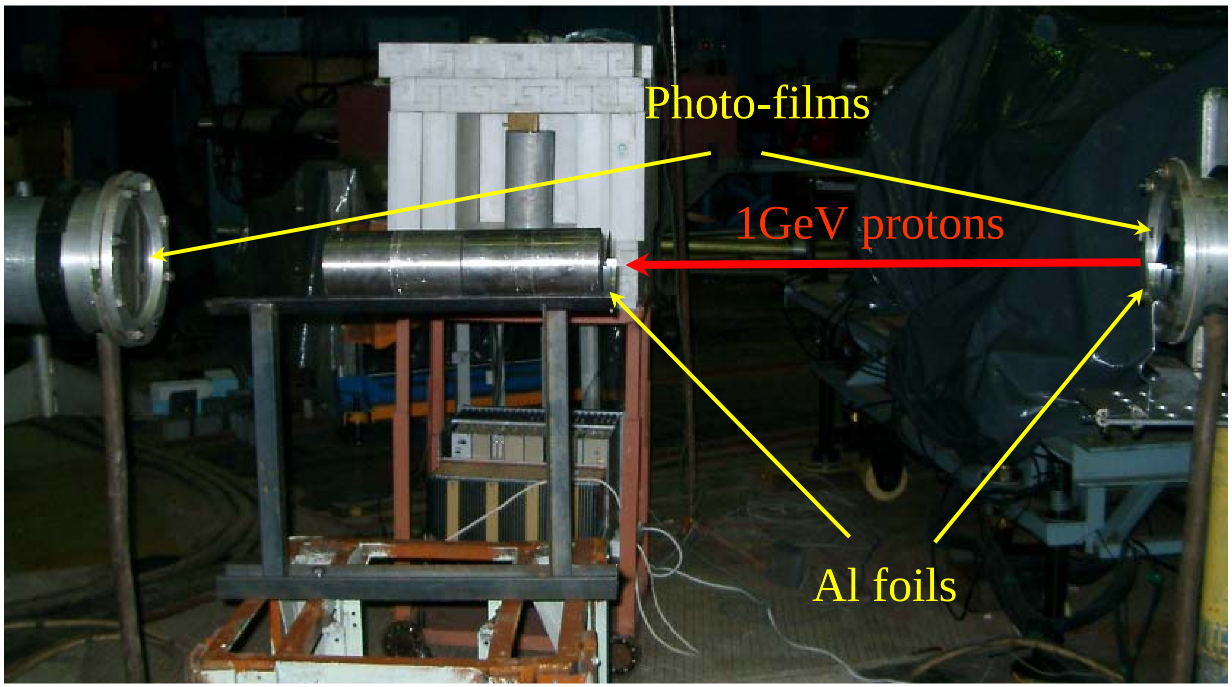
Proton beam monitoring

Beam size/profile: by photo-films at exit and entrance positions

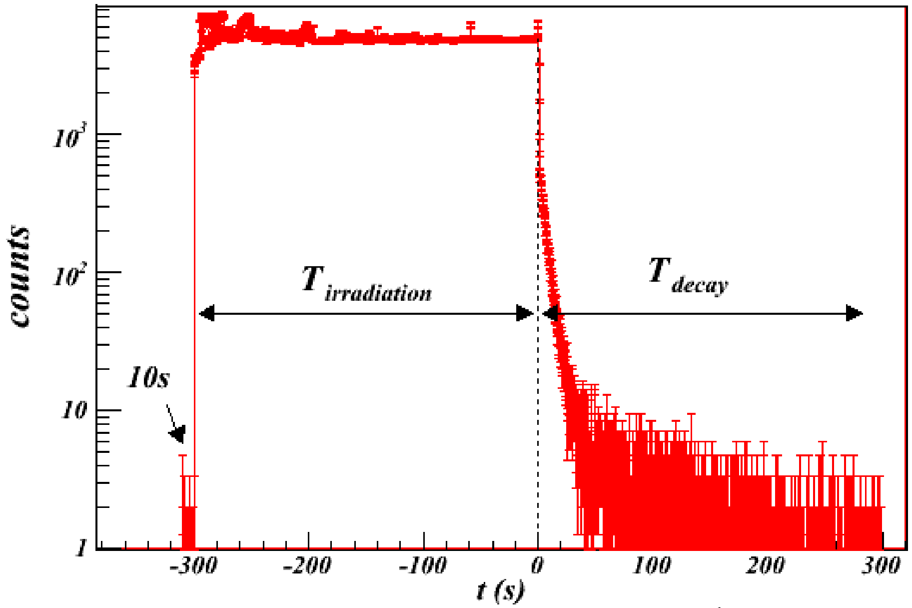
Beam intensity: by ^{27}Al foils and gamma spectroscopy from ^{22}Na, ^{24}Na and ^{7}Be

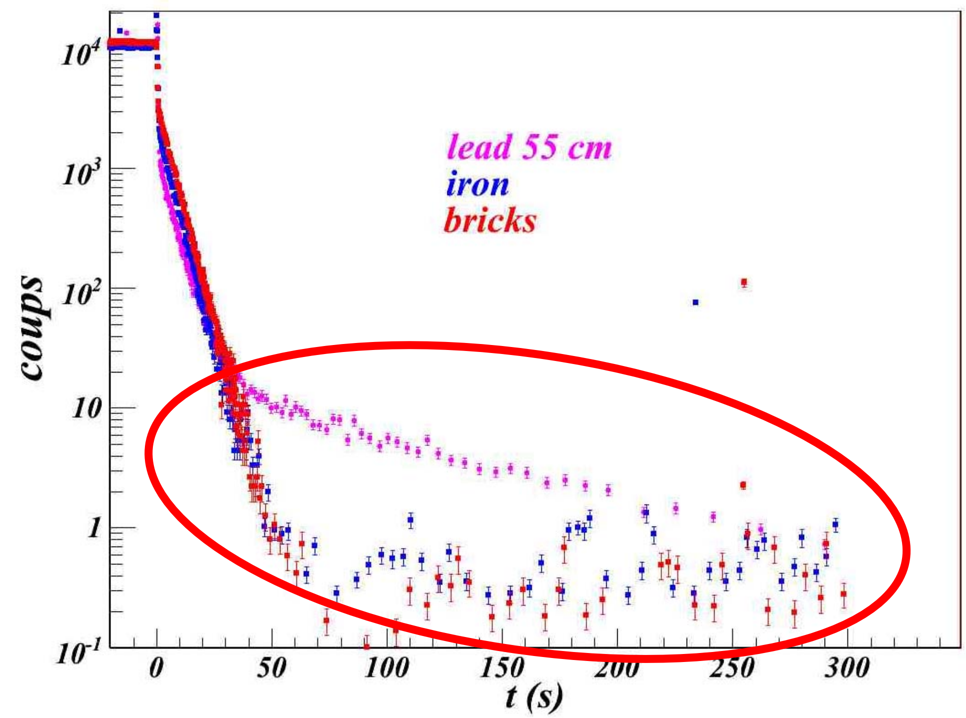


- $^{27}Al(p,x)^{7}Be$ monitor reaction cross section 7.5 ± 0.3 mb was taken as a reference
- ratios of ^{24}Na & ^{22}Na with respect to ^{7}Be were equal to 1.73 ± 0.15 & 1.99 ± 0.07

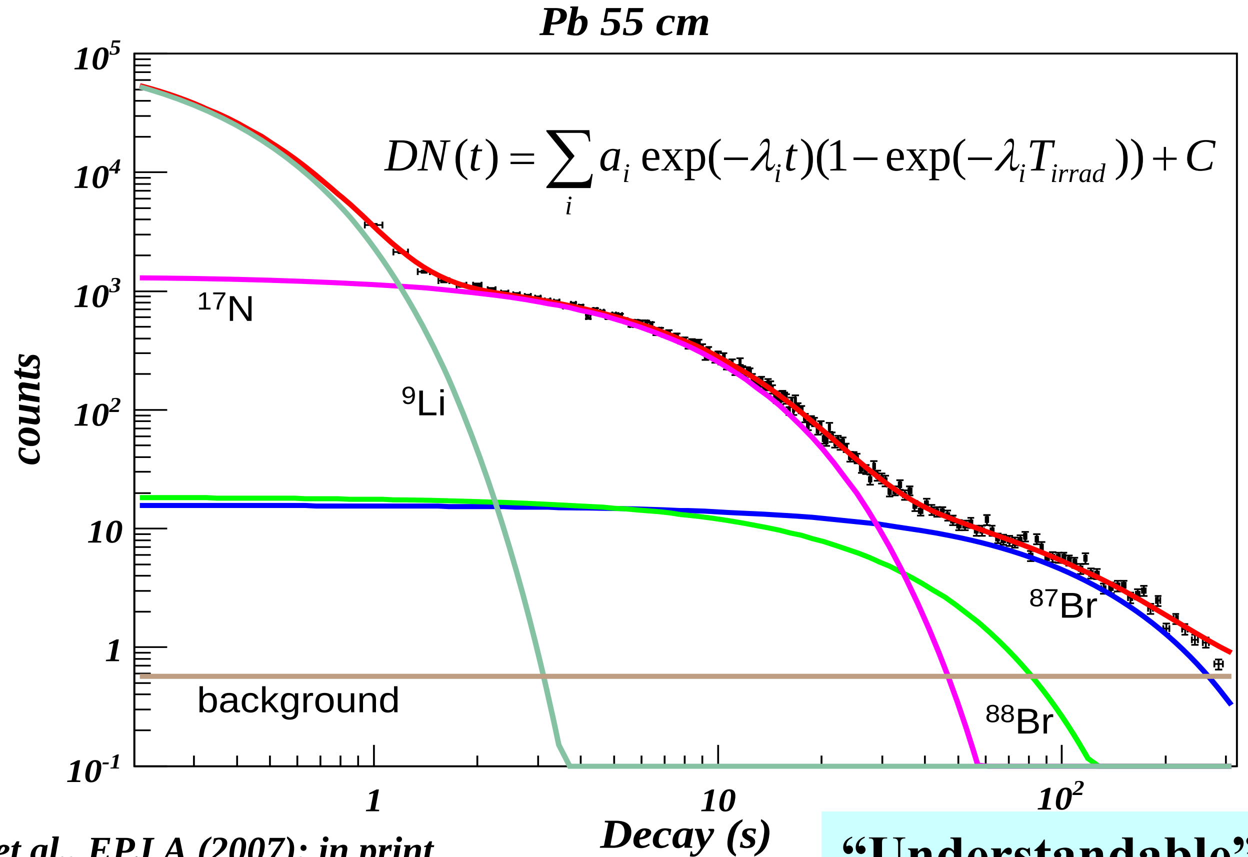
→ uncertainty in proton beam monitoring from 8 % to 12 %

