Production of a beam of tensor-polarized deuterons using a carbon target

(Physical Review Letters **104** (2010) 222501)

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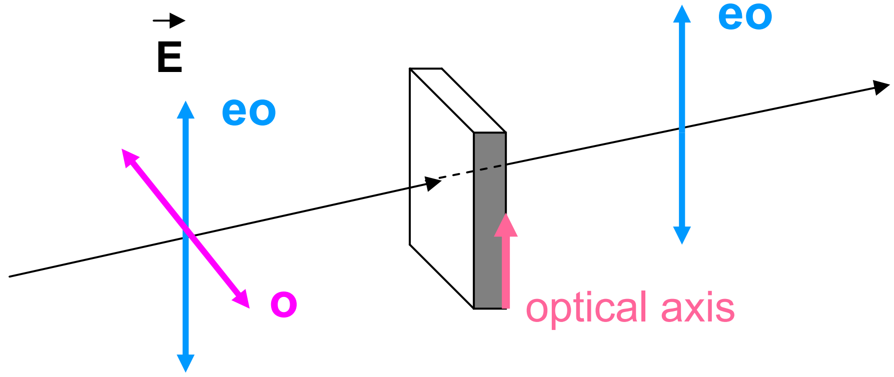
Introduction

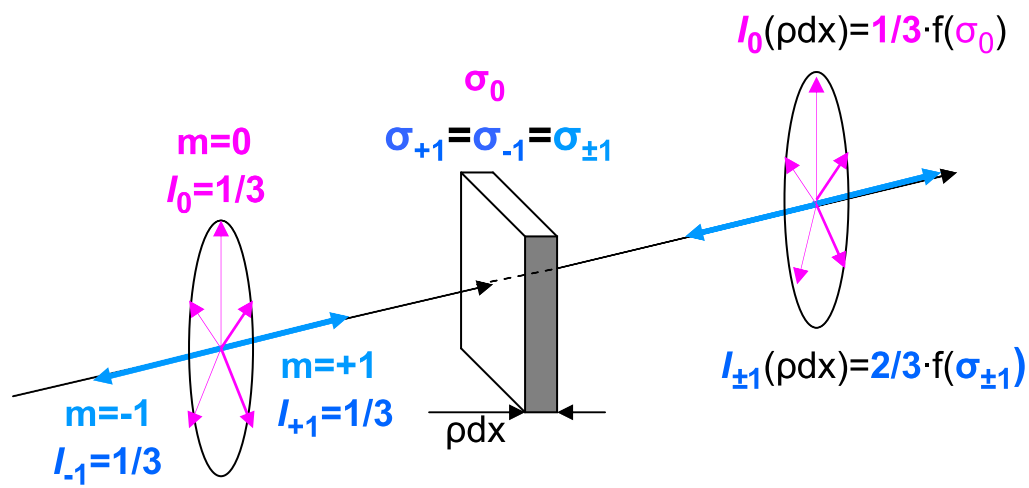
Dichroism as an optical effect

birefringent, uniaxial crystal
like Turmalin or filter foils



Nuclear (spin) dichroism

initial beam: **unpolarized deuterons**
target: **spin-zero nuclei** like **carbon**



$I_{-1} + I_{+1} = I_{\pm 1} = 2/3$

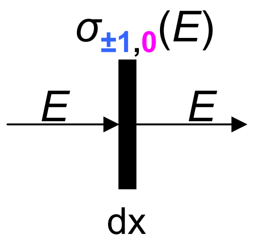
$I_{\pm 1}(\rho dx) < 2 I_0(\rho dx) \rightarrow p_{zz}(\rho dx) < 0$

$I_{\pm 1}(\rho dx) > 2 I_0(\rho dx) \rightarrow p_{zz}(\rho dx) > 0$

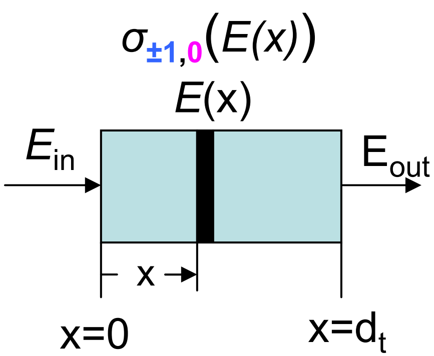
$$p_{zz}(\rho dx) \overset{\text{def}}{=} \frac{I_{+1}(\rho dx) + I_{-1}(\rho dx) - 2 I_0(\rho dx)}{I_{+1}(\rho dx) + I_{-1}(\rho dx) + I_0(\rho dx)} = \frac{I_{\pm 1}(\rho dx) - 2 I_0(\rho dx)}{I_{\pm 1}(\rho dx) + I_0(\rho dx)}$$

$$p_{zz}(\rho dx) = \frac{I_{\pm 1}(\rho dx) - 2I_0(\rho dx)}{I_{\pm 1}(\rho dx) + I_0(\rho dx)}$$

$I_{\pm 1}(\rho dx)$, $I_0(\rho dx)$?



$$p_{zz}(\rho dx) = \frac{2e^{-\rho\sigma_{\pm 1}(E)dx} - 2e^{-\rho\sigma_0(E)dx}}{2e^{-\rho\sigma_{\pm 1}(E)dx} + e^{-\rho\sigma_0(E)dx}}$$

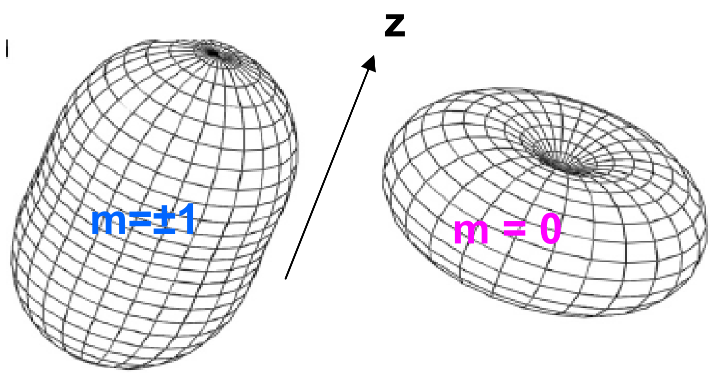


$$p_{zz}(\rho d_t) = \frac{2e^{-\rho\int_0^{d_t}\sigma_{\pm 1}\left(E(x)\right)\mathrm{d}x} - 2e^{-\rho\int_0^{d_t}\sigma_0\left(E(x)\right)\mathrm{d}x}}{2e^{-\rho\int_0^{d_t}\sigma_{\pm 1}\left(E(x)\right)\mathrm{d}x} + e^{-\rho\int_0^{d_t}\sigma_0\left(E(x)\right)\mathrm{d}x}}$$

$$\rho\int_0^{d_t}\sigma_{\pm 1}\left(E(x)\right)\mathrm{d}x \ll 1, \quad \rho\int_0^{d_t}\sigma_0\left(\mathrm{E(x)}\right)\mathrm{d}x \ll 1 \quad (\mathrm{e}^{-\mathrm{x}} \to 1 - \mathrm{x})$$

$$p_{zz}(\rho d_t) = \frac{2}{3}\rho\int_0^{d_t}\left(\sigma_0\left(E(x)\right) - \sigma_{\pm 1}\left(E(x)\right)\right)\mathrm{d}x$$

Tasks: calculate $\sigma_0(E)$, $\sigma_{\pm 1}(E)$ and measure p_{zz} as function of E_{in} and d_t (i.e., E_{out})



unpolarized deuteron beam
beam direction ≡ quantization axis z

expectation: $\sigma_0 > \sigma_{\pm1}$ resulting in $p_{zz} > 0$

Relativistic energies:

Calculation
G. Fäldt, J. Phys. G: Nucl: Phys 6 (1980) 1513: $\sigma_0 - \sigma_{\pm1} = +\,1.87\ \mathrm{fm}^2$

Experiment
L.S. Azhgirey et al., Particles and Nuclei, Letters 5 (2008) 728): $\sigma_0 - \sigma_{\pm1} = +\,7.18\ \mathrm{fm}^2$

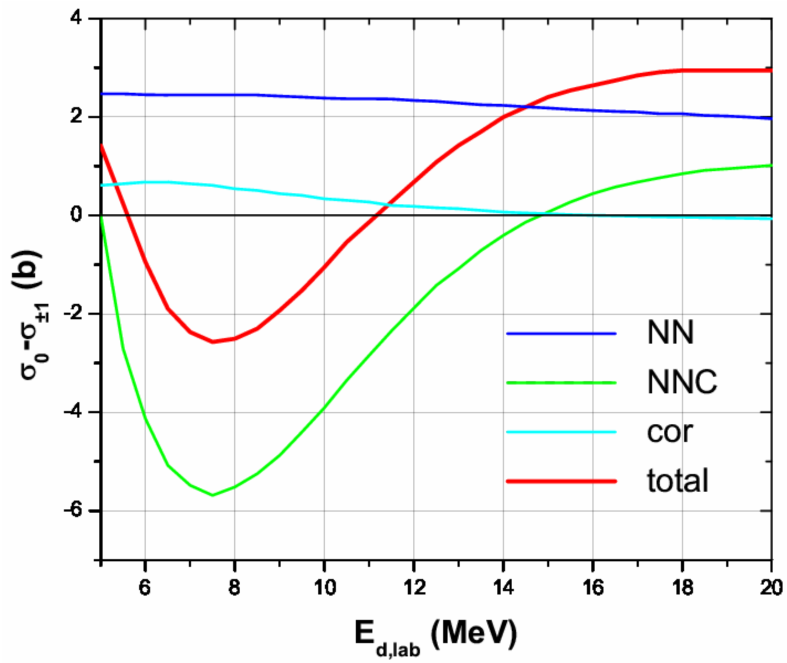
E = 5 to 20 MeV:

