The differential neutron-deuteron scattering cross section from 100 keV to 600 keV measured using a proportional counter

A.J.M. Plompen[1], J. Beyer[2], R. Nolte[3], S. Röttger[3]

[1] Institute for Reference Materials and Measurements, Geel, Belgium

[2] Technical University Braunschweig, Braunschweig, Germany

[3] Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

Overview

- Motivation: Why is n-d scattering still of interest?
- Experimental and evaluated data
- Detour: Experiment at higher energies at nELBE
- The recoil proton prop. counter P2 of PTB
- MC modelling of the P2 reponse
- Measurements
- Results and future work

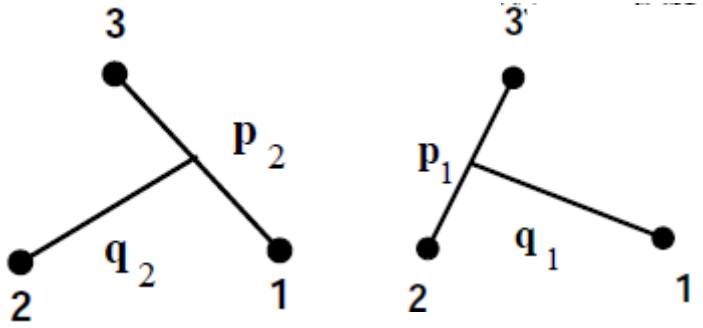
⇒ Remind: Work in progress!

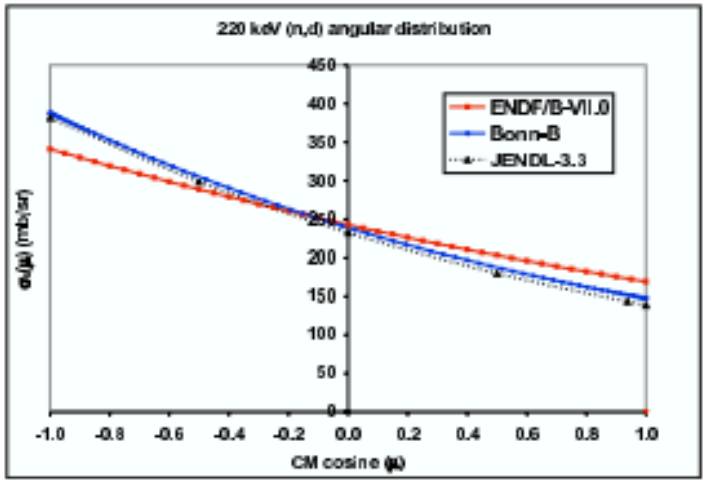
Motivation

Quantum-mechanical *N*-body problems:

- ***N* = 2: n-p scattering**
- ***N* = 3: n-d scattering**
- **Three-body problem described by Fadeev equations**
- **Nucleon-nucleon potentials required as input**

⇒Advanced theory makes precise predictions of cross sections and spin observables



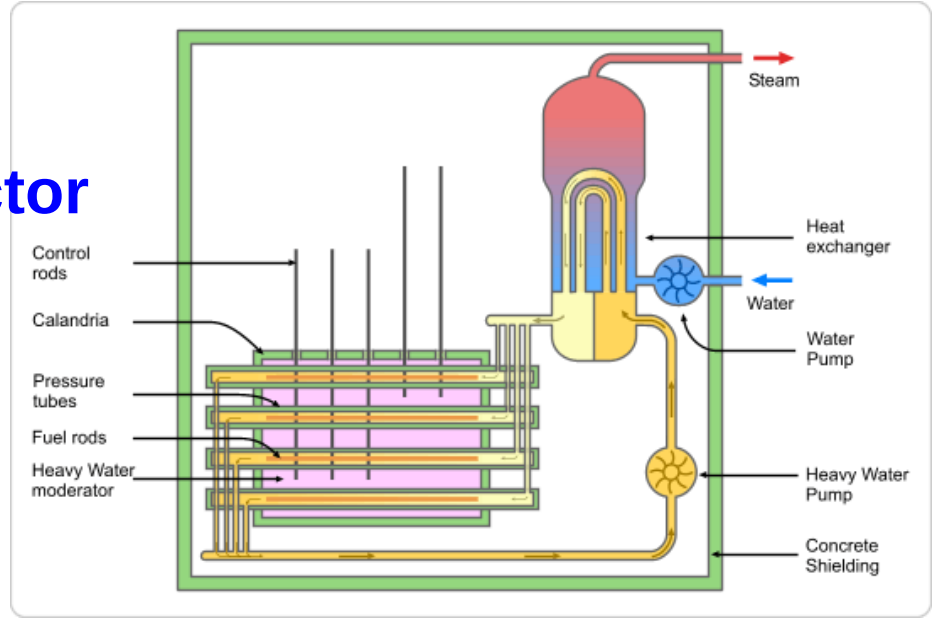


Ref. : J.P. Svenne *et al*., Proc. ND2007, 07208

Importance for Nuclear Technology

CANDU reactor:

- **D_2O moderated and cooled reactor**
- **28 operating units worldwide**
- **GenIII+: Advanced CANDU**



Heavy-water solution benchmark:

- **LANL HEU/D_2O experiment**
- **AECL coolant void reactivity critical experiment (NU/D_2O)**
- **Replacement of ENDF/B-VI.3 by ENDF/B-VII.1:**

  Calculated k_{eff} shows sensitivity to DX of D(n,n)D

Experimental Data: 100 keV – 2 MeV

Narrow Energy (optional), eV: Min: ☐ 100000.0 Max: ☐ 2000000.0

☐ Apply » Data re-normalization (for advanced users, results in: C4, TAB and Plots)