Accumulated raw data





DN decay curve: p + ^{nat}Pb (55 cm)



D. Ridikas et al., EPJ A (2007); in print

Group	Half-life, s	Precursor	P_n (β-n), %
1	**55.60**	**^{87}Br**	2.52
2	**16.29**	**^{88}Br**	6.58
3	**4.173**	**^{17}N**	95.10
4	**0.178**	**^{9}Li**	50.80

“Understandable” from x-sections

- **p(1GeV)+Pb → ^{9}Li ~ 1000 μb**
- **p(1GeV)+Pb → ^{17}N ~ 600 μb**

- **p(1GeV) +Pb → ^{87}Br ~30 μb**

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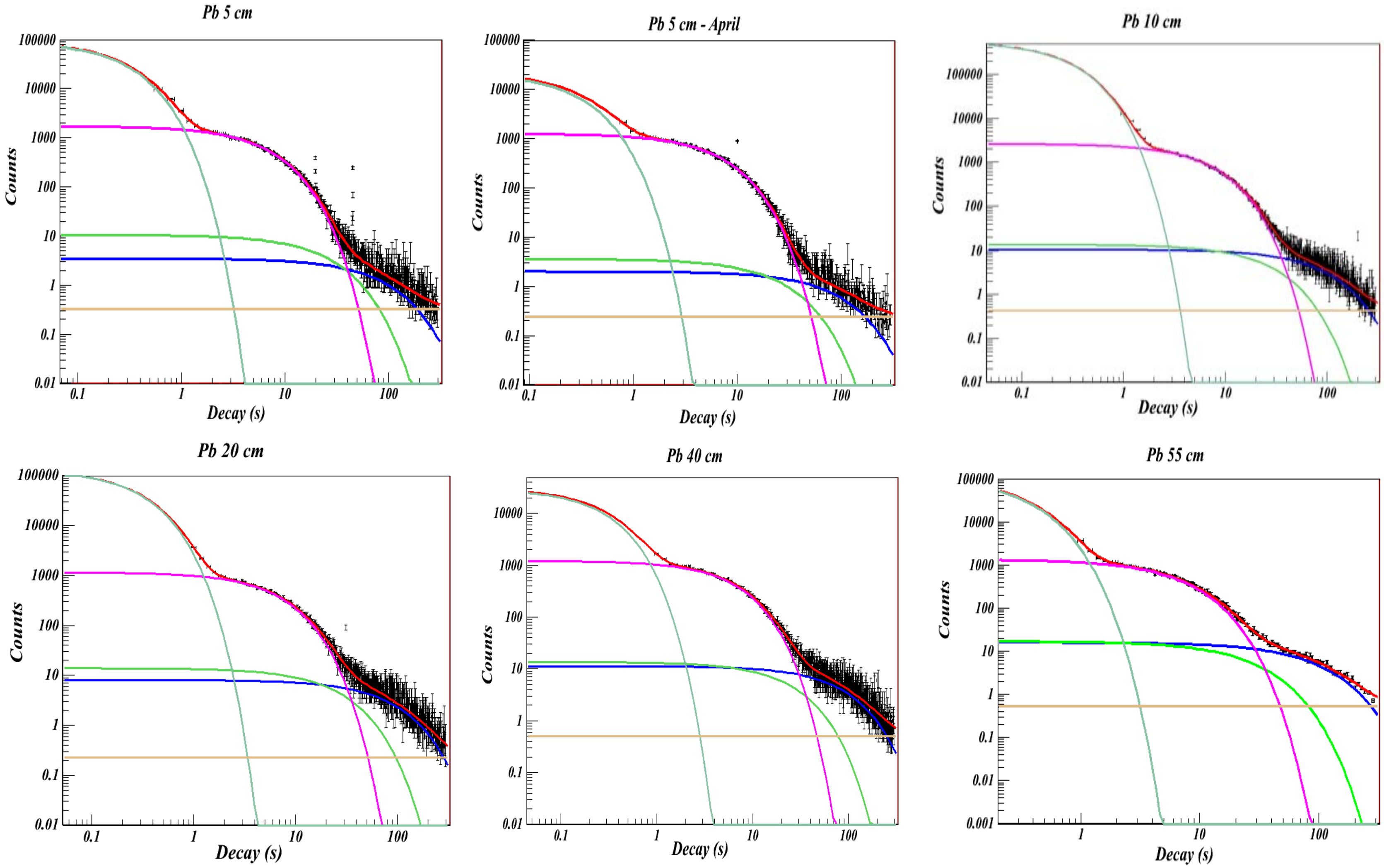
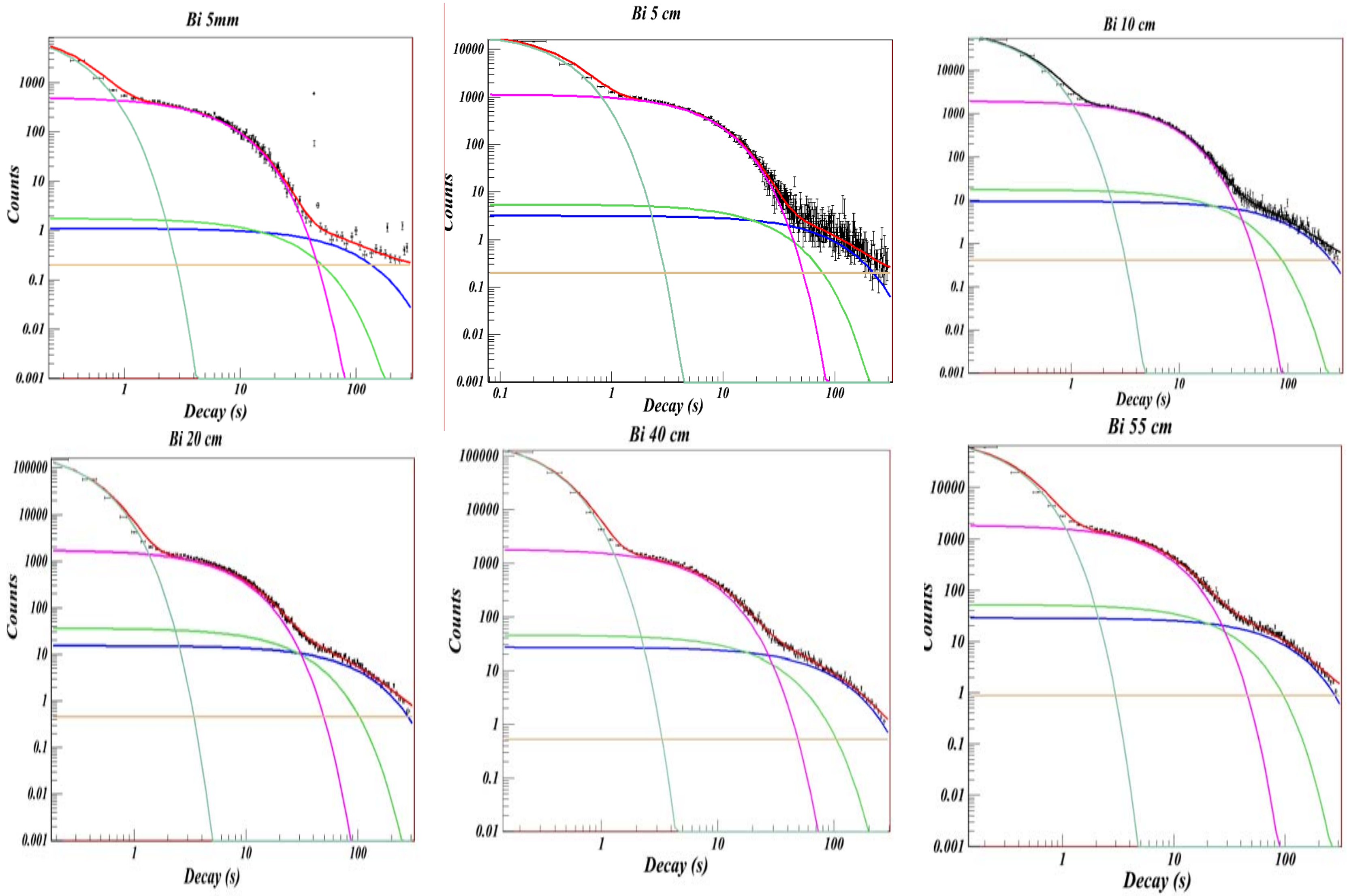
DN decay curves: p + ^{nat}Pb