Calculation
V. Baryshevsky and A. Rouba, Phys. Lett. B **683** (2010) 229

Optical theorem

$$\sigma_0(E) - \sigma_{\pm1}(E) = \frac{4\pi}{k}\mathrm{Im}\{\mathrm{f}_0(\theta = 0, \mathrm{E}) - \mathrm{f}_{\pm1}(\theta = 0, \mathrm{E})\}$$

V. Baryshevsky and A. Rouba, Phys. Lett. B **683** (2010) 229



NN nuclear interaction, n-C and p-C and Coulomb interaction p-C in eikonal approximation

NNC interference of nuclear and Coulomb interaction in eikonal approximation

cor correction term to the eikonal approximation

Essential results: (a) **σ_0 - $\sigma_{\pm1}$ up to b** compared to $fm^2 = 10^{-2}$ b at high energies
(b) **change of sign** due to nuclear-Coulomb interference

$\rho_{graphite}$ = 1 g/cm^3 or 5·10^{22} C atoms/cm^3

E_{in}= **20 MeV**, E_{out}= **11 MeV:** $$p_{zz}(\rho d_t) = \frac{2}{3}\rho \int_0^{0.18\mathrm{cm}} \Big(\sigma_0\big(E(x)\big) - \sigma_{\pm1}\big(E(x)\big)\Big)\,\mathrm{dx} = +0.014$$

E_{in}= **11 MeV**, E_{out}= **5.5 MeV:** $$p_{zz}(\rho d_t) = \frac{2}{3}\rho \int_0^{0.07\mathrm{cm}} \Big(\sigma_0\big(E(x)\big) - \sigma_{\pm1}\big(E(x)\big)\Big)\,\mathrm{dx} = -0.0035$$

Measurements

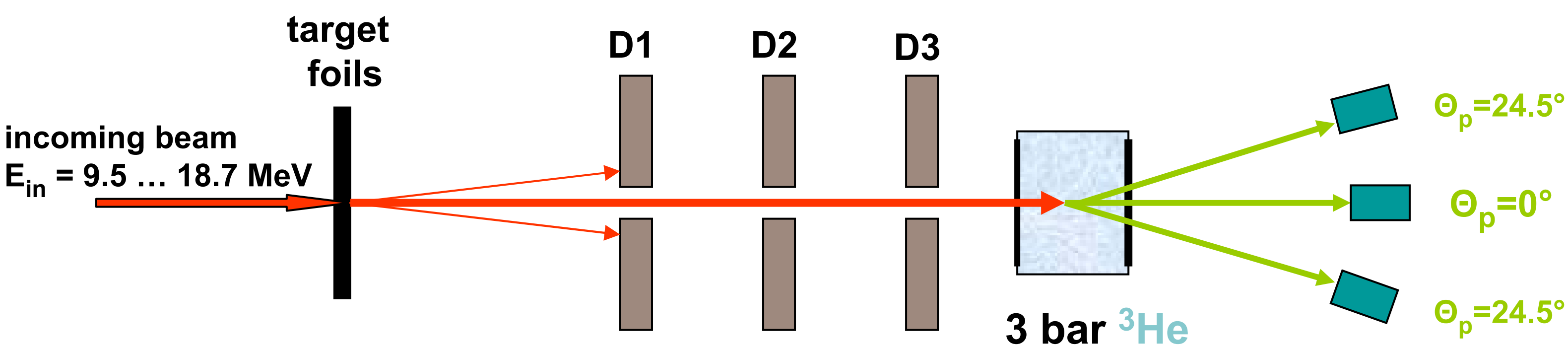
Performed with

unpolarized deuteron beam from Van-de-Graaff tandem accelerator

operated by

Institut für Kernphysik of Universität zu Köln

(J. Jolie, H. Paetz gen Schieck, J. Eberth, and A. Dewald, Nucl. Phys. News **12**, 4 (2002))



thickness mg/cm^2		labelled as
empty		
Au	5.0	**Au5**
Au	9.7	Au10
C	35.90	**C36**
C	57.69	**C58**
C	93.59	**C94**
C	129.49	**C129**
C	152.63	**C153**
C	165.39	**C165**
C	187.93	**C188**

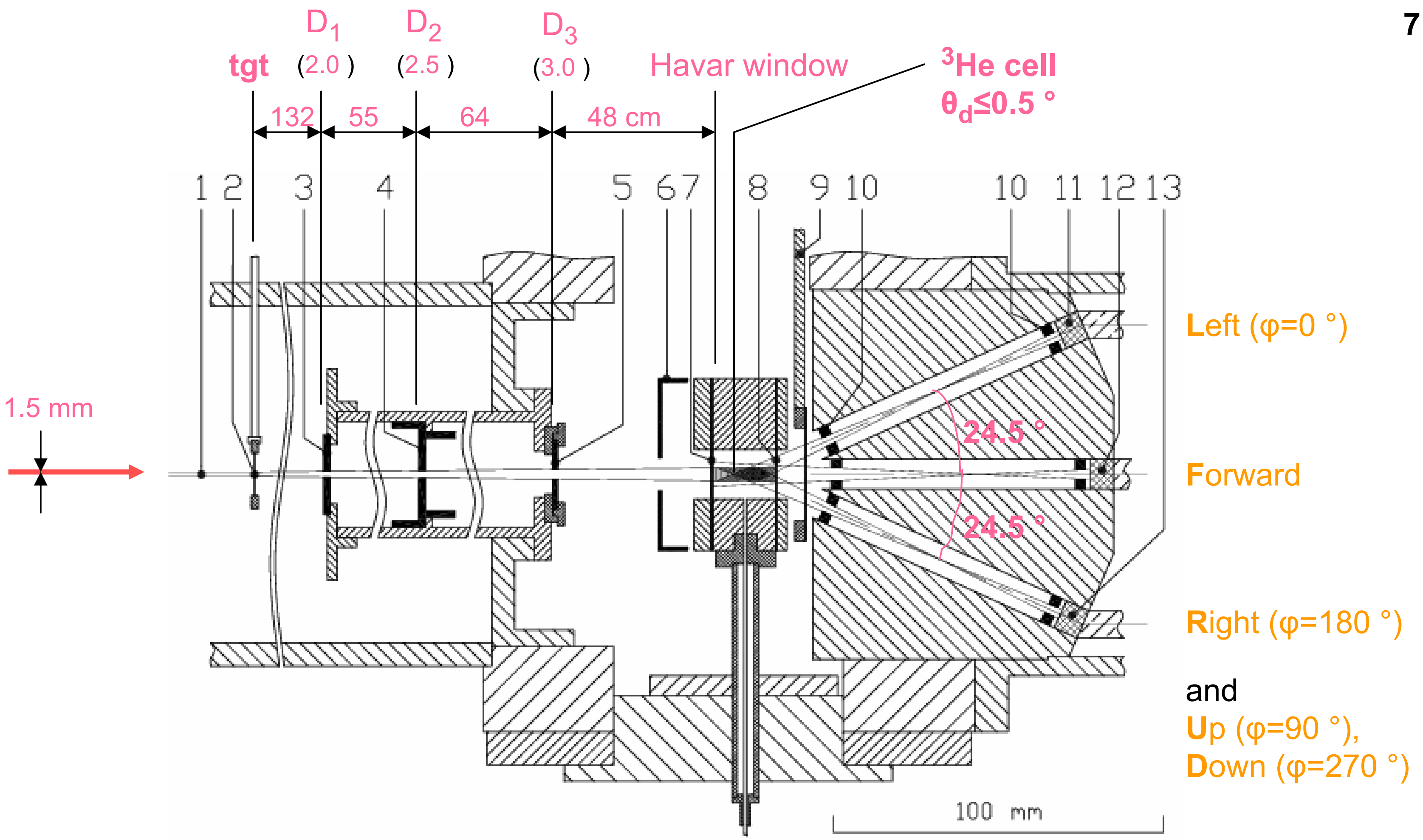
$$\vec{d} + {}^3He \rightarrow {}^4He + p$$

$$E_{cell} = f(E_{in}, d_{target})$$

$$\sigma(E_{cell}, \theta_p) = \sigma_o(E_{cell}, \theta_p) \cdot [1 + 1/2 \cdot p_{zz}(E_{cell}) \cdot A_{zz}(E_{cell}, \theta_p)]$$