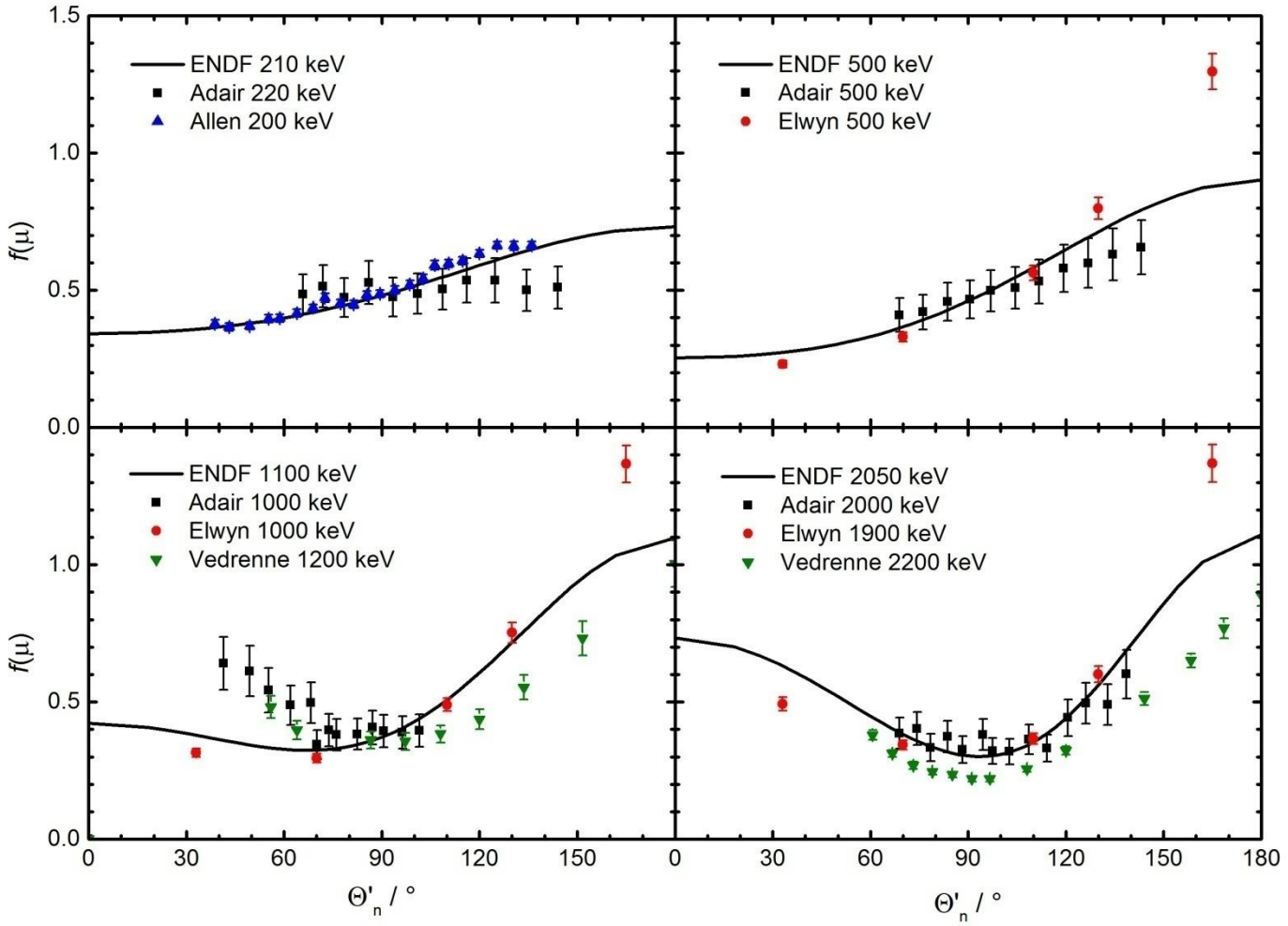
n	Display	Year	Author-1	Energy range,eV		Points
1)	1-H-2(N,EL)1-H-2,,DA C4: MF4 MT2					
	Quantity: [DA] Differential c/s with respect to angle					
1 ☐	Info X4+ X4± T4	1966	G.Vedrenne	1.20e6	1.42e7	98
2 ☐	Info X4+ X4± T4	1962	A.J.Elwyn+	5.00e5	1.95e6	15
3 ☐	Info X4+ X4± T4	1953	R.K.Adair+	2.20e5	2.50e6	88
2)	1-H-2(N,EL)1-H-2,,DA,,LEG C4: MF154 MT2					
	Quantity: [DA] Legendre coef. d/dA=a(0)+Sum(a(L)*P(L))					
4 ☐	Info X4+ X4± T4	1966	G.Vedrenne	1.20e6	1.42e7	35
3)	1-H-2(N,EL)1-H-2,,DA,D C4: MF=4 MT=?					
	Quantity: [DA] Angular distribution of particle specified					
5 ☐	Info X4+ X4± T4	1955	W.D.Allen+	1.00e5	2.00e5	44

Detection method:

- **Recoil deuteron: Tunnicliffe 1953, Adair 1955, Allen 1955**
- **Scattered neutron: Elwyn 1962, Vedrenne 1966**

… Is this list complete ??

Experimental Data: Overview



ENDF: ENDF/B-VII.0

OECD/NEA HPRL

Data Bank > Nuclear Data Services

NEA Nuclear Data High Priority Request List, HPRL

HPRL-Main Search New request template New request guidelines Related references

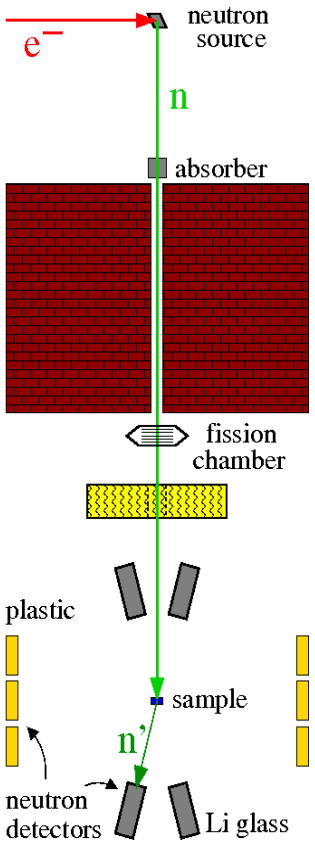
Request ID	8		Status of the request	High Priority request	
Target	Reaction and process	Incident Energy	Secondary energy or angle	Target uncertainty	Covariance
1-H-2	(n,ela) dA/dE	0.1 MeV-1 MeV	0-180 Deg	5	Y
Field	Subfield	Date Request created	Date Request accepted	Ongoing action	
Fission	Heavy Water Reactors	25-JUL-06	16-APR-07		

⇒ **two ERINDA proposals by A.J.M. Plompen *et al.*:**

Measurement of D(n,n)D angular distribution

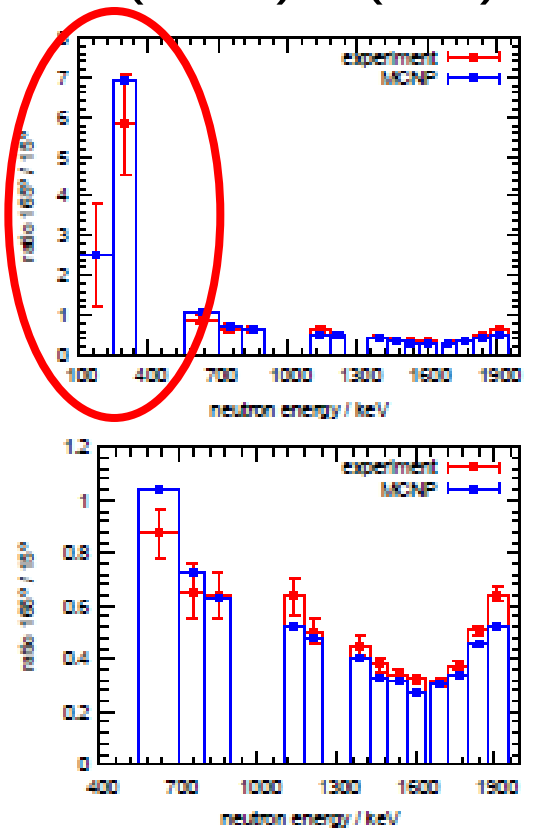
- **nELBE: neutron detection using LiGlas detectors**
- **PTB: deuteron detection in a proportional counter**

Detour: The experiment at nELBE



- ^{6}Li-glass detectors
  51 mm Ø x 12.7 mm thick
- CD_2 target supplied by AECL
- Ratio 15°/165° measured
- Corrections for multiple scattering and background calculated using MCNP

N(165°)/*N*(15°)



Ref: *N. Nankov et al., 'The angular distribution of neutrons scattered from deutrium below 2 MeV'*, Proceedings of the conference ND2013 , PR80