- Reproduced with 4 major contributions : ^{9}Li, ^{17}N, ^{88}Br, and ^{87}Br

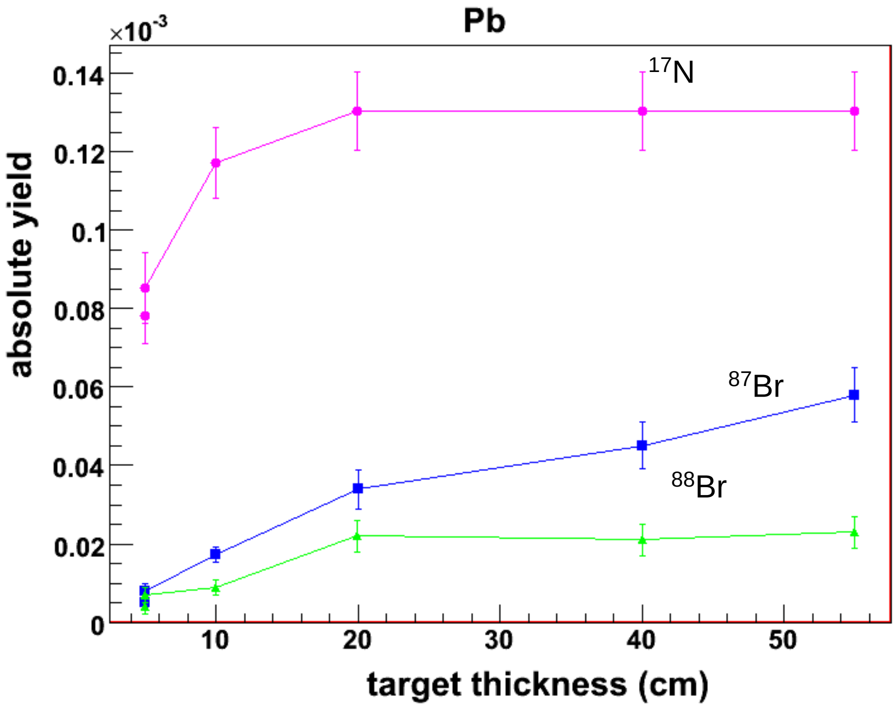


DN decay curves: p + ^{209}Bi

- The same 4 major contributions : ^{9}Li, ^{17}N, ^{88}Br, and ^{87}Br



Experimental precursor yields (atoms/proton)



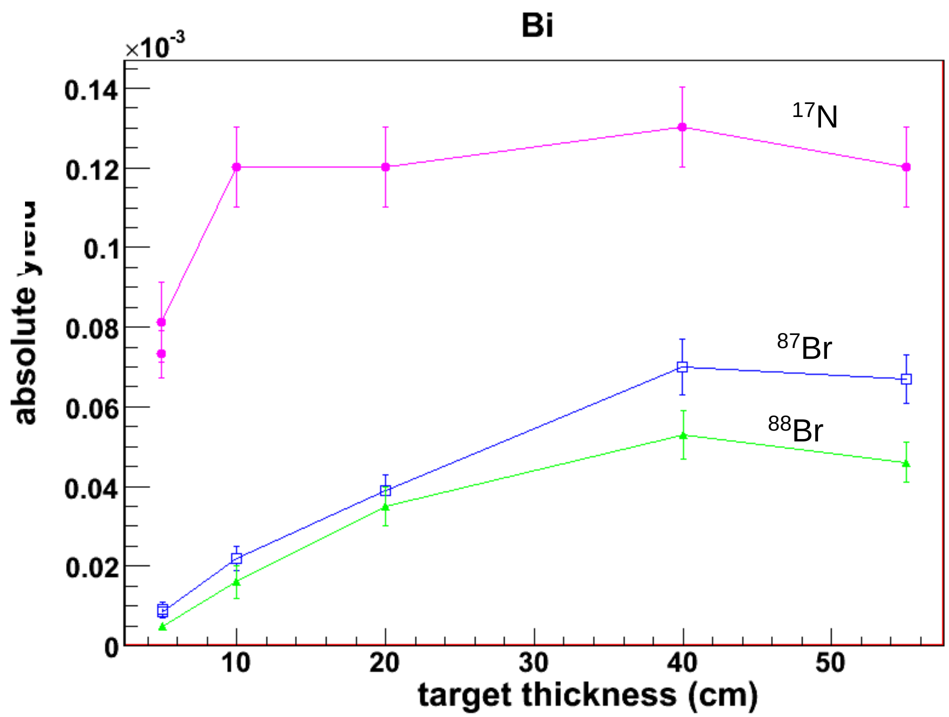
$$DN(t) = \sum_i a_i \exp(-\lambda_i t)(1-\exp(-\lambda_i T_{irrad})) + C$$

$$DN(t=0) = \sum_i a_i + C$$

$$P_n^i Y^i = a_i / (\varepsilon_{He-3} I_p \Delta t_{ch} N_{cycles})$$

- Saturation is observed for targets thicker than 20 cm

- Similar shapes and absolute values both for Pb and Bi



D. Ridikas et al., EPJ A (2007); in print

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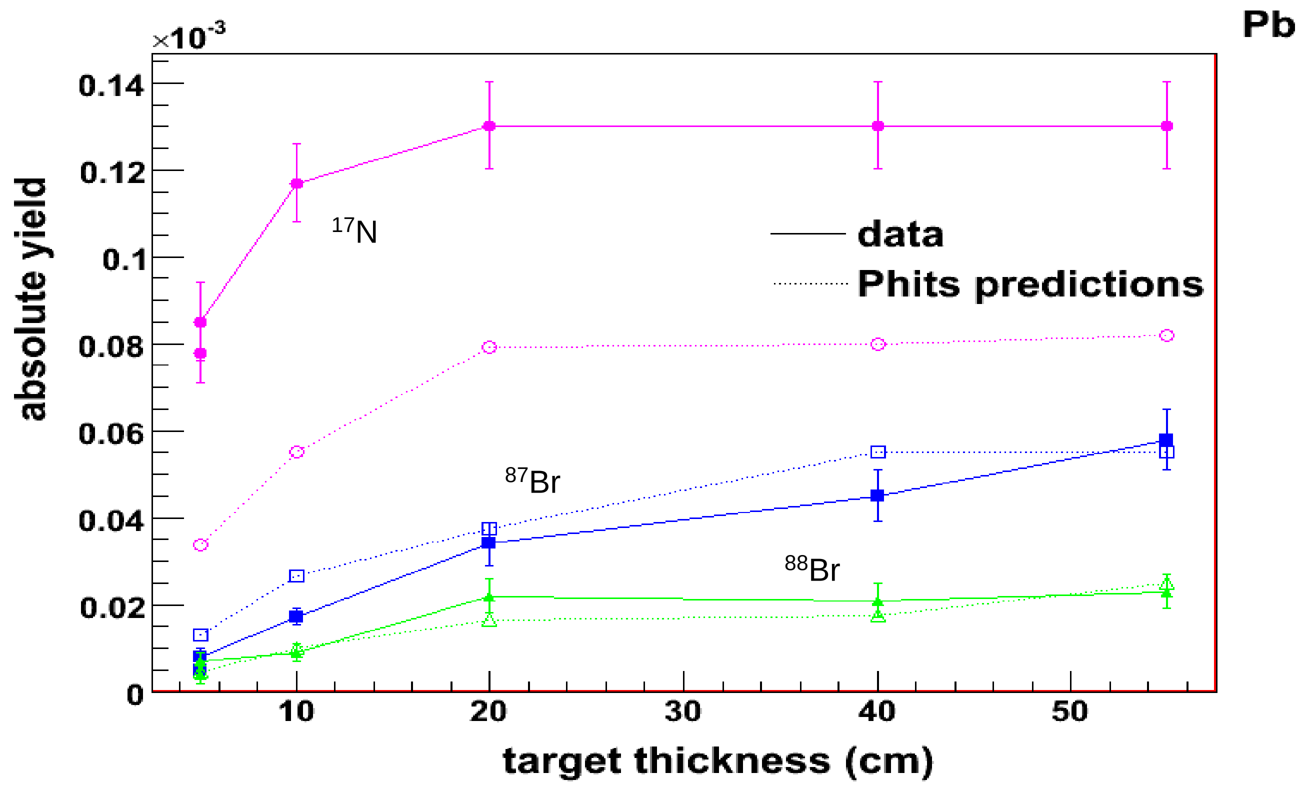
Precursor yields: data versus PHITS simulations



- INC (JAM) + EVAP(GEM)

JAM: Jet AA Microscopic Transport Model

GEM: Generalized Evaporation Model

H. Iwase, K. Niita, T. Nakamura, Journal of Nuclear Science & Technology 39 (2002) 1142.

→ Predictions within a factor of 2!