known — known

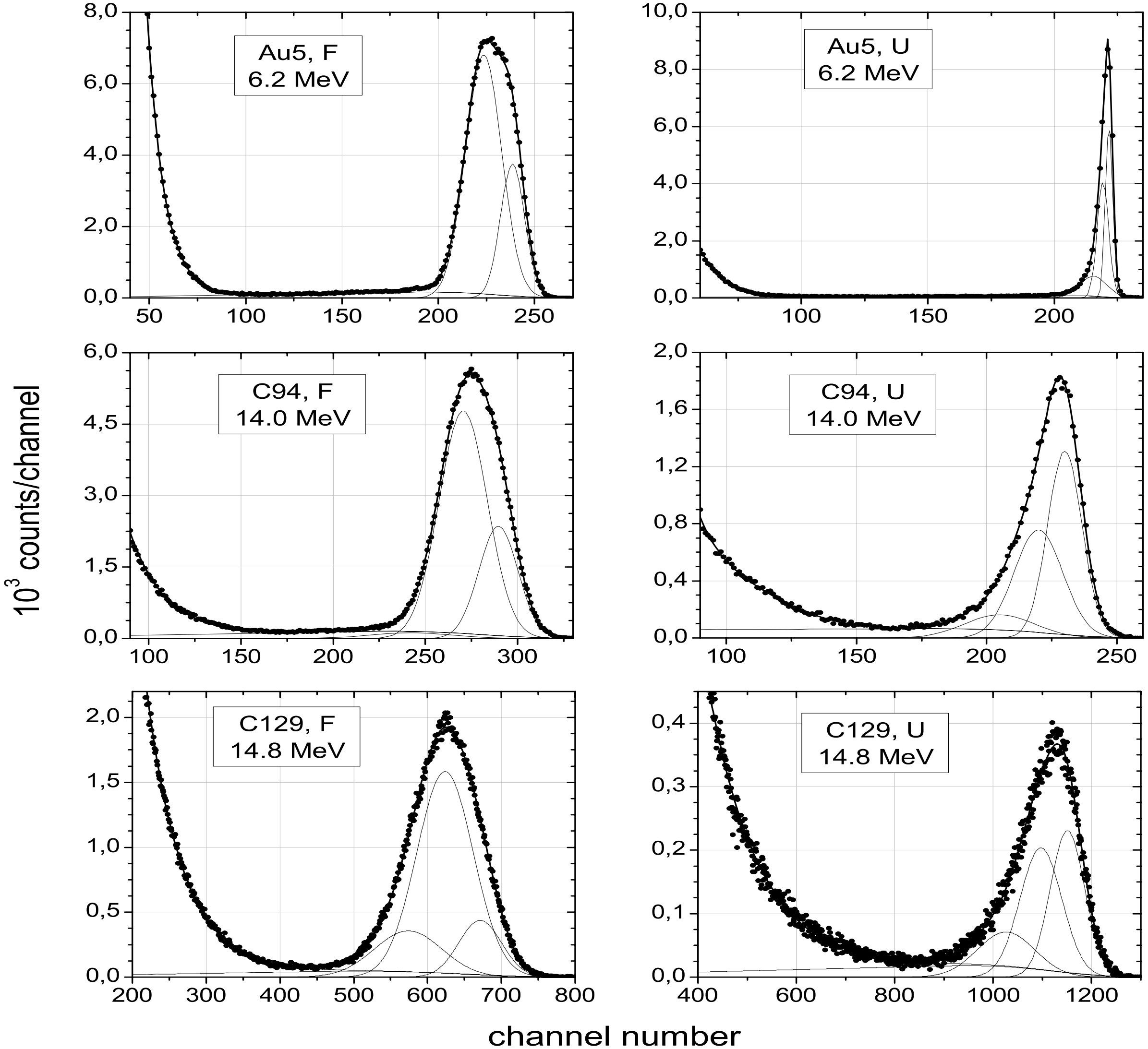
measured — to derive



$$r(E_{\mathrm{cell}}) = \frac{N_{\mathrm{L}}(E_{\mathrm{cell}}) + N_{\mathrm{U}}(E_{\mathrm{cell}}) + N_{\mathrm{R}}(E_{\mathrm{cell}}) + N_{\mathrm{D}}(E_{\mathrm{cell}})}{N_{\mathrm{F}}(E_{\mathrm{cell}})}$$

$$N_{\mathrm{i}}(E_{\mathrm{cell}}) = \rho_{\mathrm{He}} \cdot l_{\mathrm{i}} \cdot \Omega_{\mathrm{i}} \cdot \varepsilon_{\mathrm{i}} \cdot \int j_{\mathrm{cell}}(t)\mathrm{d}t \cdot \overline{\sigma(E_{\mathrm{cell}}, (24.5 \pm 2.9)^{\circ}}$$

$$N_{\mathrm{F}}(E_{\mathrm{cell}}) = \rho_{\mathrm{He}} \cdot l_{\mathrm{F}} \cdot \Omega_{\mathrm{F}} \cdot \varepsilon_{\mathrm{F}} \cdot \int j_{\mathrm{cell}}(t)\mathrm{d}t \cdot \overline{\sigma(E_{\mathrm{cell}}, (0 \pm 2.6)^{\circ}}$$



Au5, F
6.2 MeV
Au5, U
6.2 MeV
C94, F
14.0 MeV
C94, U
14.0 MeV
C129, F
14.8 MeV
C129, U
14.8 MeV
10^3 counts/channel
channel number

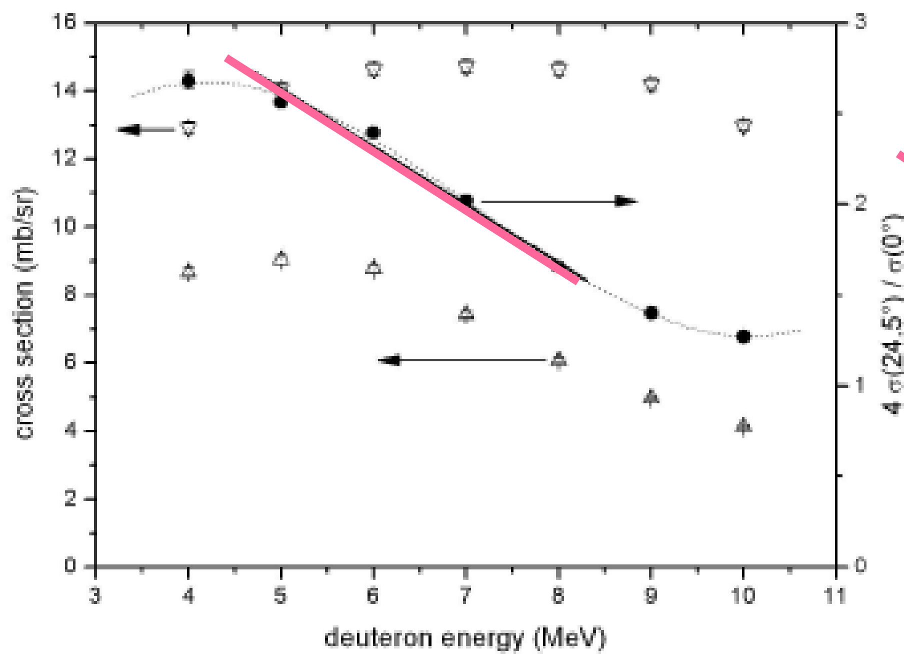
What is expected with an unpolarized beam?

$$\sigma(E_{cell},\ \theta_p)=\sigma_o(E_{cell},\theta_p)\cdot[1+1/2\cdot p_{zz}(E_{cell})\cdot A_{zz}(E_{cell},\theta_p)]$$

Unpolarized cross sections from M. Bittcher et al., Few-Body Systems **9** (1990) 165