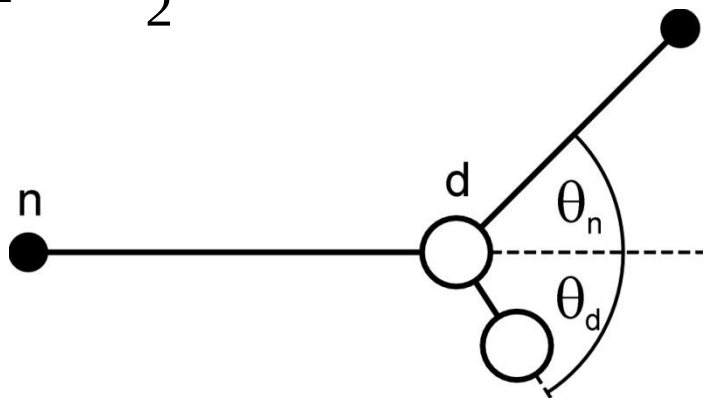
Recoil Detection

Elastic scattering of neutrons:

$$E_{\mathrm{rec}} = E_{\mathrm{n}} \frac{4A}{(A+1)^2} \cos^2 \Theta_{\mathrm{rec}}^{\mathrm{LAB}} = E_{\mathrm{n}} \frac{4A}{(A+1)^2} \frac{1+\cos \Theta_{\mathrm{rec}}^{\mathrm{CM}}}{2}$$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_{\mathrm{rec}}} = \frac{1}{\Phi} \frac{\mathrm{d}N}{\mathrm{d}E_{\mathrm{rec}}} = \frac{1}{\Phi} \frac{\mathrm{d}N}{\mathrm{d}\Omega_{\mathrm{rec}}^{\mathrm{CM}}} \frac{2\pi \,\mathrm{d}\cos \Theta_{\mathrm{rec}}^{\mathrm{CM}}}{\mathrm{d}E_{\mathrm{rec}}}$$

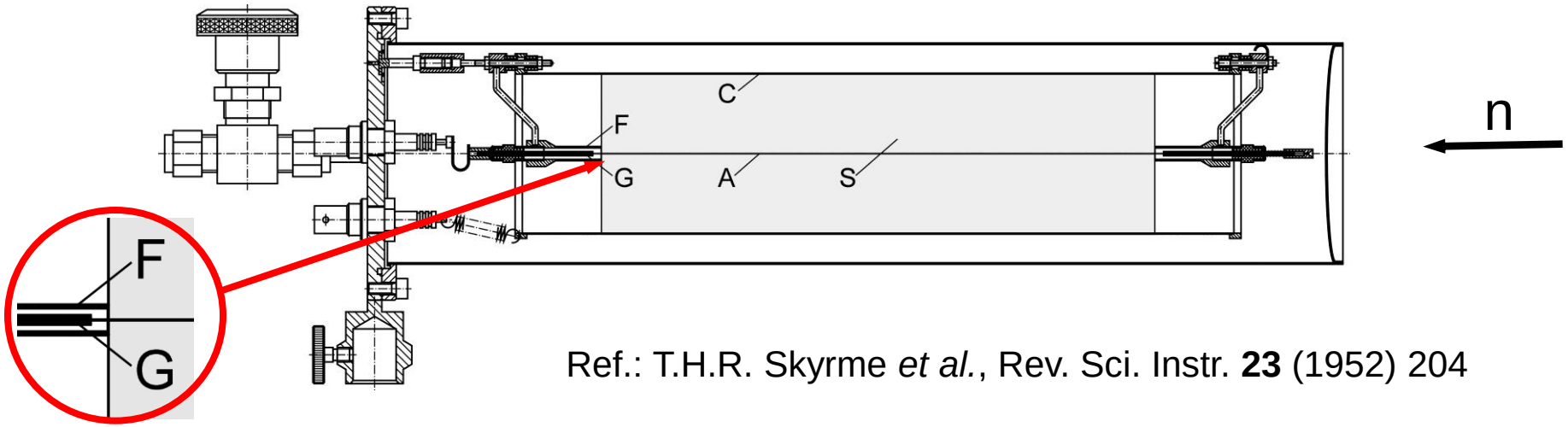
$$\Rightarrow \frac{\mathrm{d}\sigma}{\mathrm{d}E_{\mathrm{rec}}} = \frac{4\pi}{E_{\mathrm{n}}} \frac{(A+1)^2}{4A} \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega^{\mathrm{CM}}} \right) (E_{\mathrm{rec}})$$



Ideal recoil detectors yield the angular distribution, but:

- incomplete energy deposition: wall effects
- conversion of deposited energy to detected signal: light yield, *W*-value
- non-linearity of the detection process: gas amplification
- competing reactions: n-^{12}C scattering
- photon interactions

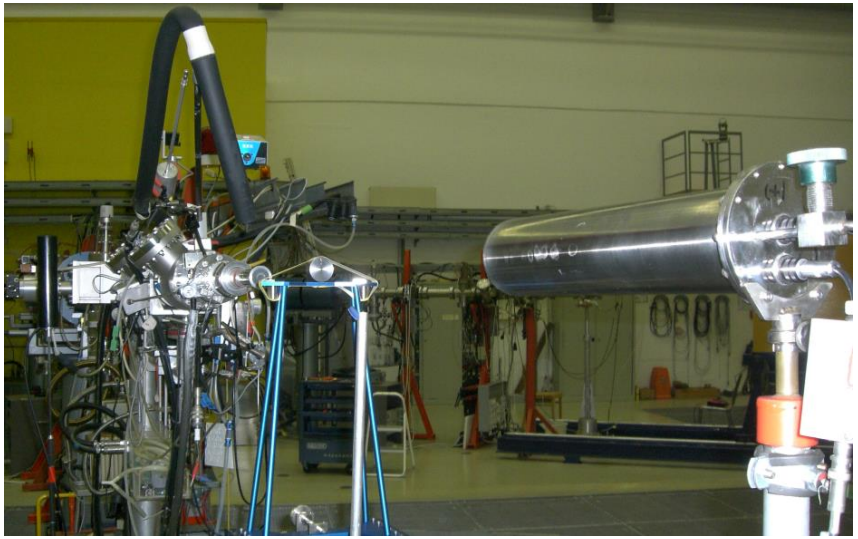
The PTB Proportional Counter P2

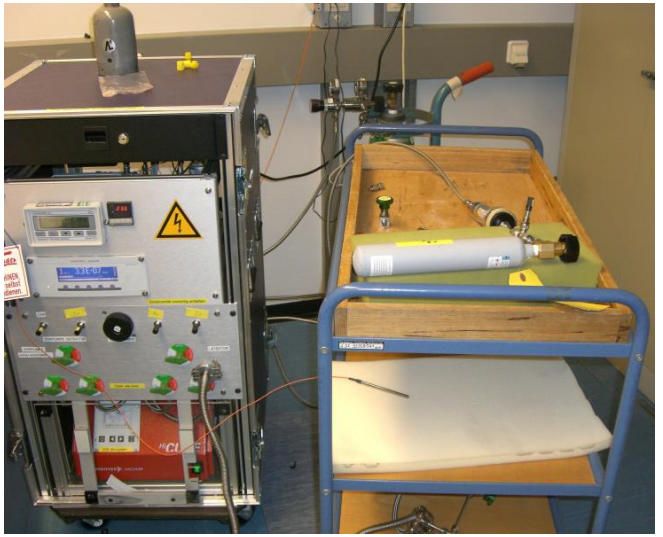


Ref.: T.H.R. Skyrme *et al.*, Rev. Sci. Instr. **23** (1952) 204

- **total volume: ≈ 1.6 dm³**
- **active volume: ∅55.5 mm, *l* = 193.3 mm**
- **el. field: defined by ∅4 mm field tubes at ground potential**
- **anode: ∅ 100 µm gold-plated tungsten wire (selected)**
- **counting gas: H_2/CH_4 (3.5 vol.%), C_3H_8**
- **energy range: 20 keV – 2 MeV**