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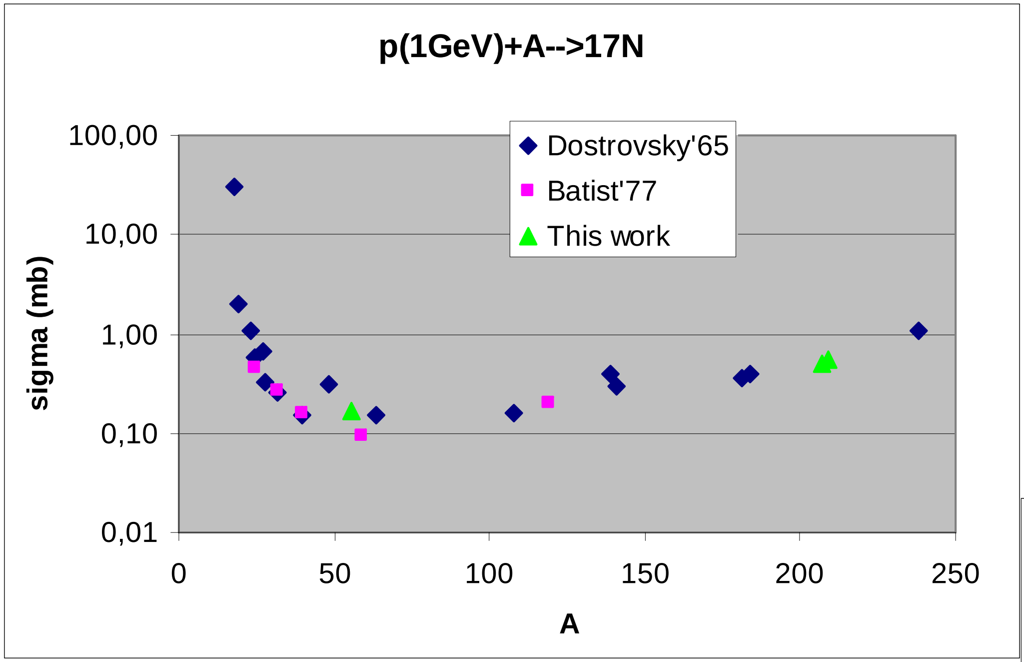
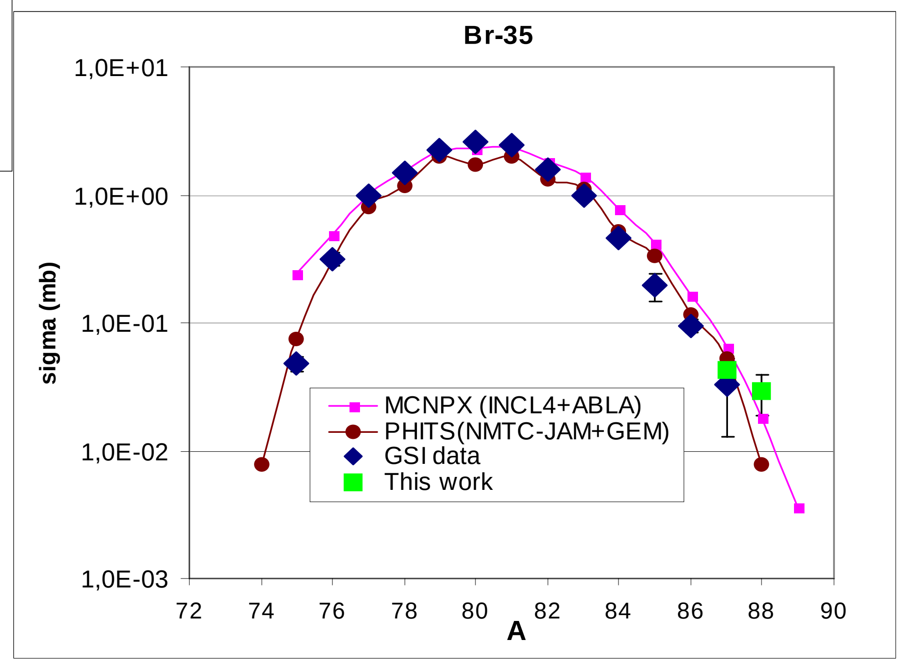
Extraction of x-sections : ^{17}N & ^{87,88}Br



Using thin targets



→ **Good agreement with old data and/or systematics!**

Conclusions and outlook

- importance of DNs in liquid metal targets for radioprotection issues
- importance of the measurements to test model calculations

- **DN yields and time spectra measured for the 1st time for p(1GeV) on thick ^{nat}Pb and Bi targets**
- **Estimates of errors on DN decay curves : below 20 %**
- **Major contributors are: ^{87}Br, ^{88}Br and ^{17}N → extraction of x-sections**
- **PHITS code "recommended" for such studies**

- Consequences and "in-situ" experiment…

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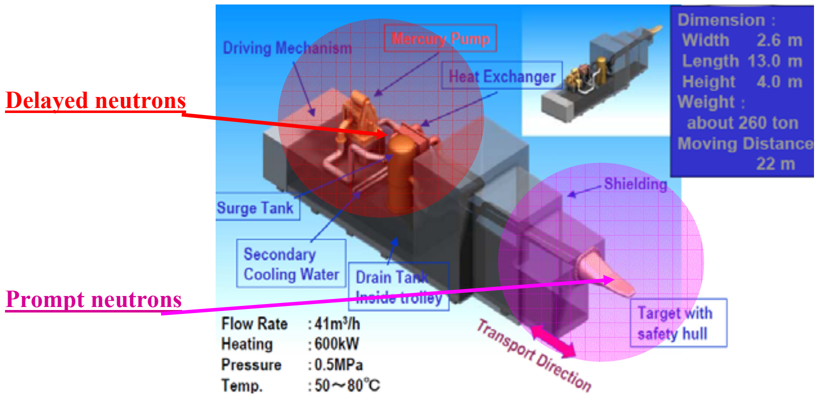
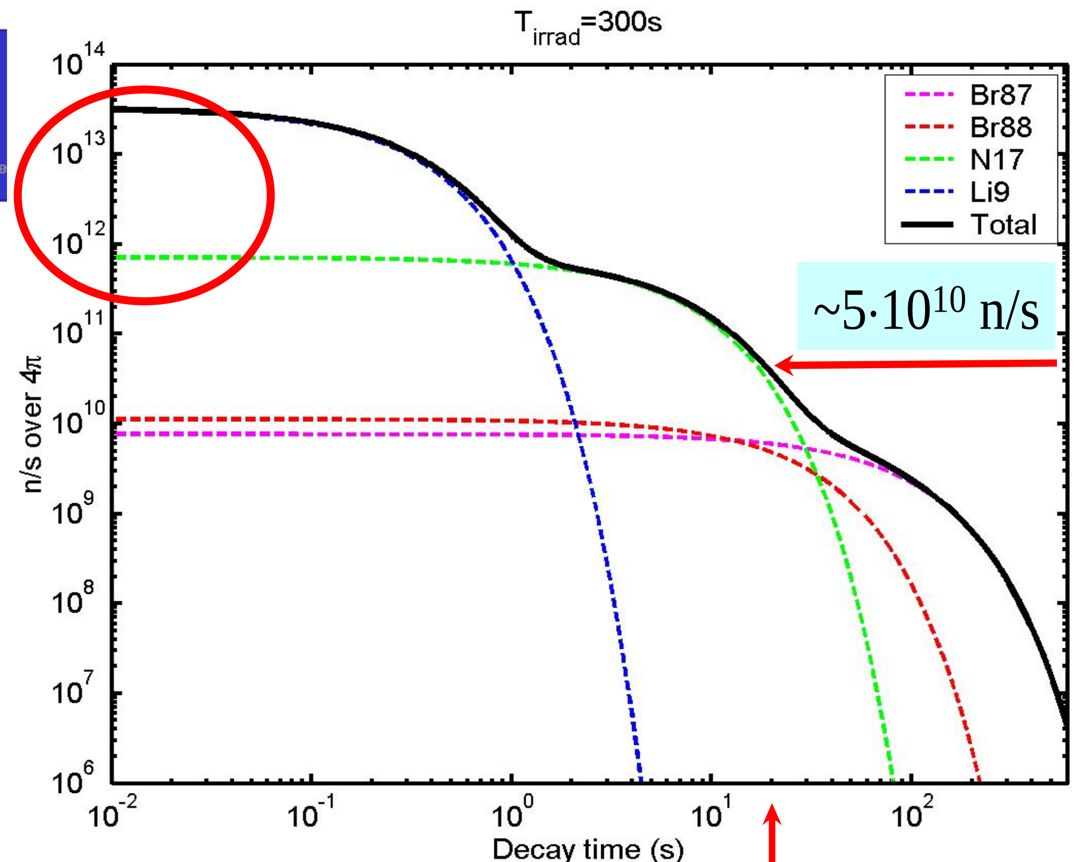
Absolute DN production yields: consequences

Assumption: p(1GeV) + Pb (55 cm thick; 10 cm ∅) at 1mA (1 MW)





~$5\cdot10^{10}$ n/s

~20 s after

Important data for:

- SNS based on liquid metal targets
- ToF facilities (DNs →background neutrons)

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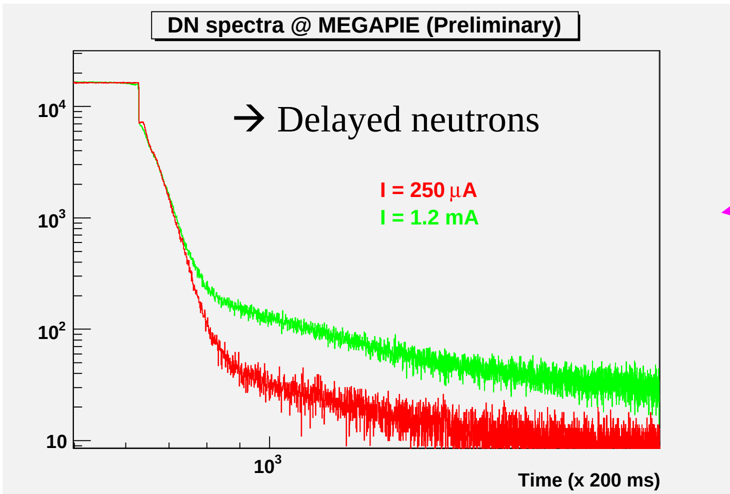
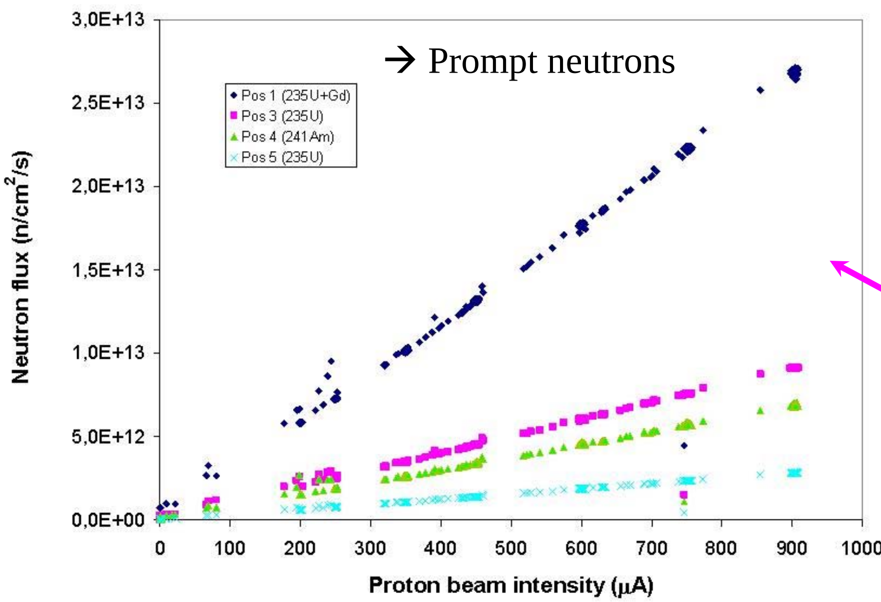
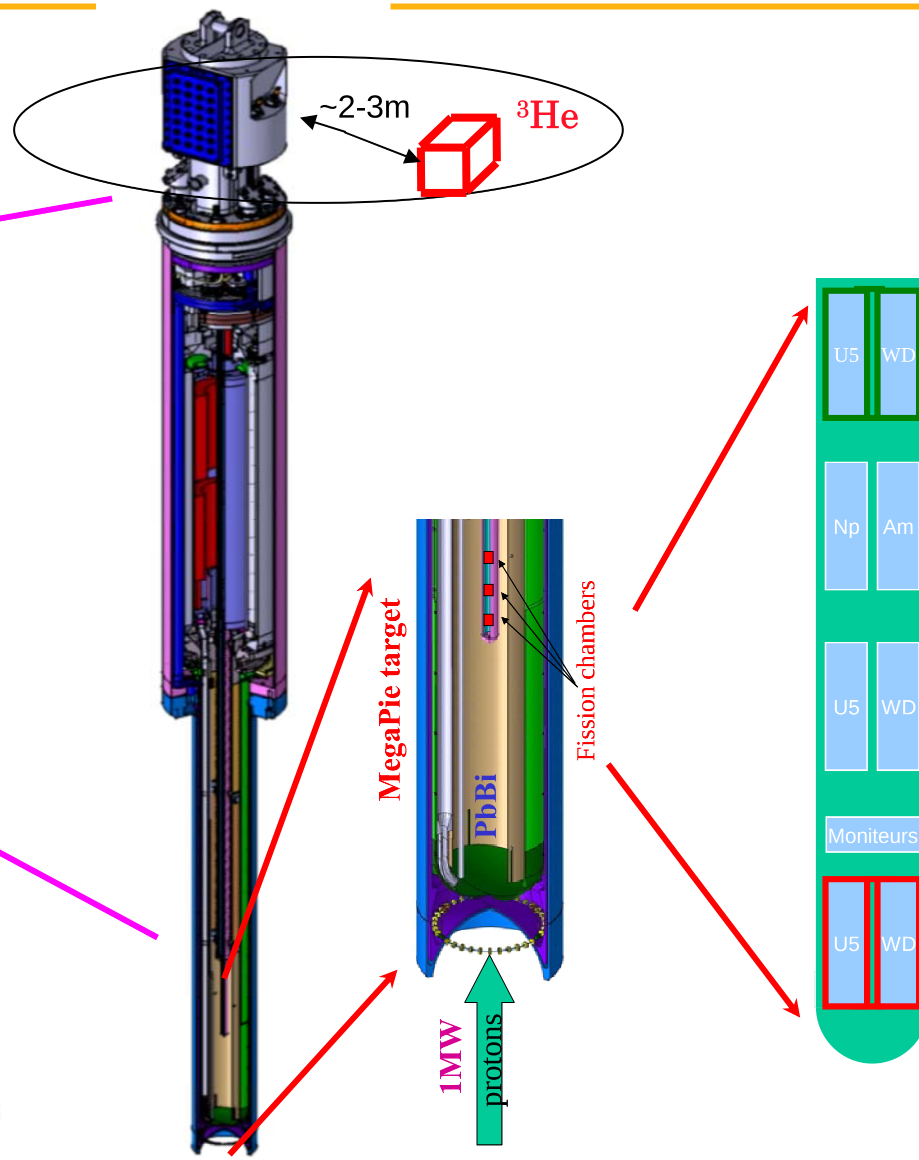
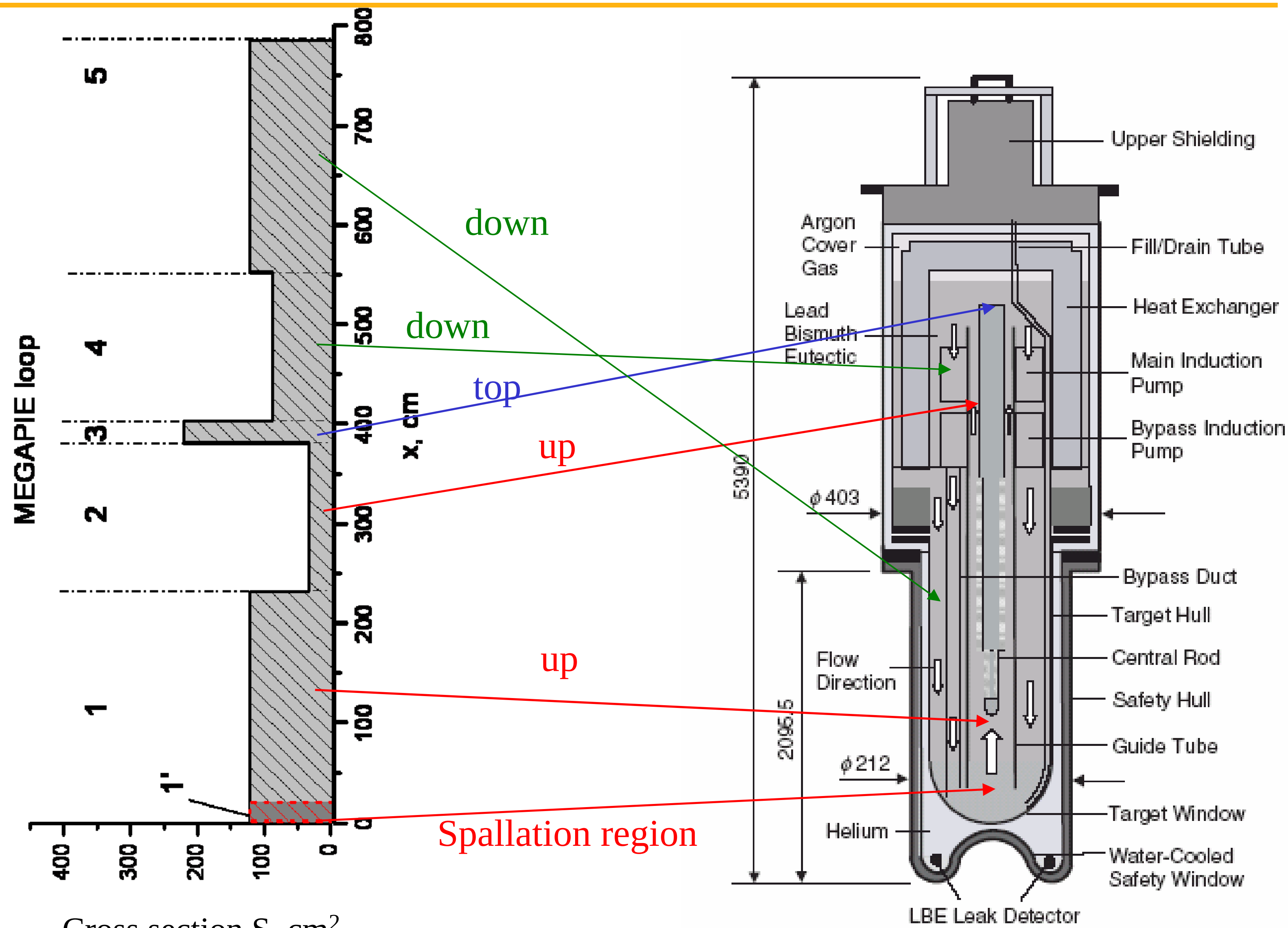
CEA/DSM/DAPNIA's contribution for MegaPie