∇: $\sigma_0(0\ °)$

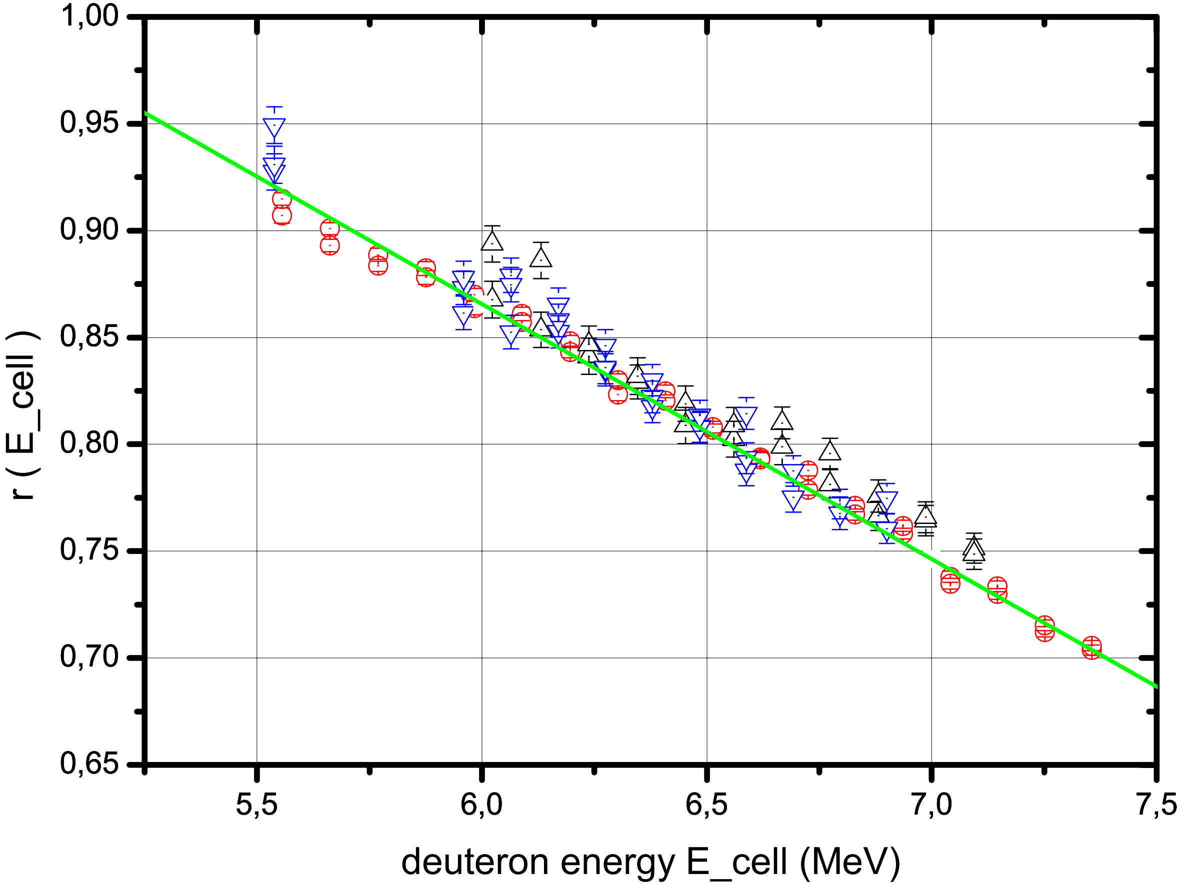
Δ: $\sigma_0(24.5\ °)$



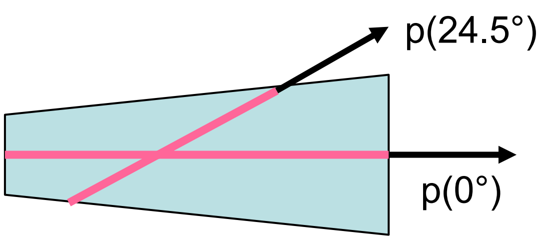
$$\frac{4\cdot\sigma_0(24.5\ °)}{\sigma_0(0\ °)}$$

E_{in} (MeV) ← E_{cell} (MeV)

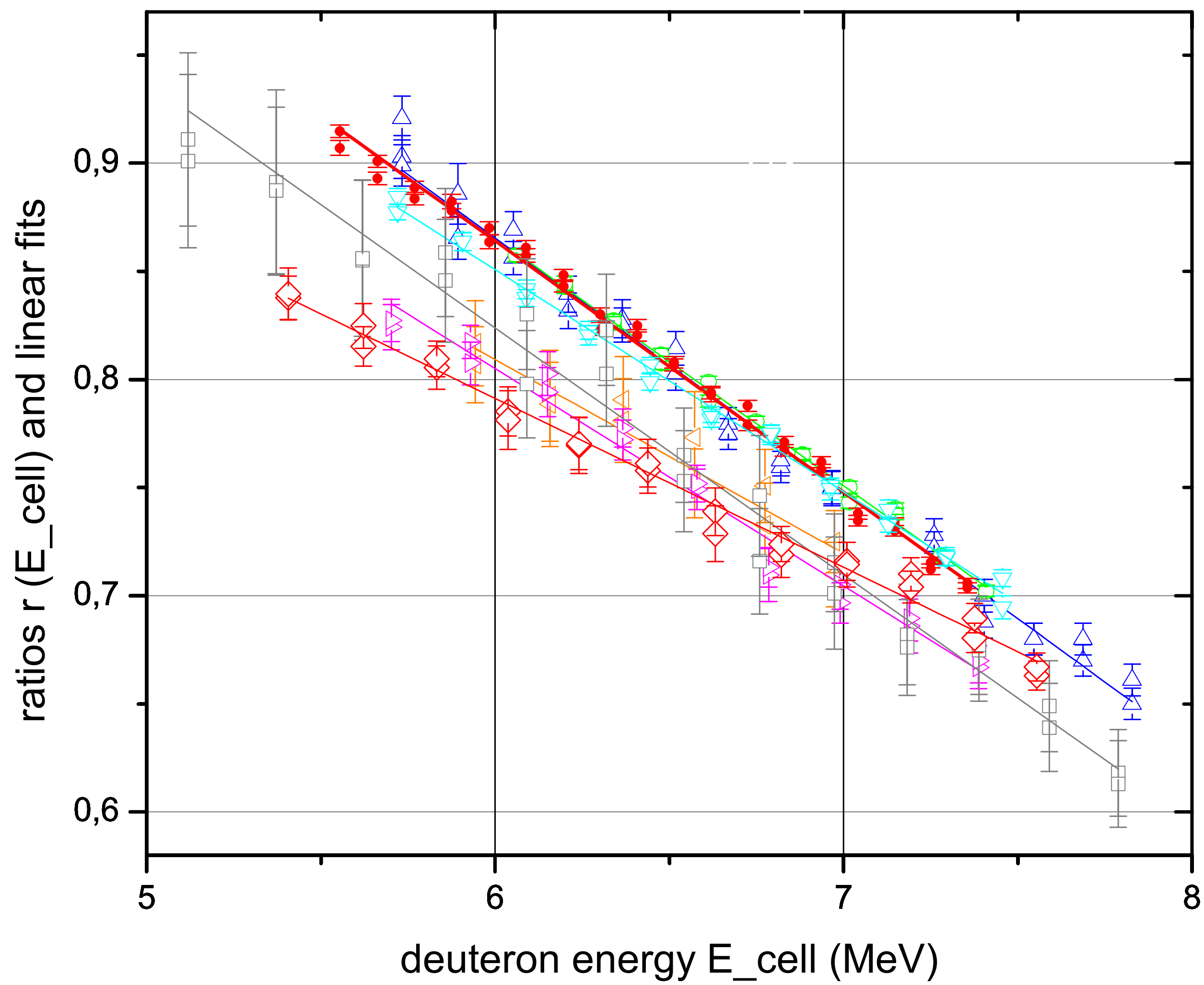
	E_{in} (MeV)	E_{cell} (MeV)
Au5	6.20 …. 7.90	**5.56 …. 7.36**
C36	9.50 …. 10.50	**6.06 …. 7.41**
C188	17.50 …. 18.70	**5.11 …. 7.78**



$$4\sigma_0(24.5^\circ)/\sigma_0(0^\circ)|_{\mathrm{calc}} \cdot f_{\mathrm{norm}}\left(r^{\mathrm{fit}}_{\mathrm{Au5}}(6.5MeV)\right)$$