Measurements at PTB





- **deuterated gases: H/D ≈ 0.01**
  - **D_2**
  - **CD_4, C_3D_8: purified using OxiSorb cartriges**
- **^{7}Li(p,n): metallic Li target, Ta backing, I_p = 3 µA, E_n = 150, 200, 250, 300, 500 keV**
- **room-return neutrons: shadow-cone technique**
- **target scattering: MC calculation**

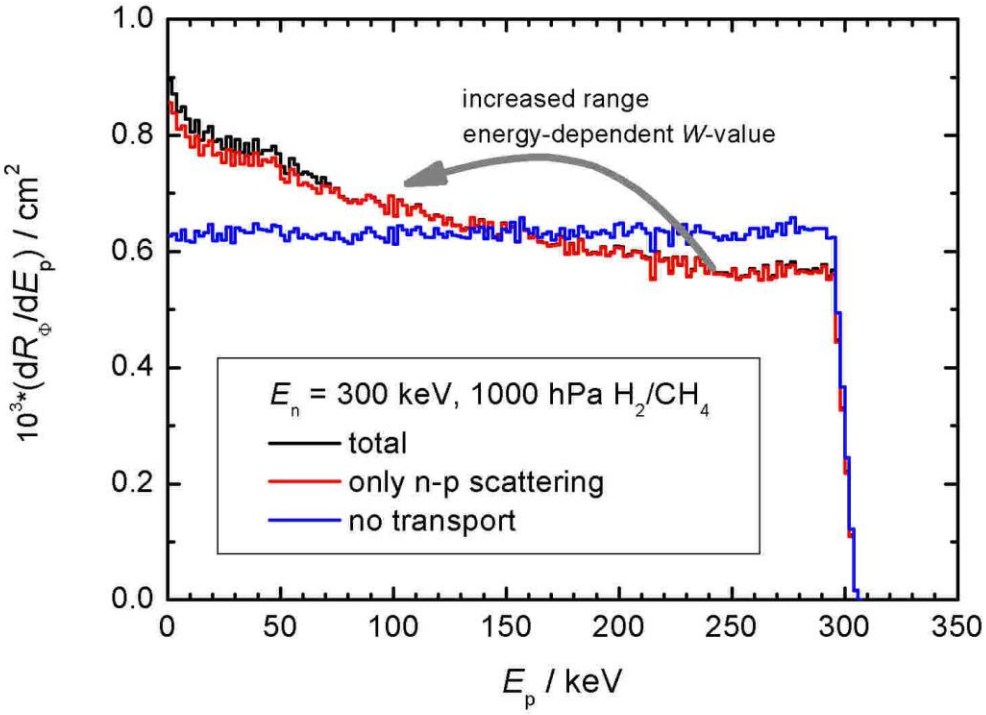
Modelling of the RPPC Response

MCNPX:

- **dedicated PTRAC filter**
- **new ACE files required**

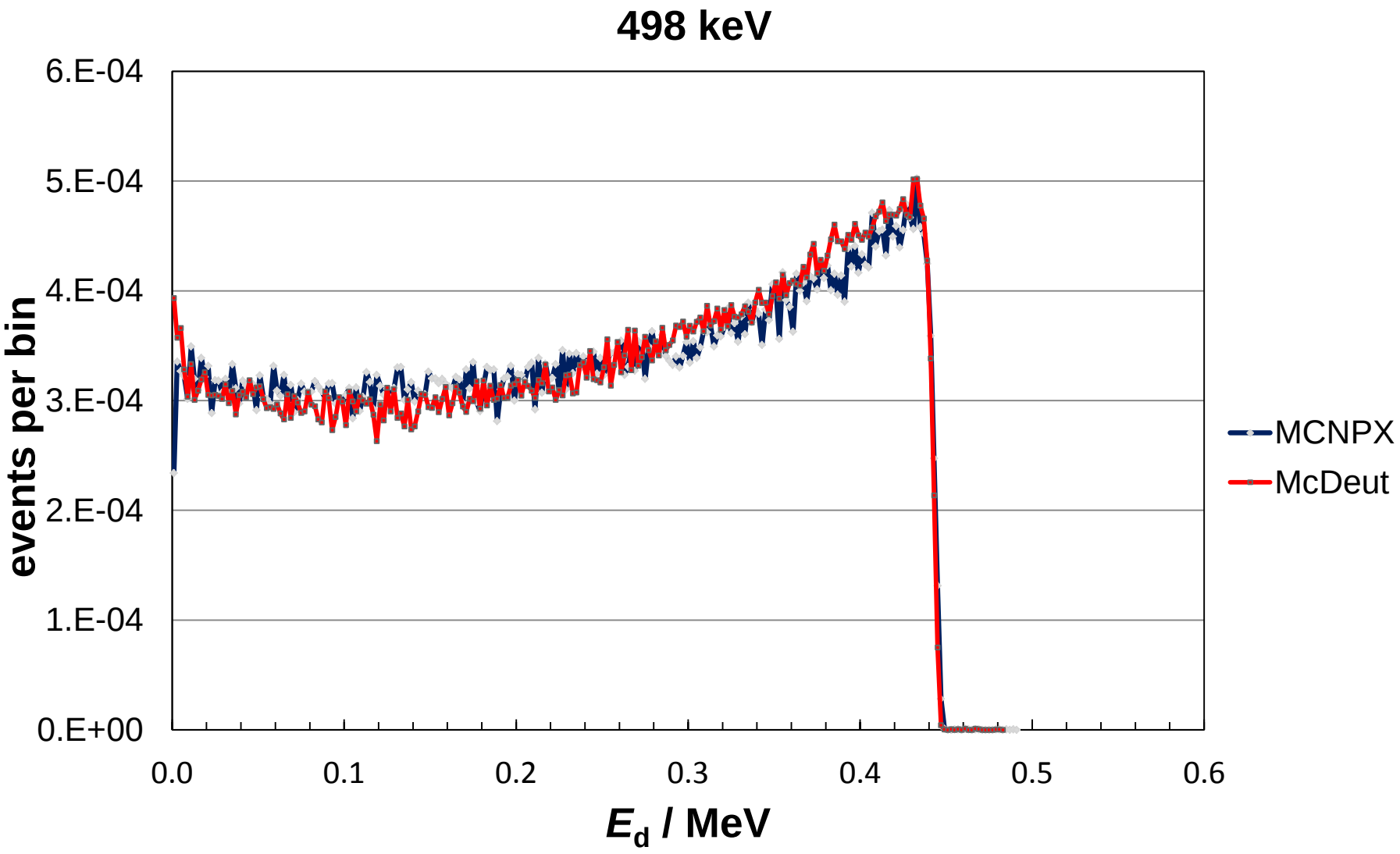
Dedicated MC code:

- **energy-dependent *W*-value**
- **carbon recoils included**
- **exchange of range and DX data possible**
- **single $P_\ell(\cos\Theta)$ distributions**
- **fully analogue simulation**