MegaPie: geometrical model



MegaPie measurements ←→PNPI data

→ Use of parameters extracted from PNPI/Gatchina experiments

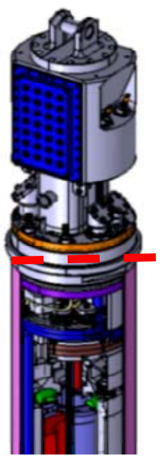
Estimates:

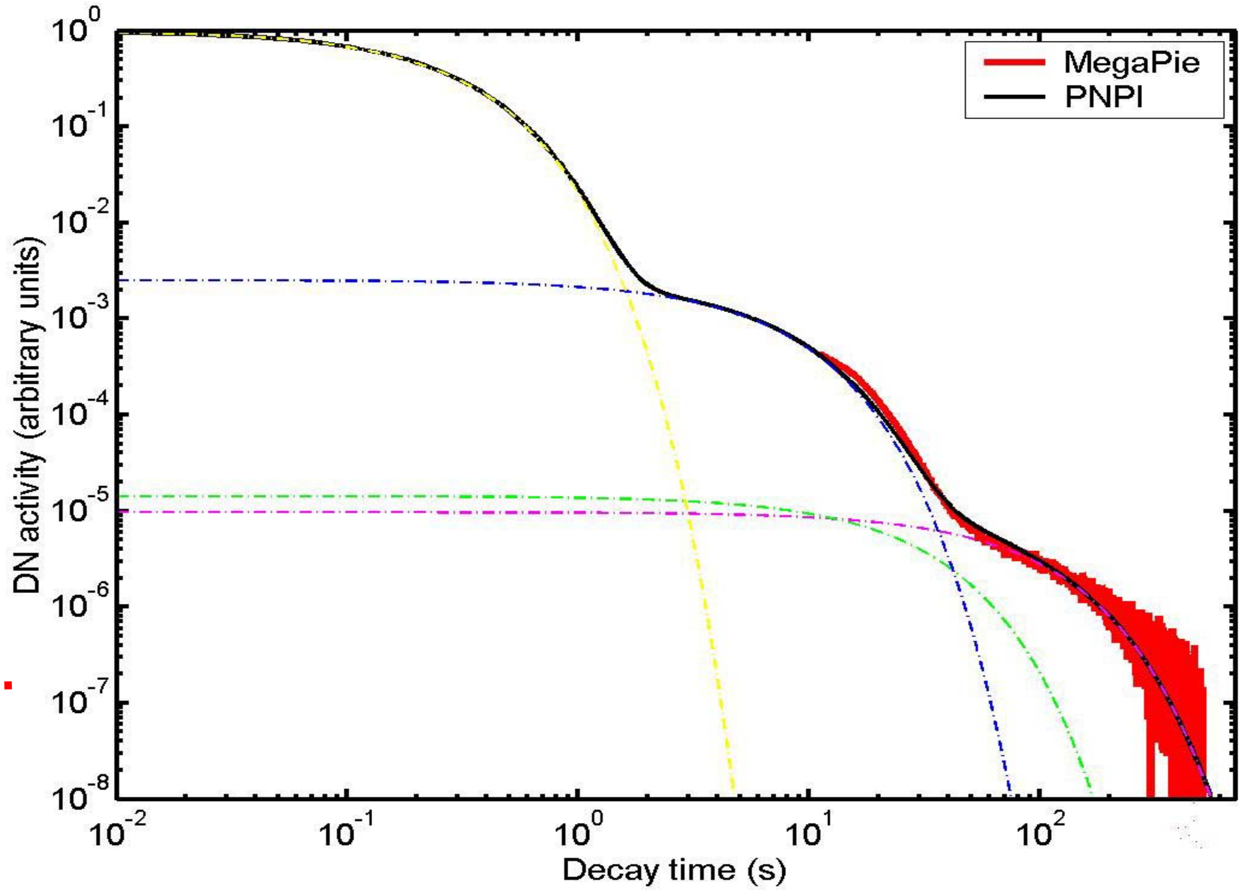
τ_a ~0.5 s irradiation

T ~20 s relaxation

τ_d ~10 s **heat exchanger**

$$a(x)=\sum_{i=1}^{n}a_i(x)=\sum_{i=1}^{n}a_i^a\frac{1-\exp(-\lambda_i\tau_a)}{1-\exp(-\lambda_i T)}\exp(-\lambda_i\tau_d(x))$$





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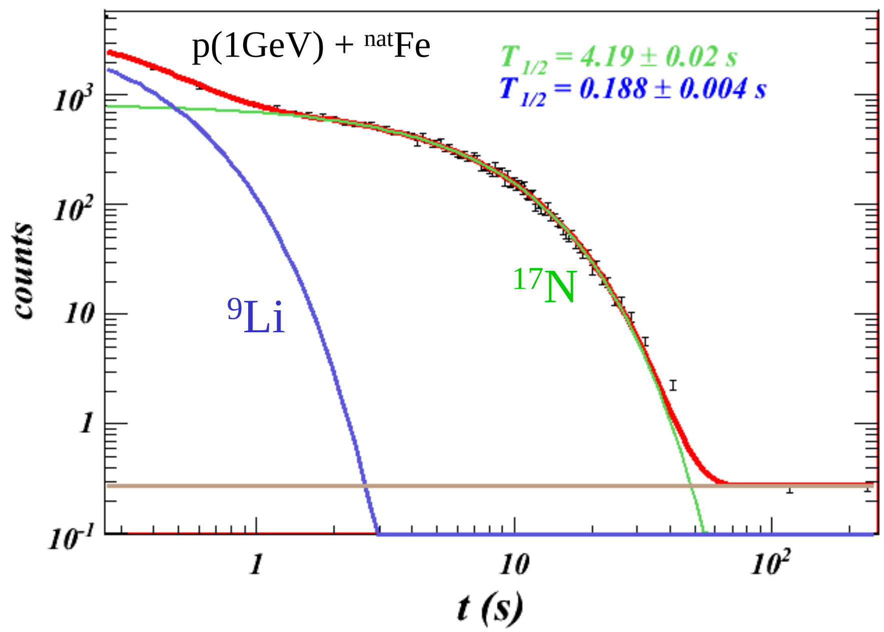
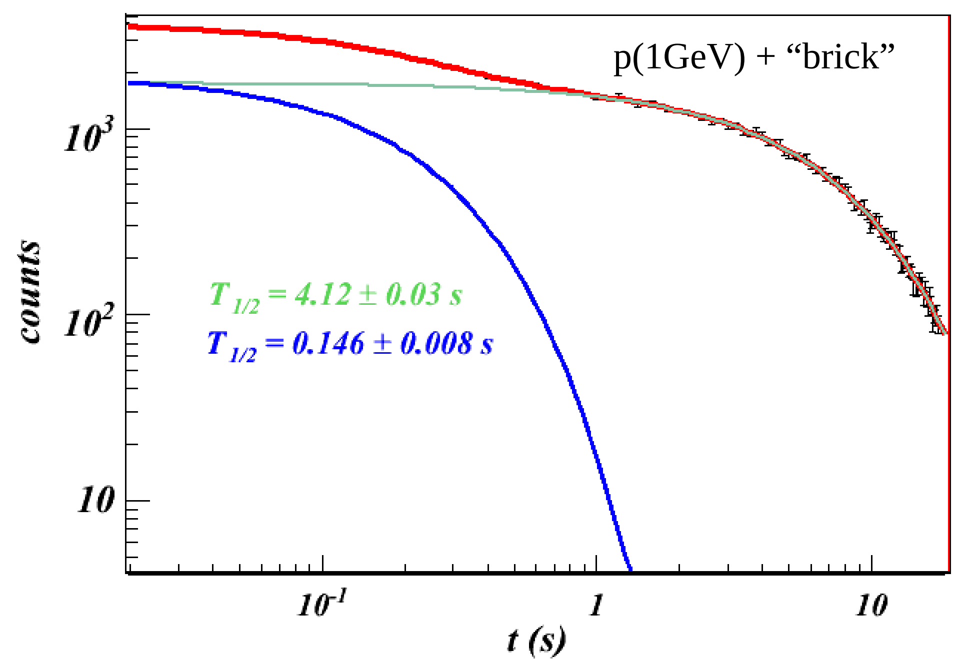
DN decay curves: Fe and "brick"