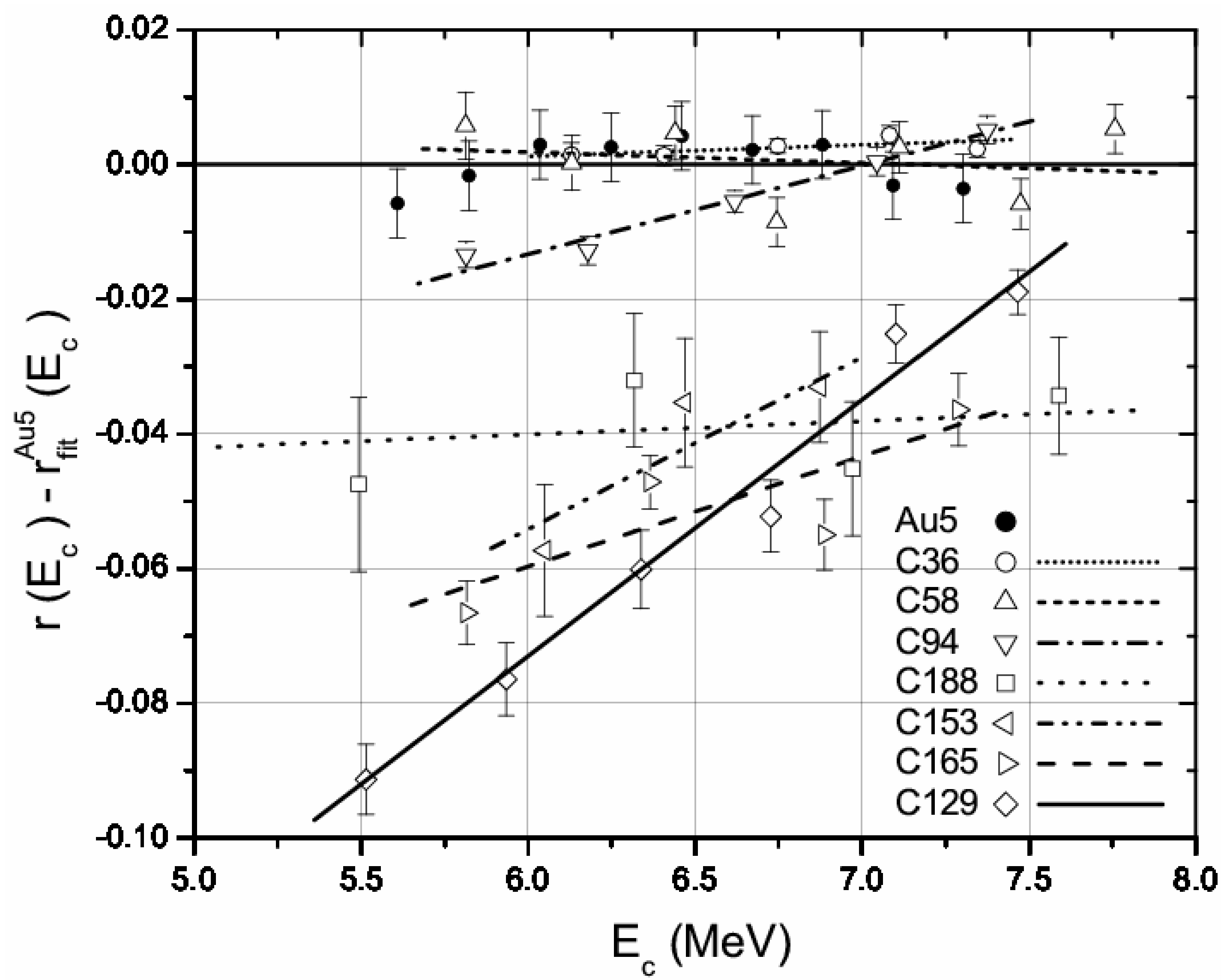


f_{norm}=0.374



Measured proton-peak ratios with linear fits

• $Au5$ ○ $C36$ △ $C58$ ▽ $C94$ ◇ $C129$ ◁ $C153$ ▷ $C165$ □ $C188$



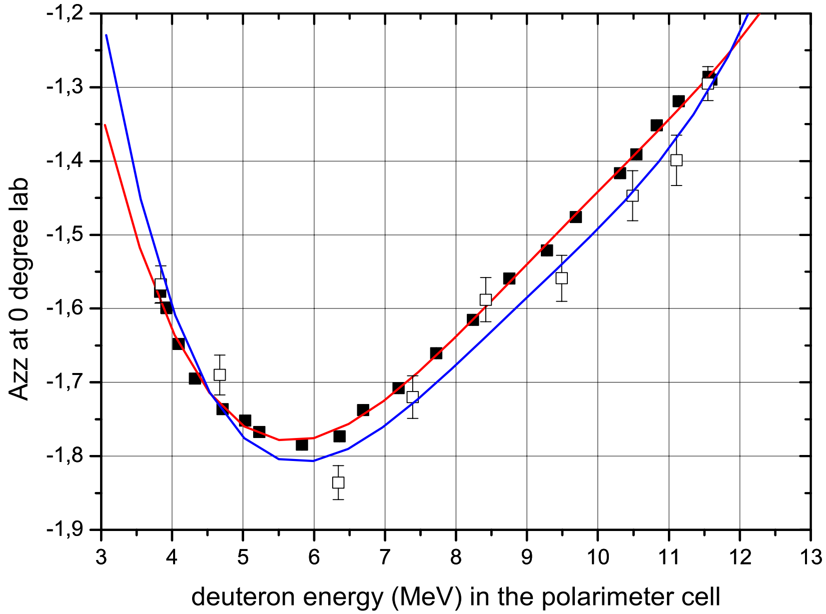
0.02
0.00
-0.02
-0.04
-0.06
-0.08
-0.10
5.0
5.5
6.0
6.5
7.0
7.5
8.0
r (E_c) - r_fit^Au5 (E_c)
E_c (MeV)
Au5
C36
C58
C94
C188
C153
C165
C129

$$\frac{r^{\mathrm{fit}}_{\mathrm{Cx}}(E_{\mathrm{cell}})}{r^{\mathrm{fit}}_{\mathrm{Au5}}(E_{\mathrm{cell}})} = \frac{\left[\frac{(C_{\mathrm{L}}+C_{\mathrm{R}}+C_{\mathrm{U}}+C_{\mathrm{D}})\cdot\sigma_0(E_{\mathrm{cell}},\ 24.5^\circ)\cdot[1+\frac{1}{2}p_{\mathrm{zz}}(E_{\mathrm{cell}})A_{\mathrm{zz}}(E_{\mathrm{cell}},\ 24.5^\circ)]}{C_{\mathrm{F}}\cdot\sigma_0(E_{\mathrm{cell}},\ 0^\circ)\cdot[1+\frac{1}{2}p_{\mathrm{zz}}(E_{\mathrm{cell}})A_{\mathrm{zz}}(E_{\mathrm{cell}},\ 0^\circ)]}\right]_{\mathrm{Cx}}}{\left[\frac{(C_{\mathrm{L}}+C_{\mathrm{R}}+C_{\mathrm{U}}+C_{\mathrm{D}})\cdot\sigma_0(E_{\mathrm{cell}},\ 24.5^\circ)}{C_{\mathrm{F}}\cdot\sigma_0(E_{\mathrm{cell}},\ 0^\circ)}\right]_{\mathrm{Au5}}}$$

$$C_{\mathrm{i}} = \rho_{\mathrm{He}}\cdot l_{\mathrm{i}}\cdot\Omega_{\mathrm{i}}\cdot\varepsilon_{\mathrm{i}}\cdot\int j_{\mathrm{cell}}(t)\mathrm{dt}$$

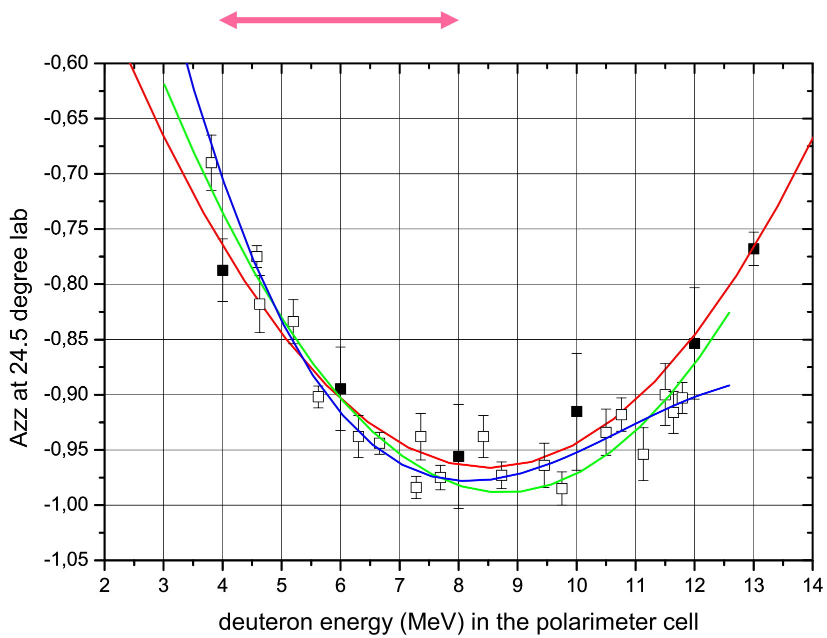
$$= \frac{1+\frac{1}{2}p_{\mathrm{zz}}(E_{\mathrm{cell}})\cdot A_{zz}(E_{\mathrm{cell}},\ 24.5^\circ)}{1+\frac{1}{2}p_{zz}(E_{\mathrm{cell}})\cdot A_{zz}(E_{\mathrm{cell}},\ 0^\circ)}$$

$$p_{\mathrm{zz}}(E_{\mathrm{cell}}) = \frac{2\cdot[\ r^{\mathrm{fit}}_{\mathrm{Au5}}(E_{\mathrm{cell}}) - r^{\mathrm{fit}}_{\mathrm{Cx}}(E_{\mathrm{cell}})\ ]}{r^{\mathrm{fit}}_{\mathrm{Cx}}(E_{\mathrm{cell}})\cdot A_{\mathrm{zz}}(E_{\mathrm{cell}},0^\circ) - r^{\mathrm{fit}}_{\mathrm{Au5}}(E_{\mathrm{cell}})\cdot A_{\mathrm{zz}}(E_{\mathrm{cell}},24.5^\circ)}$$



A_{zz} (E_{cell}, 0 °)