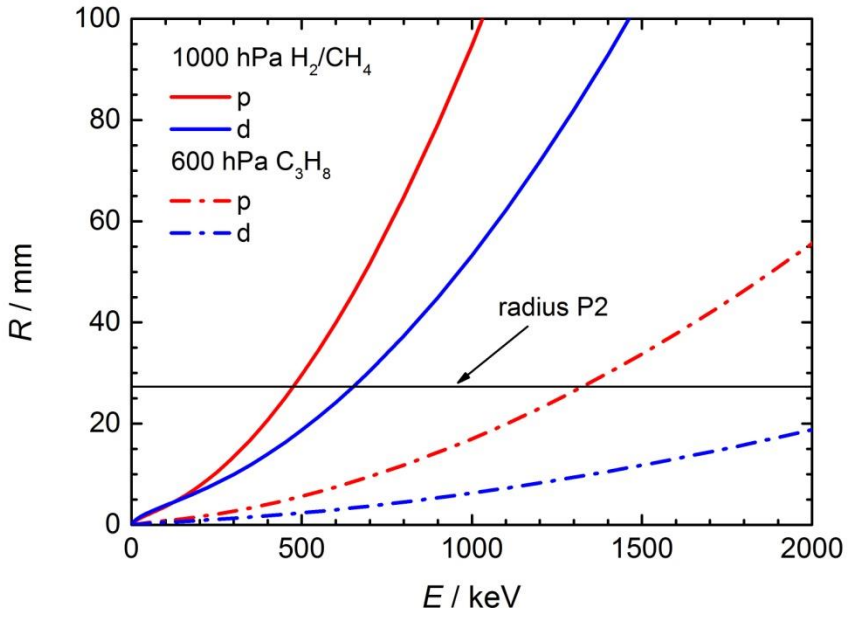


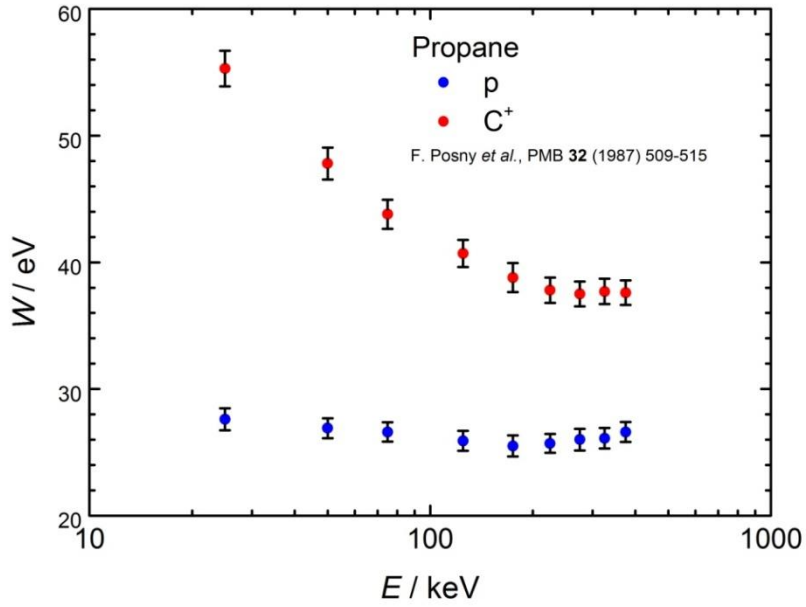
PH resolution:
Gaussian broadening, σE = const

MCNPX calculation



Input: Range Data, *W*-values





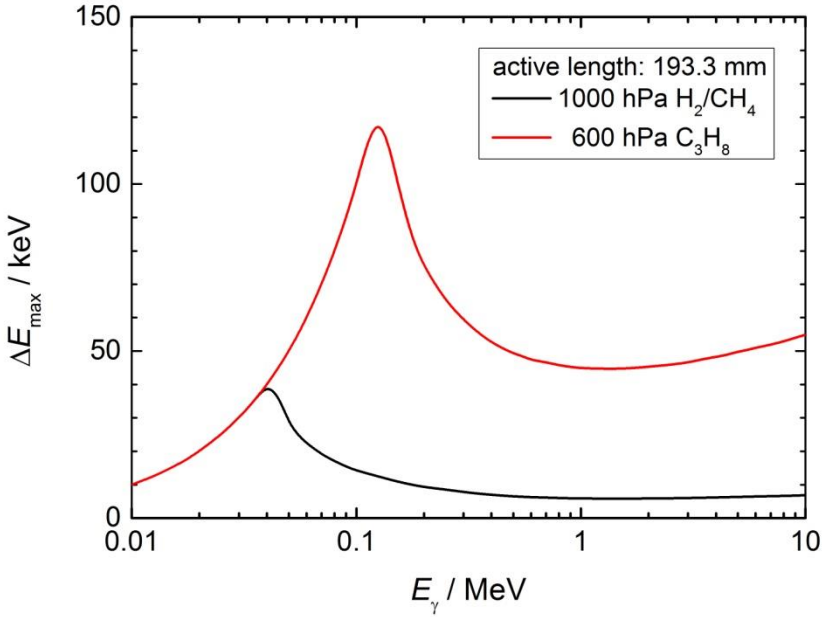
Range data: SRIM2012

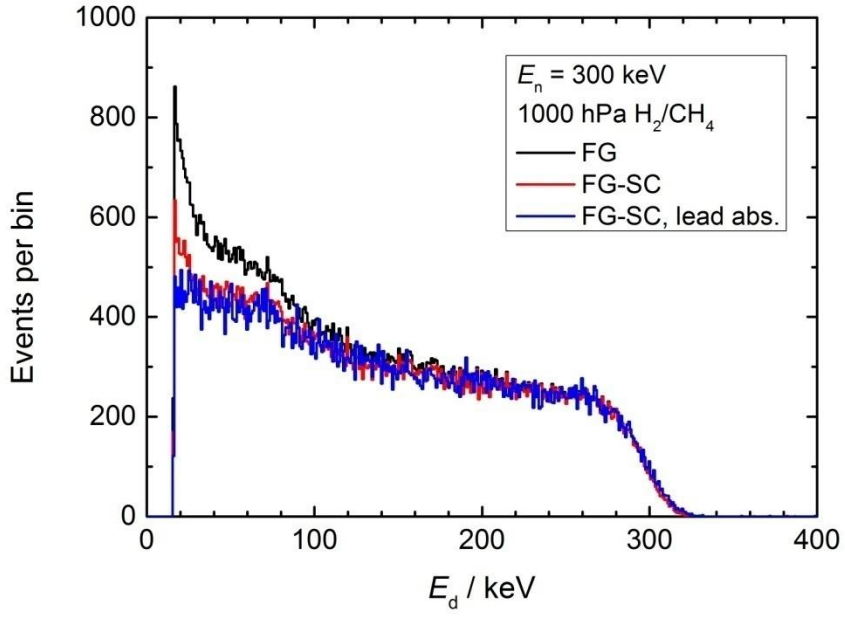
Uncertainty: $u_S/S \approx 3\%$
$u_R/R > 3\%$?