p + ^{nat}Fe → ^{9}Li, ^{17}N, …

p + "brick" → ^{9}Li, ^{17}N, …



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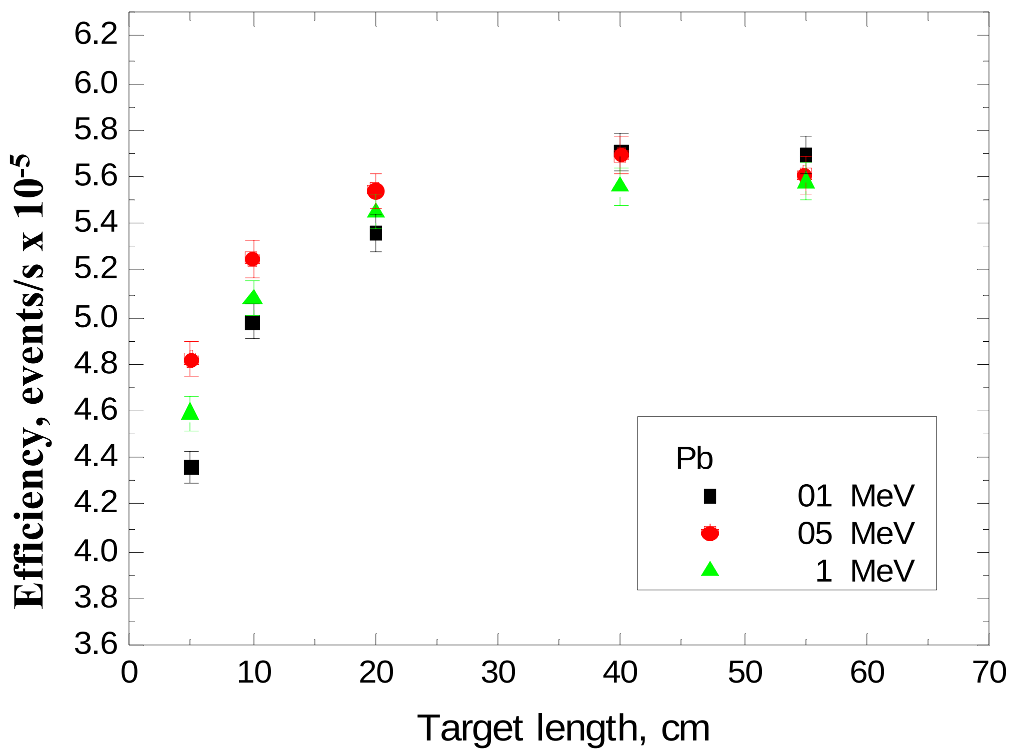
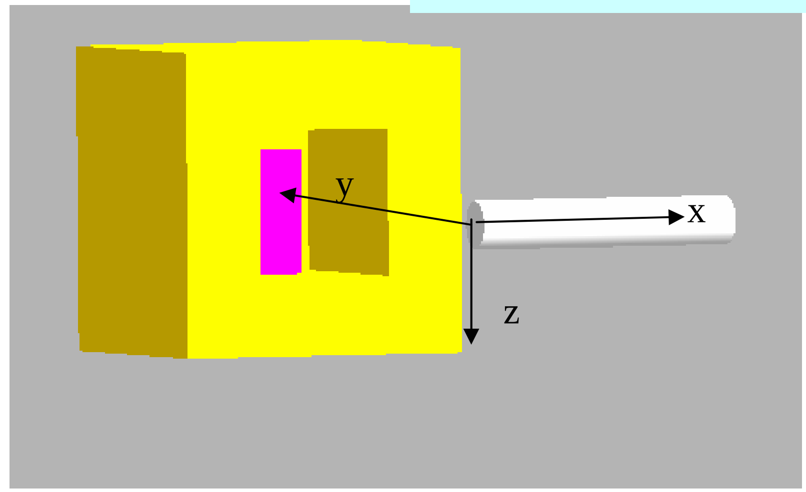
He-3 counter calibration

1. ^{252}Cf neutron source at y = 170cm and different x
→ modeling with MCNPX: agreement within 5-6 %

3D modeling with Monte Carlo





2. Use of Monte Carlo with
→ exact experimental conditions
→ variable target thickness
→ variable DN energy

→ estimated uncertainty below 10 %

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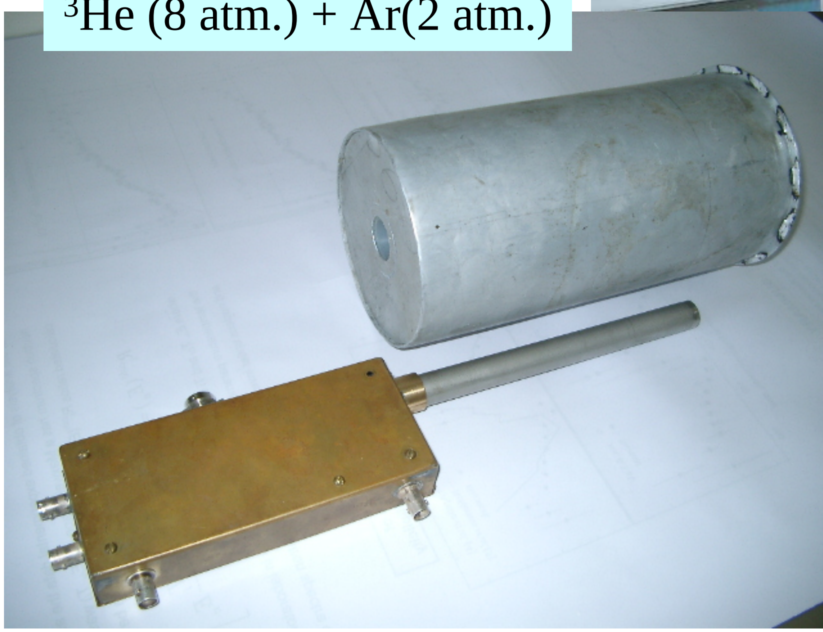
Photo of the experimental setup

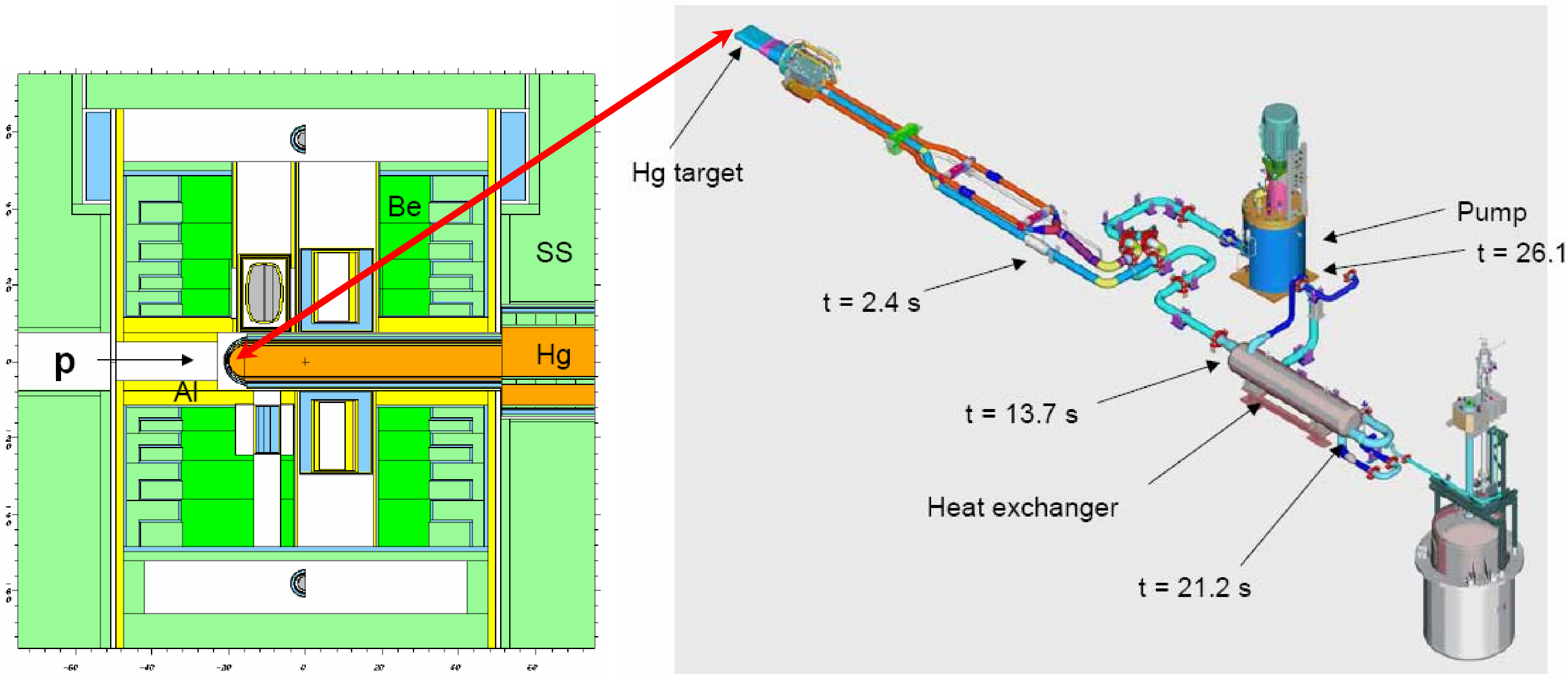
He-3 neutron counter
^3He (8 atm.) + Ar(2 atm.)