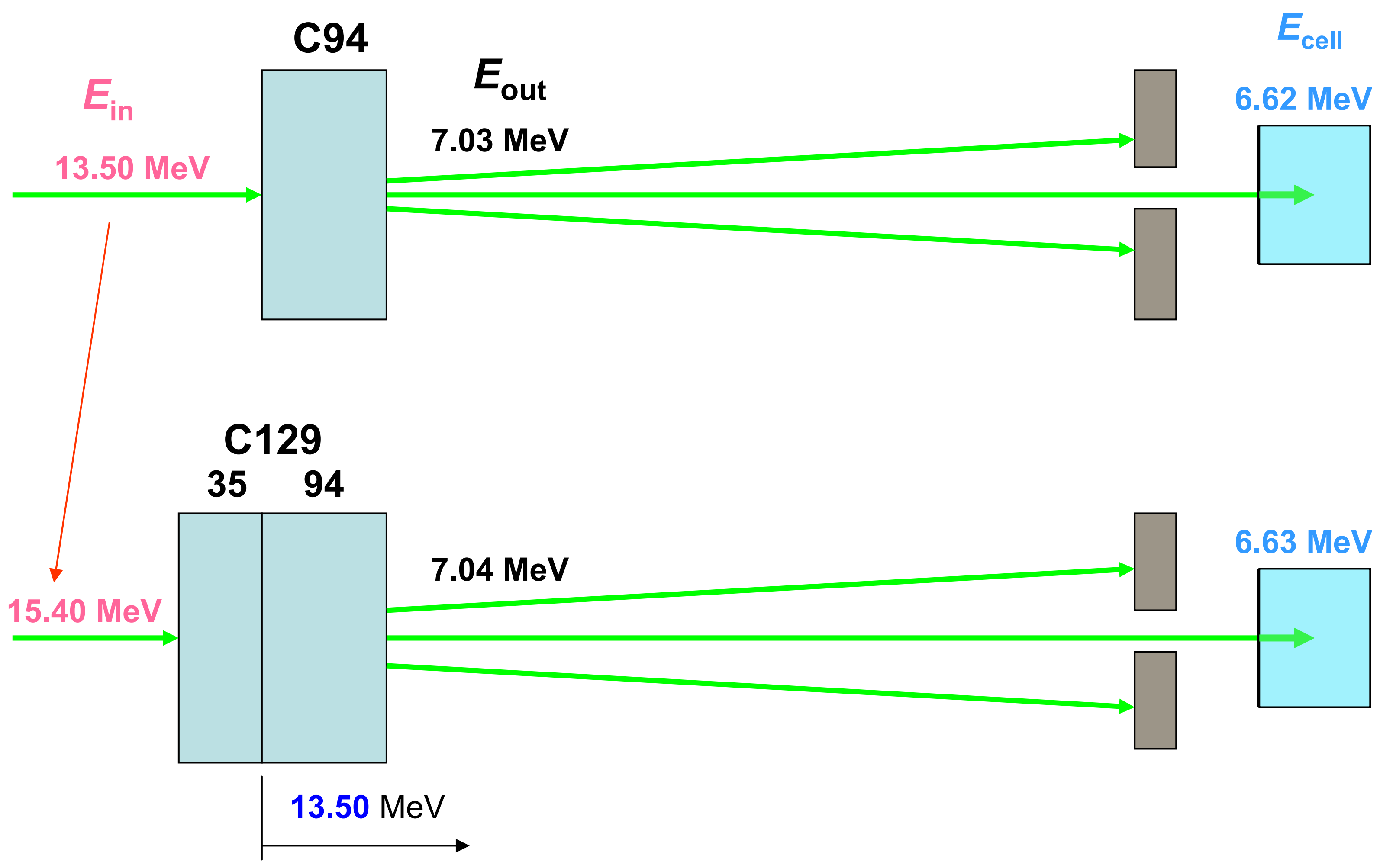
- ■ P.A. Schmelzbach, W. Grüebler, V. König, R. Risler, D.O. Boerma, and B. Jenny, Nucl. Phys. **A264**, 45 (1976) .
- □ S.A. Tonsfeldt, PhD Thesis, University of North Carolina, 1983.



A_{zz} (E_{cell}, 24.5 °)

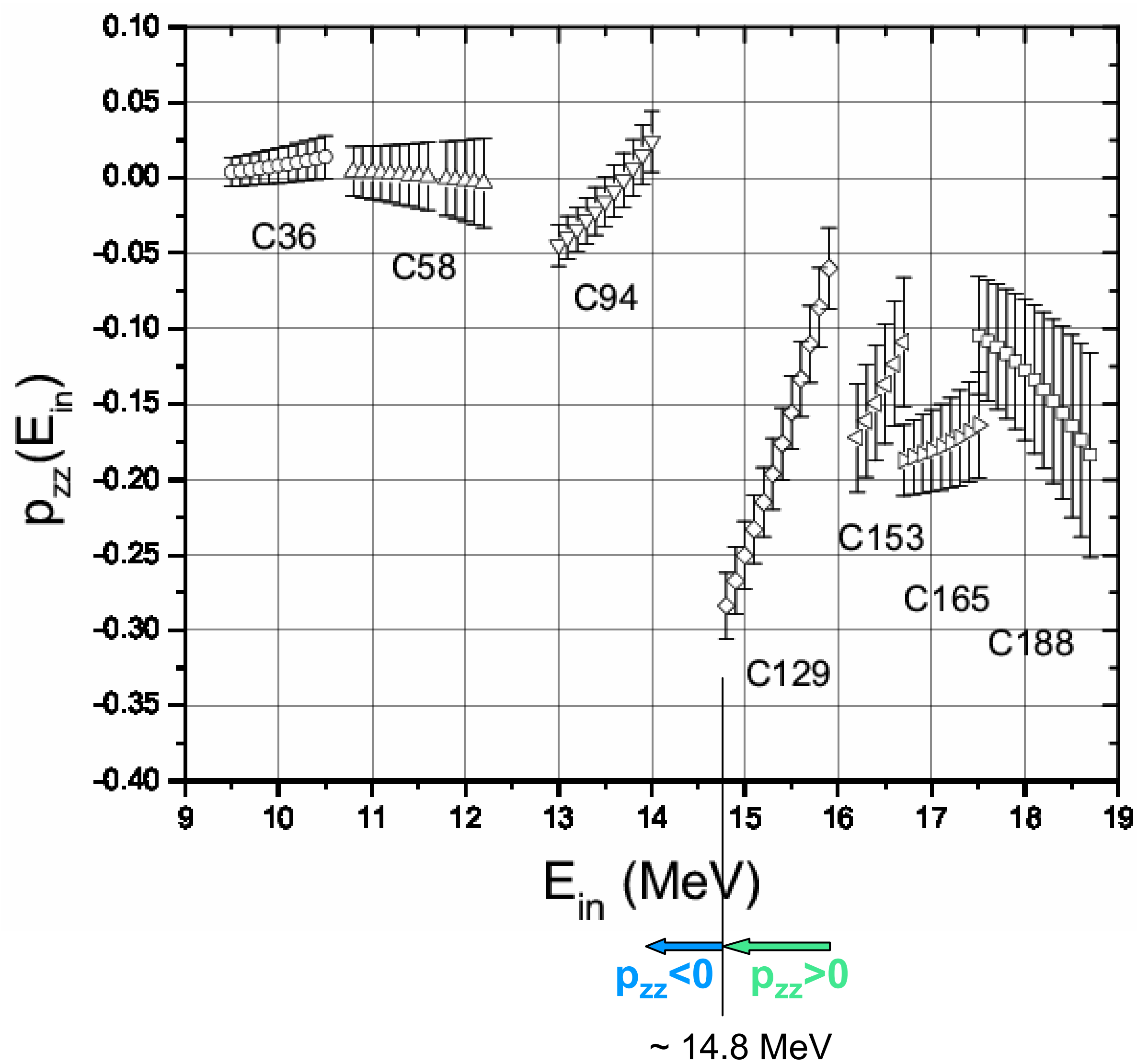
- ■ M. Bittcher, W. Grüebler, V. König, P.A. Schmelzbach, B. Vuaridel, and J. Ulbricht, Few-Body Systems 9, 165 (1990)
- □ S.A. Tonsfeldt, PhD Thesis, University of North Carolina, 1983.

p_{zz} measured at E_{cell} in the polarimeter cell

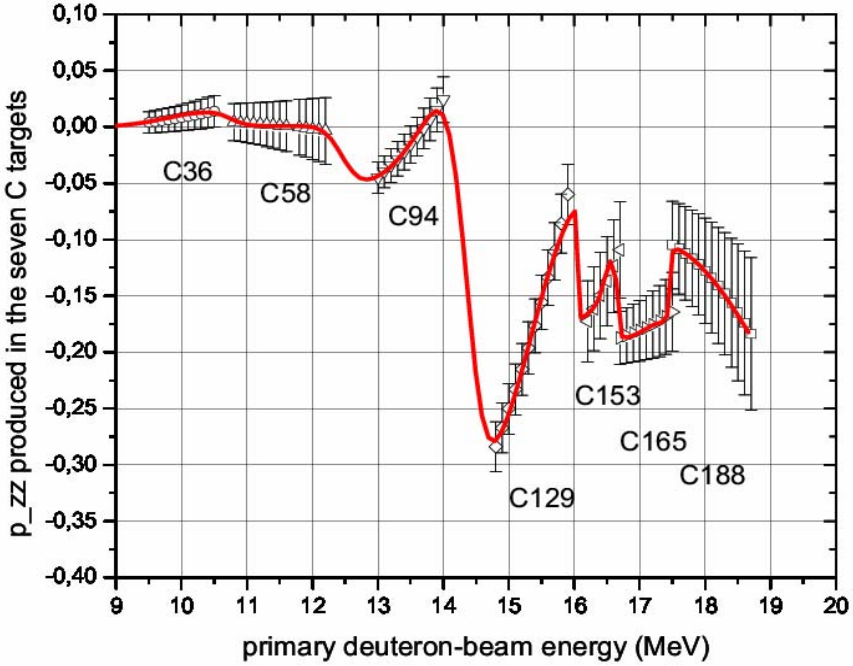


$$p_{zz}(E_{cell}) \rightarrow p_{zz}(E_{in})$$

The (unexpected) experimental result



Theoretical values in the order of 10^{-2}, change of sign at 11 Mev, energy dependence much slower