Rel. *W*-values: $W(Z_T,z_p,v_p)/W(Z_T,1,\infty)$

- **p, d in H_2: $W_r = 1$ for $E > 10$ keV**
- **p,d in C_3H_8: $W_r = 1$?**
- **C^+ in H_2, C_3H_8: $W_r = a \cdot \log(E) + b$**

Photon Interference

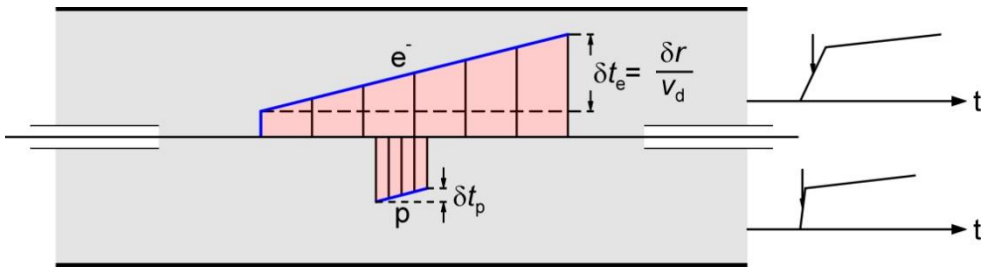




Photon interference suppressed by:

- **metallic Li/Ta target: only ^{7}Li(p,p'γ), Ta(p,p'γ), ^{7}Be decay**
- **20 mm lead absorber: only el. scattering below 570 keV**
- **subtraction of a sub-threshold measurement**
- **electronic discrimination**

Risetime Discrimination



Risetime:

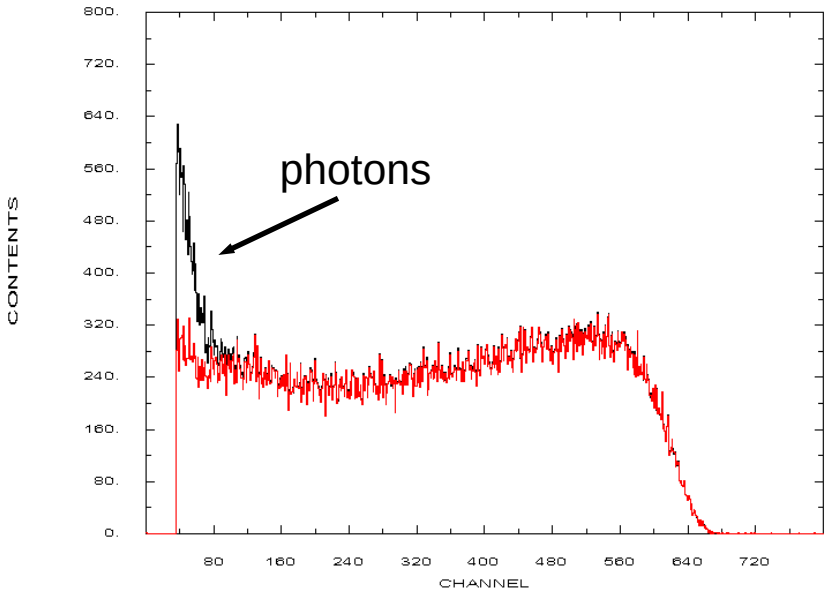
fast filter amp. :t_{diff} = 50 ns, t_{int} = 500 ns

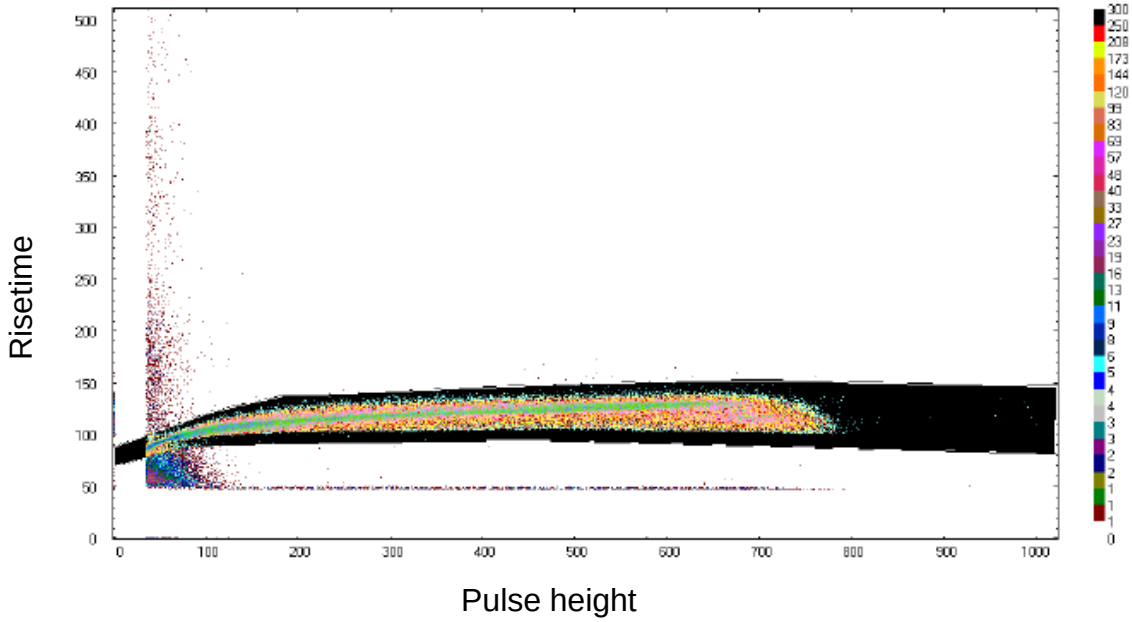
- **start: LE-disc. close to noise**
- **stop: CF-disc. (f = 0.4)**

Pulse height:

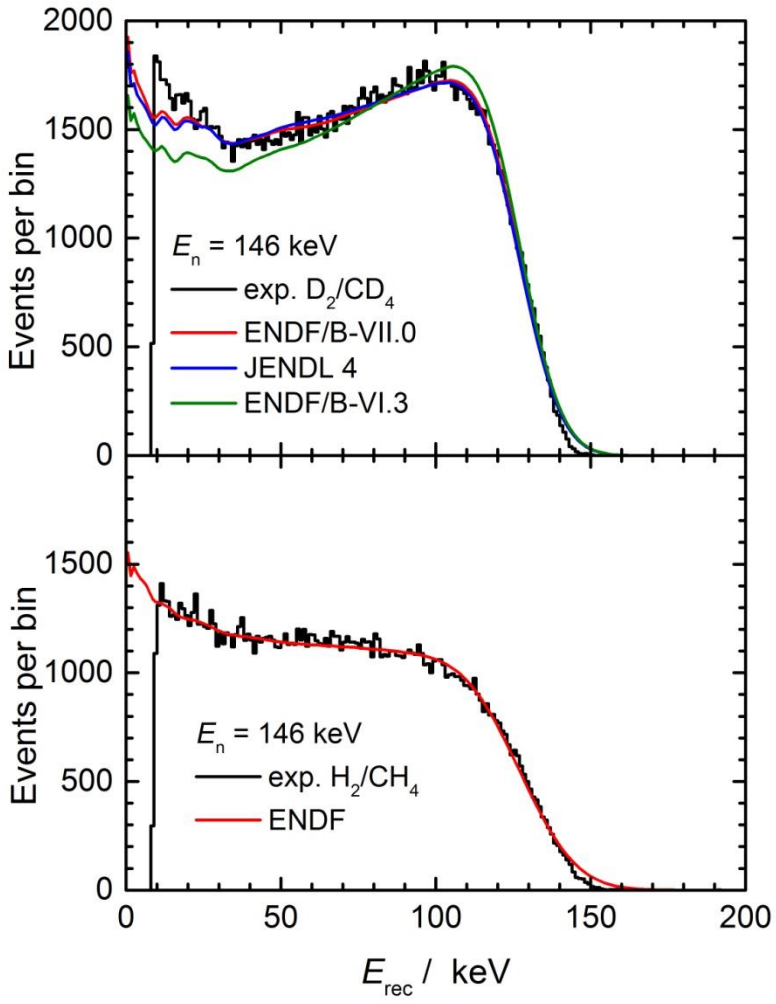
shaping amp.: t_s = 2 µs

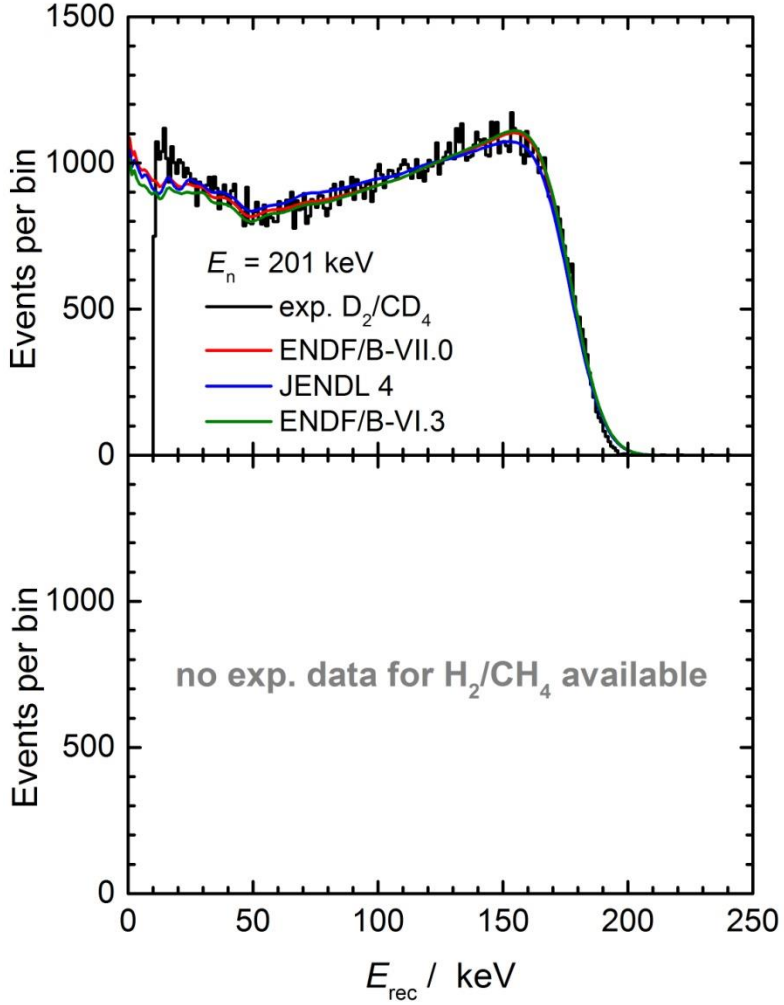
300 keV D_2/CD_4



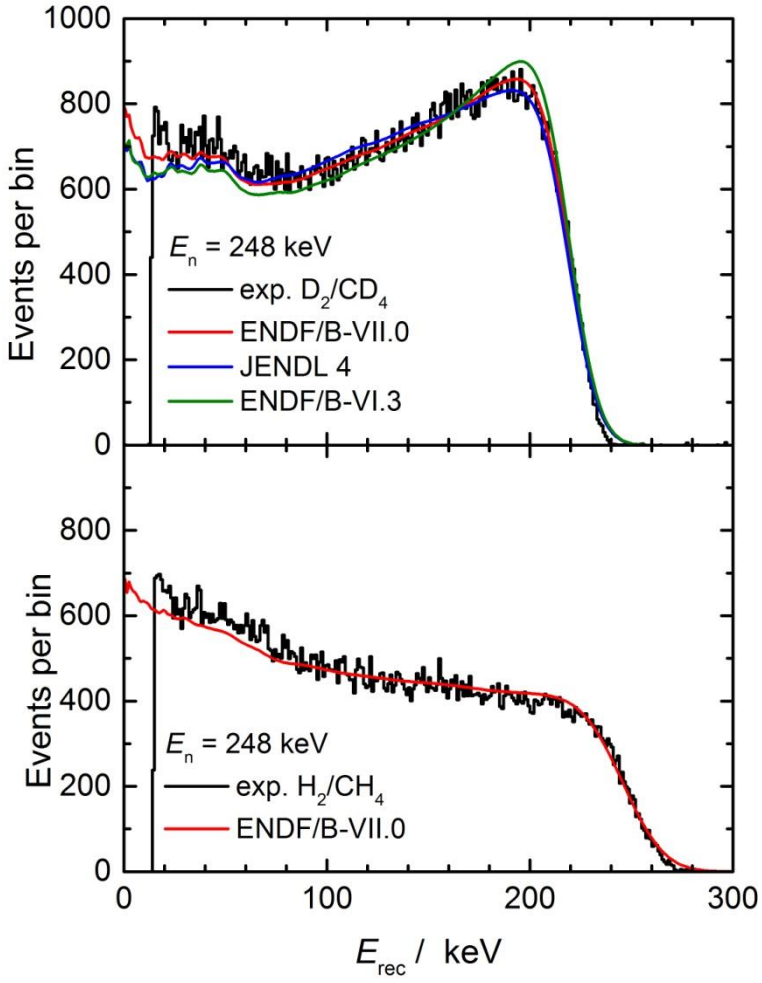


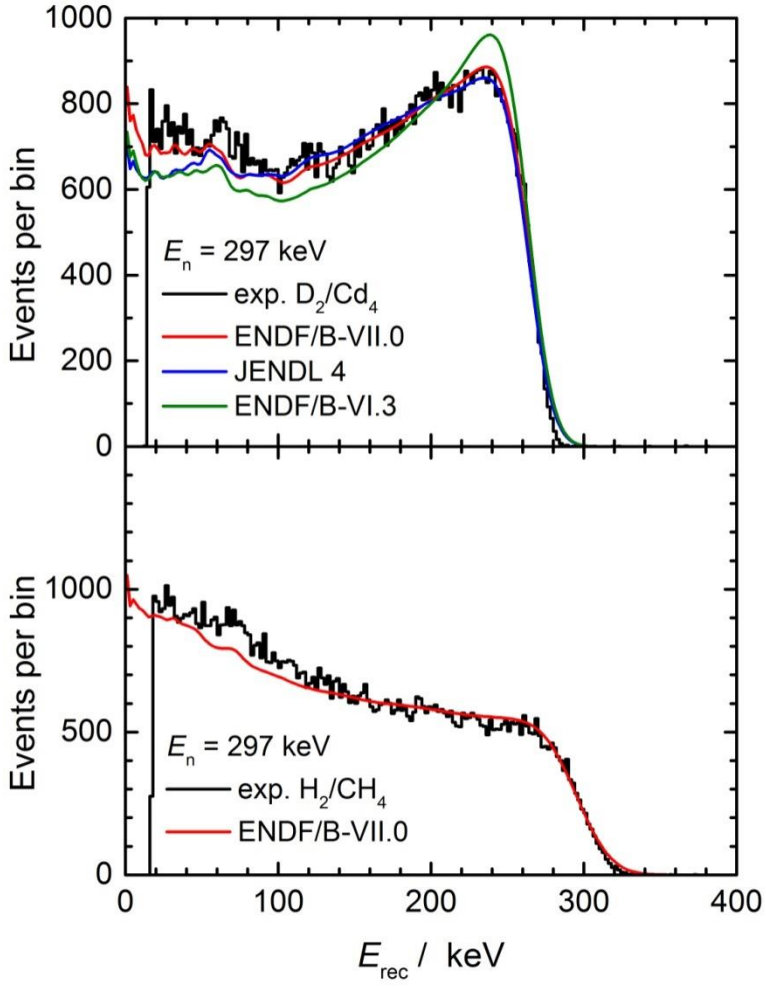
Results: 150 keV, 200 keV



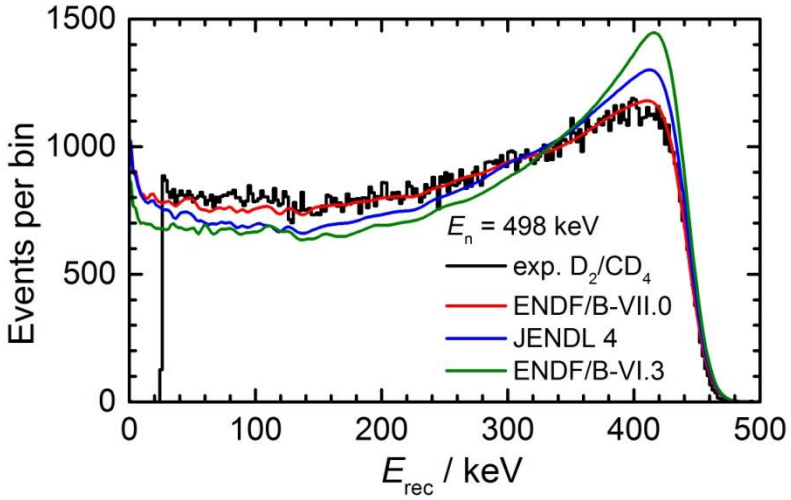


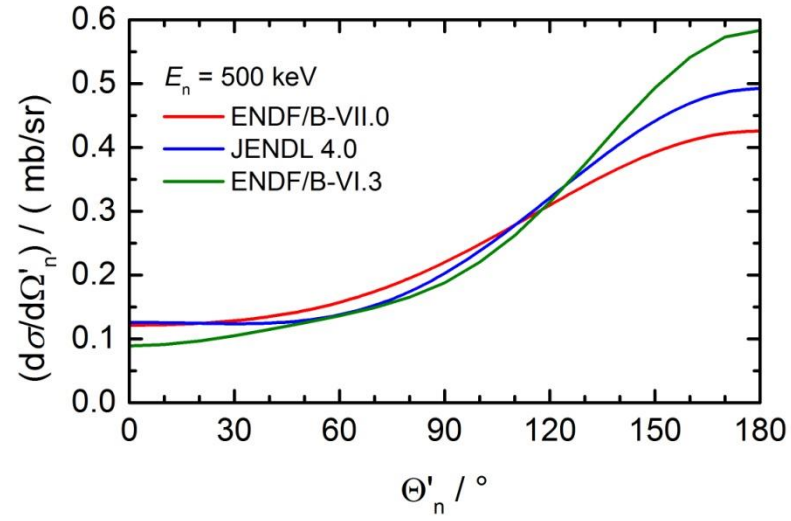
Results: 250 keV, 300 keV

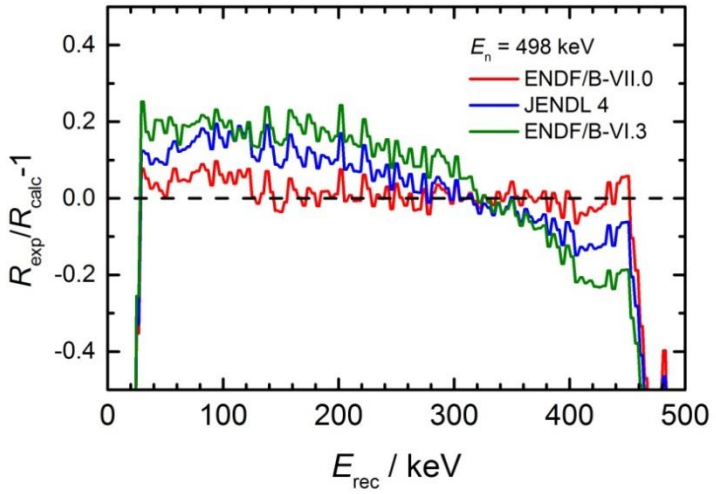




Results: 500 keV

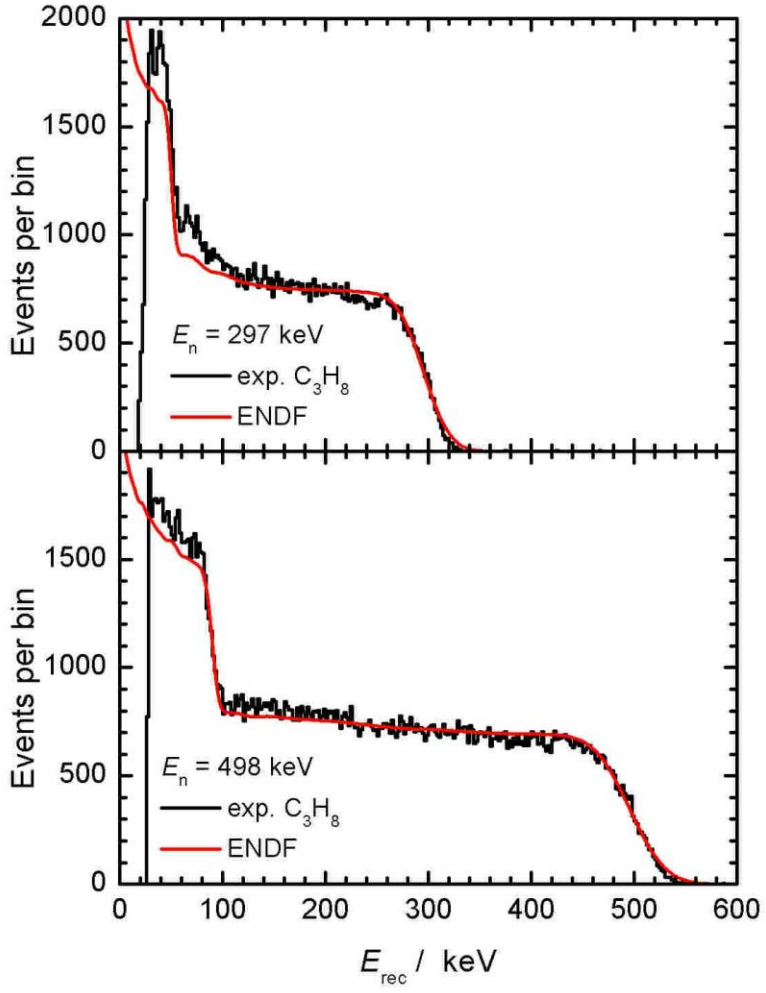






- **Still discrepancies at low pulse height**
- **ENDF/B-VI.3 and JENDL 4.0 are too anisotropic**
- **ENDF/B-VII.0: fair agreement**
- **Uncertainty: still > 5% at backward angles**

Results: 300 keV, 500 keV (Propane)



- **Same discrepancies below 100 keV as for hydrogen**
- **Energy dependence of *W*-value?**
- **So far no data for C_3D_8**

Summary and Outlook

- **Measurements of DX for D(n,n)D using a recoil counter were revisited:**
  - Reduced photon interference
  - Response from realistic MC simulations
  - Uncertainties from *W*-values and range data remained
  - Still residual photon interference at low pulse-heights

⇒ **ENDF/B-VII.0 evaluation is consistent with present results, ENDF/B-VI.3 is too anisotropic**

⇒ **Results relevant for a re-analysis of U/D_2O benchmarks**

- **Future work:**
  - Elimination of the photon interference
  - Extension to higher energies using C_3D_8 gas