Example (A)

- SNS, J-PARC, EURISOL → liquid Hg
- MegaPie, ADS → liquid PbBi

SNS/ORNL - thanks to F. Gallmeier



Physics: ratios of relative yields relative to ^{87}Br

Experiment

Target thickness, cm	$a_2(^{88}Br)/a_1(^{87}Br)$	$a_3(^{17}N)/a_1(^{87}Br)$
5	1.7	354
10	1.4	235
20	1.3	118
40	1.3	102
55	1.4	90

stable decreasing

→ Produced by different reaction mechanisms

Target thickness, cm	$a_2(^{88}Br)/a_1(^{87}Br)$	$a_3(^{17}N)/a_1(^{87}Br)$	$a_4(^{9}Li)/a_1(^{87}Br)$
5	0.96	104	235
10	0.95	89	200
20	0.89	86	159
40	0.86	64	125
55	0.97	62	121

Confirmed by PHITS predictions

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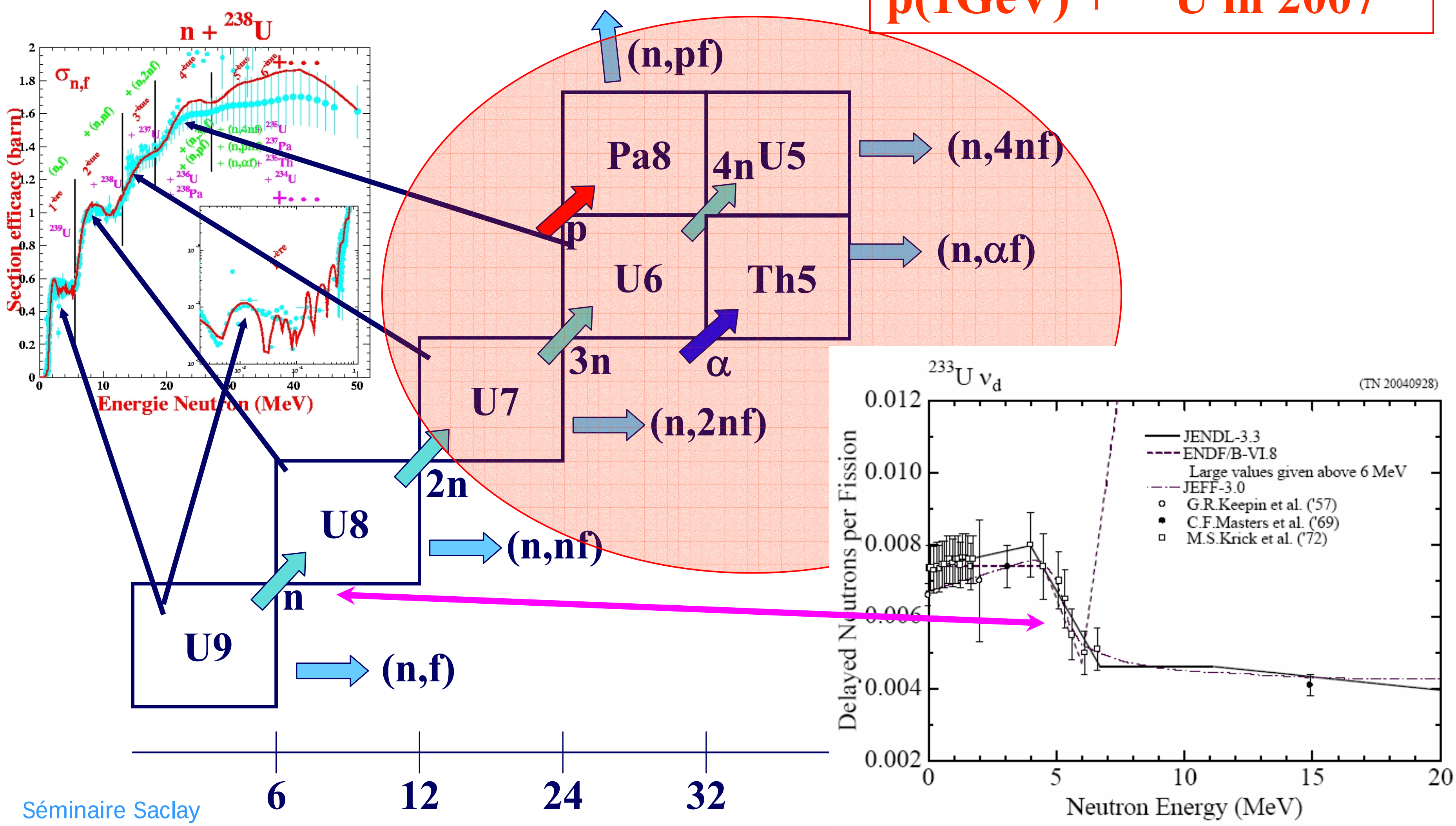
DN yield as a function of incident neutron energy

p(1GeV) + ^{238}U in 2007

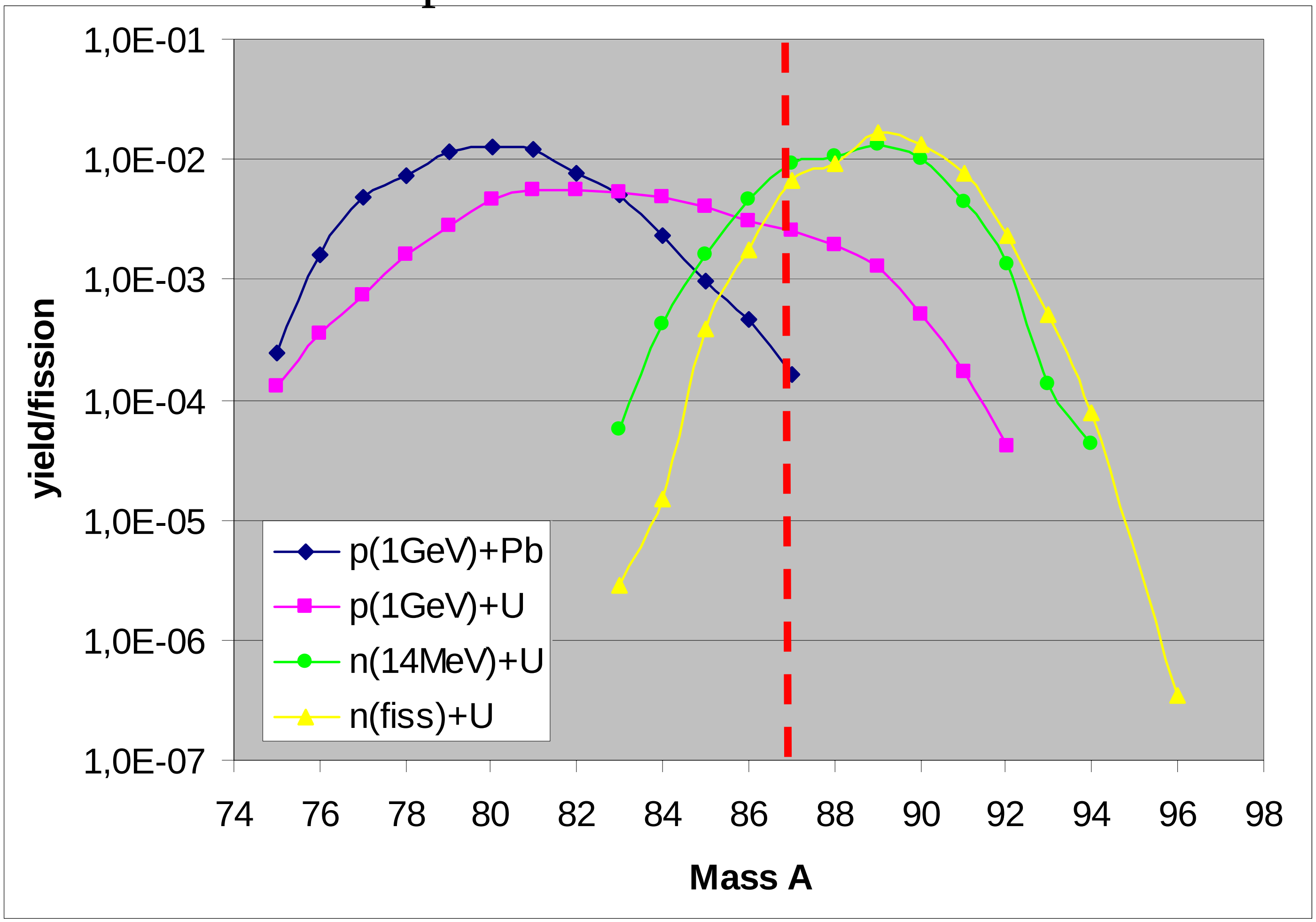


What is beyond 20 MeV?

Thanks to P. Romain et al. CEA/DIF/DPTA

Why only 4 exponentials are sufficient?

Production of Br isotopes



U fission ←→Pb fission; low energy ←→ high energy

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