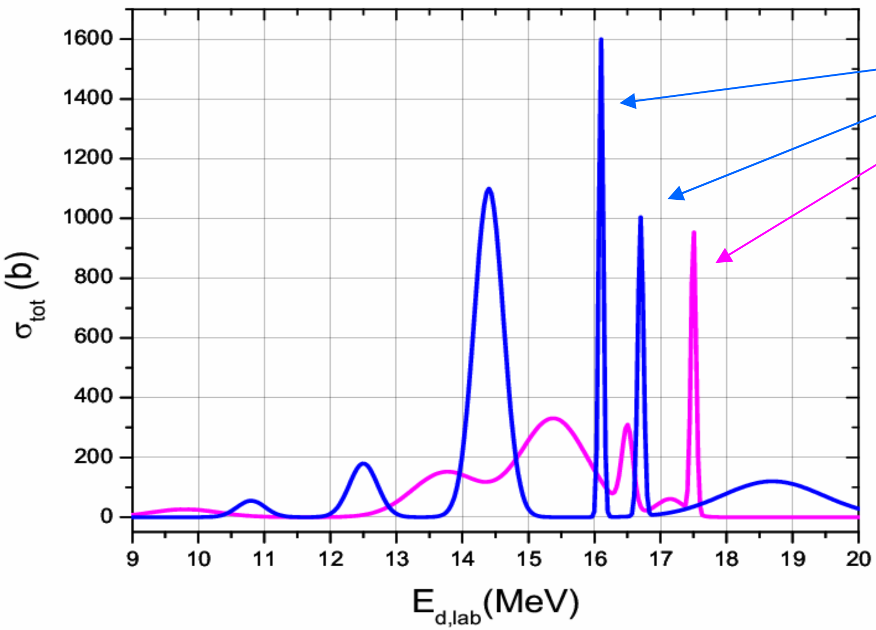
$$p_{zz}(\rho d_t) = \frac{2e^{-\rho\int_0^{d_t}\sigma_{\pm1}\left(E(x)\right)\mathrm{d}x} - 2e^{-\rho\int_0^{d_t}\sigma_0\left(E(x)\right)\mathrm{d}x}}{2e^{-\rho\int_0^{d_t}\sigma_{\pm1}\left(E(x)\right)\mathrm{d}x} + e^{-\rho\int_0^{d_t}\sigma_0\left(E(x)\right)\mathrm{d}x}}$$

Fit by **12 Gaussian-distributed cross sections**

Adjustment of E_0, $\sigma(E_0)$, Γ

For **6** of them $\sigma_{\pm1}=0$ → $p_{zz} > 0$

For **6** of them $\sigma_0=0$ → $p_{zz} < 0$



16.1, **16.7**, and **17.5** MeV possibly caused by uncertainties in the target thicknesses

$\sigma_{\pm1} \neq 0$, $\sigma_0 = 0$ → $p_{zz} < 0$

$\sigma_{\pm1} = 0$, $\sigma_0 \neq 0$ → $p_{zz} > 0$

$$E^*(^{14}N) = E_d^{cms} + m_d + m_{^{12}C} - m_{^{14}N} = \frac{m_{^{12}C}}{m_d + m_{^{12}C}} E_d^{lab} + m_d + m_{^{12}C} - m_{^{14}N}$$
$$= 0.85628 \cdot E_d^{lab} + 10.2720\ [MeV].$$

resonance data from the present fit						$^{12}C(d, \alpha_2)^{10}B^*(1.74MeV)$					
no.	E_0^{lab} [MeV]	$\sigma(E_0)$ [b]	Γ [keV]	p_{zz} produced by isolated resonance	$E^*(^{14}N)$ [MeV]	$(d\sigma/d\omega)_{c.m.}$ backward $E^*(^{14}N)$ [MeV]	μb/sr	ref.	$(d\sigma/d\omega)_{c.m.}$ forward $E^*(^{14}N)$ [MeV]	μb/sr	ref.
1	18.7±0.3	120±40	1800±300	– 0.14±0.03	26.3±0.3						
2	17.5±0.2	950±100	90±30	+0.06±0.01	25.3±0.2						
3	17.15±0.4	60±20	500±100	$+0.05^{+0.01}_{-0.03}$	25.1±0.3						
4	16.7±0.2	1000±200	100±30	$-0.083^{+0.006}_{-0.033}$	24.6±0.2	~24.6	4±1	a			
5	16.5±0.3	280±50	200±50	+0.062±0.013	24.4±0.3	~24.3	6±2	a			
6	16.1±0.2	1600±400	80±30	– 0.12±0.02	24.0±0.2	~24.1	5±1	a			
7	15.38±0.03	330±40	1200±400	+0.228±0.016	23.44±0.03	~23.5	6±2	a	23.36	~60	b
8	14.4±0.1	1100±100	520±100	– 0.375±0.014	22.6±0.1	~22.6	19^{+4}_{-12}	a	22.6±0.1	~90	b, c
9	13.75±0.05	150±20	1200±200	+0.10±0.02	22.05±0.04						
									21.8	~40	d
									21.2	~110	d
10	12.5±0.1	180±20	500±100	$-0.05^{+0.01}_{-0.03}$	21.0±0.1						
									20.7	~90	d
11	10.8±0.1	50±30	500±200	$-0.011^{+0.004}_{-0.021}$	19.5±0.1						
									~19.0	~50	e
12	9.8±0.1	25±25	1200±500	$+0.014^{+0.018}_{-0.006}$	18.7±0.1						

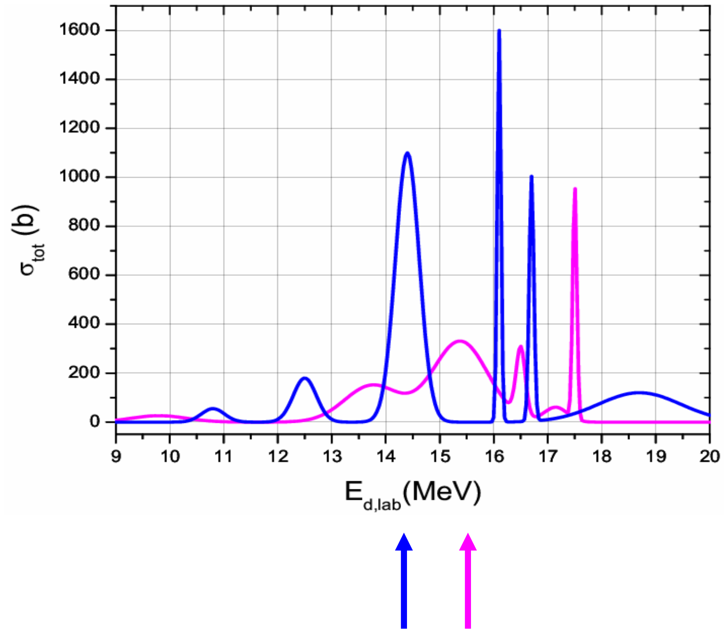
$\sigma(E_o)\cdot\Gamma$ **(b·MeV)**

400

570

a) D. von Ehrenstein et al., Phys. Rev. Lett. **27**, 107 (1971); b) P.L. Jolivette, Phys. Rev. **C 9**, 16 (1974); c) J. Jänecke et al., Phys. Rev. **175**, 1301(1968); d) H. Vernon Smith, Jr., and H.T. Richards, Phys. Rev. Lett. **23**, 1409 (1969); e) L. Meyer-Schützmeister et al.,Phys. Rev. **147**, 743 (1966).

An attempt to interprete the two strong resonances at 14.4 and 15.4 MeV



present work

E_o (MeV)	14.4±0.1	15.38±0.03
$\sigma(E_0)$ (b)	**1100±100**	**330±40**
Γ (keV)	520±100	1000±250
p_{zz}	-0.375±0.014	+0.228±0.016
$E^*(^{14}N)$ (MeV)	**22.6±0.1**	**23.44±0.03**

earlier (d,α) experiments

D. von Ehrenstein et al., Phys. Rev. Lett. **27**, 107 (1971):

$E^*(^{14}N)$ (MeV)	**~22.6**	**~23.5**
$d\sigma/d\Omega$ (μb/sr)	~19	~6

P.L. Jolivette, Phys. Rev. **C 9**, 16 (1974):

$E^*(^{14}N)$ (MeV)	**22.6±0.1**	**23.36**
$d\sigma/d\Omega$ (μb/sr)	90	60

The giant resonance in ^{14}N spreads around 22.5 MeV with a width (FWHM) of 3.5 MeV

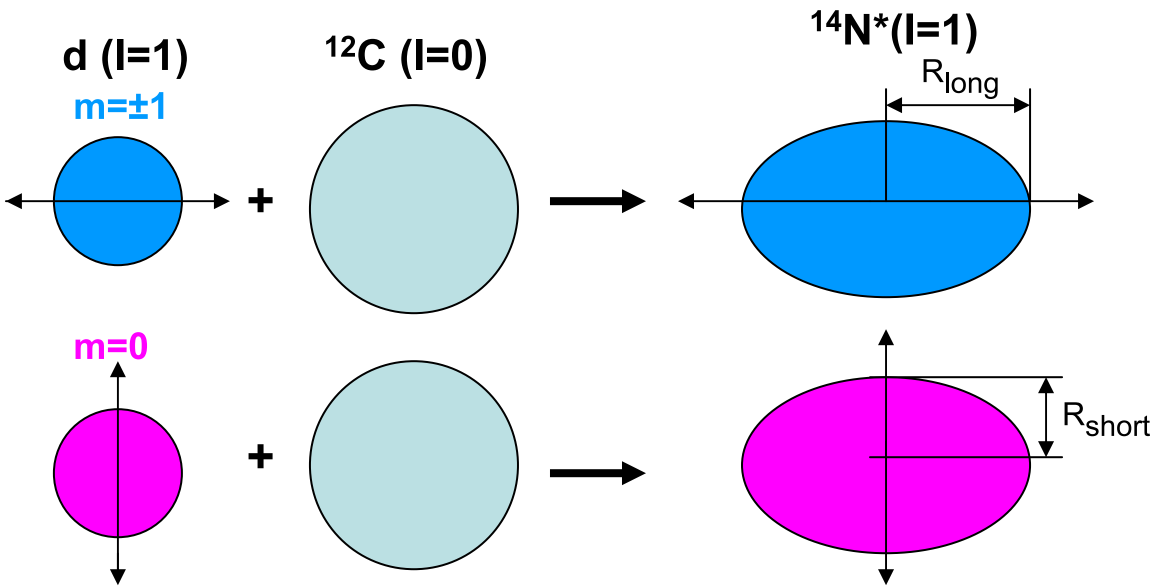
M. Goldhaber and E. Teller, Phys. Rev. 74, 1046 (1948): **dipole vibration of the bulk of protons against that of neutrons**

$$\hbar\omega = \left(\frac{3\varphi\hbar^2}{\varepsilon R_0 m}\right)^{\frac{1}{2}}$$

φ=30 MeV, ε=2.4 fm, and $R_0=R_e$=3.13 fm → **ħω= 22.3 MeV**

Extension of the vibrational model to 2 orthogonal vibrations in a deformed nucleus

Tentative use of the quadrupole moment of the ^{14}N ground state of +0.0193 b yields $R_{long}=R_0+0.07$ fm=3.20 fm and $R_{short}=R_0-0.07$fm=3.06 fm



These modified values of R_0 yield

$\hbar\omega$ (R_{long})=22.1 MeV

Creation of the compound state leads to the removal of deuterons in the m=±1 state from the beam

and

$\hbar\omega$ (R_{short})=22.6 MeV

Creation of the compound state leads to the removal of deuterons in the m=0 state from the beam

vibrational model			present experiment	
excitation energy (MeV)	spin-projection quantum number m	p_{zz}	resonance energy E*(^{14}N) (MeV)	p_{zz} produced by the resonance
22.1	±1	<0	22.6±0.1	-(0.375±0.014)
22.6	0	>0	23.44±0.03	+(0.228±0.016)

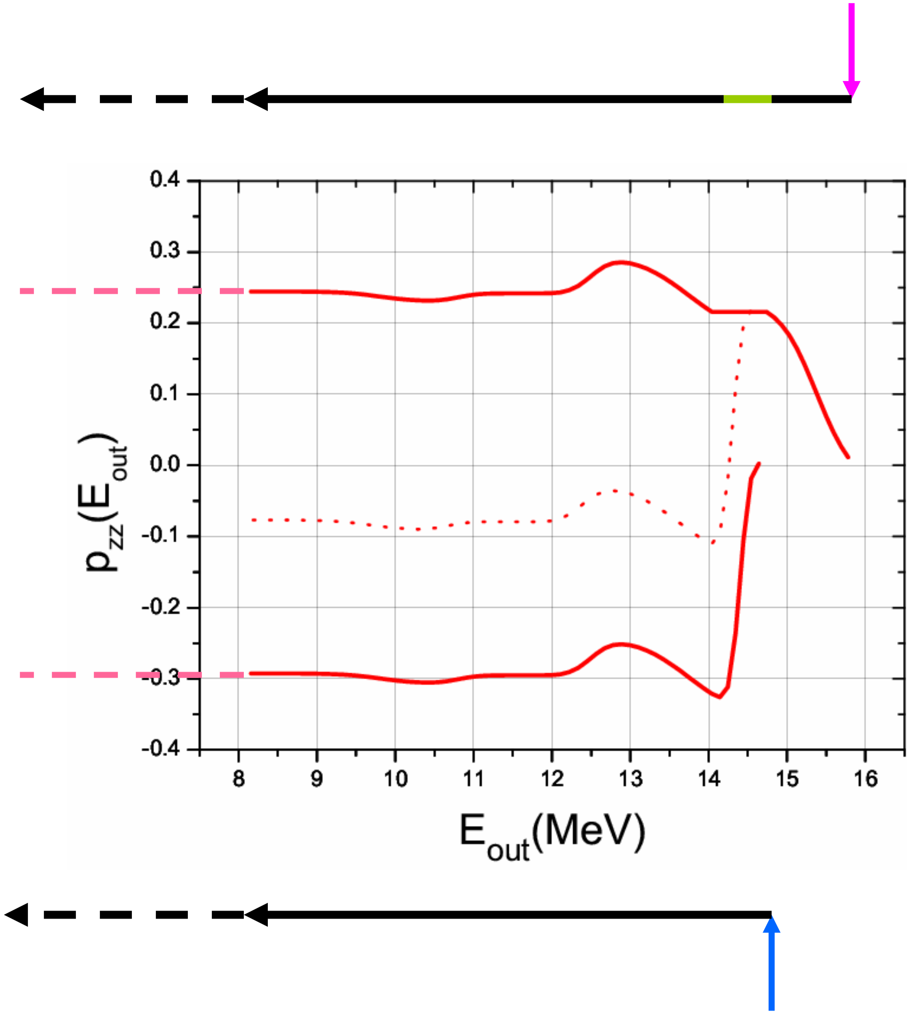
The simple picture would allow a first interpretation. Is it, however, valid?

At present **no real understanding** of the surprising results, mainly due to the requested **large cross section** values

Extra-nuclear effects?
(polarization of the deuterons in the Coulomb field, i.e., change of the deuteron wave function,
spin-orbit coupling?)

The results, however, would allow the (inexpensive) production of tensor-polarized deuteron beams

E_{in} at the upper edge of the 15.38 MeV resonance



E_{in} at the upper edge of the 14.4 MeV resonance

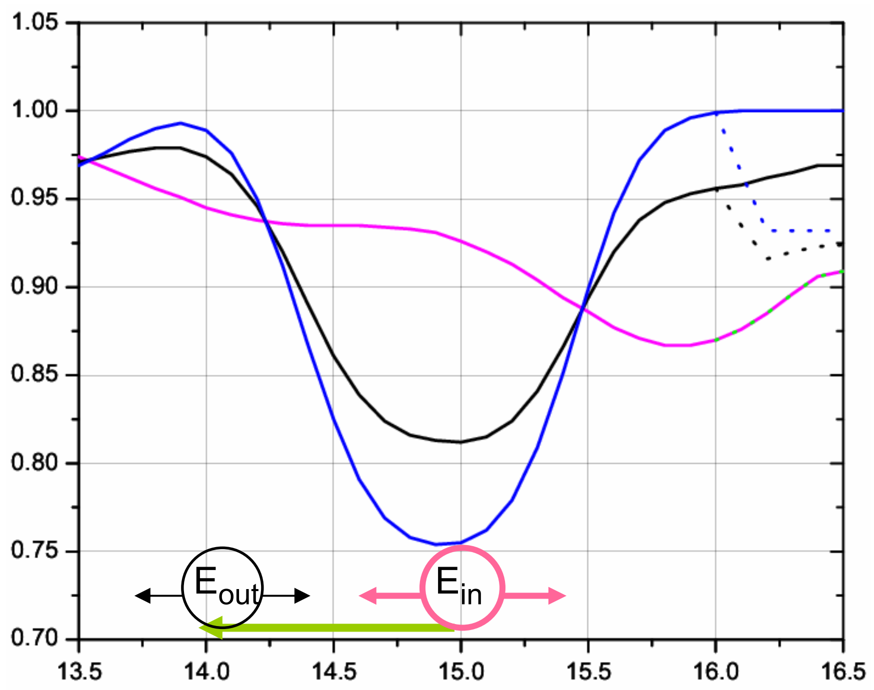
deceleration in the carbon (graphite) target **with** production of p_{zz}

deceleration in a sandwiched material **without** production of p_{zz}

Confirmatory measurement under consideration:

Transmission of 13.5 to 16.5 MeV deuteron beams through a **20 mg/cm^2 carbon foil**

Energy loss in the foil **ΔE_d ~ 1 MeV**



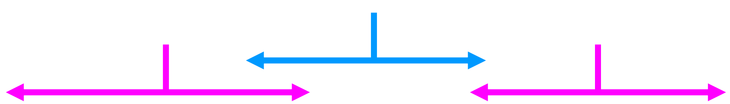
E_{in} (MeV)

p_{zz}= + 1, p_z = 0 (100% m=±1)

unpolarized beam (2/3 m=±1, 1/3 m=0)

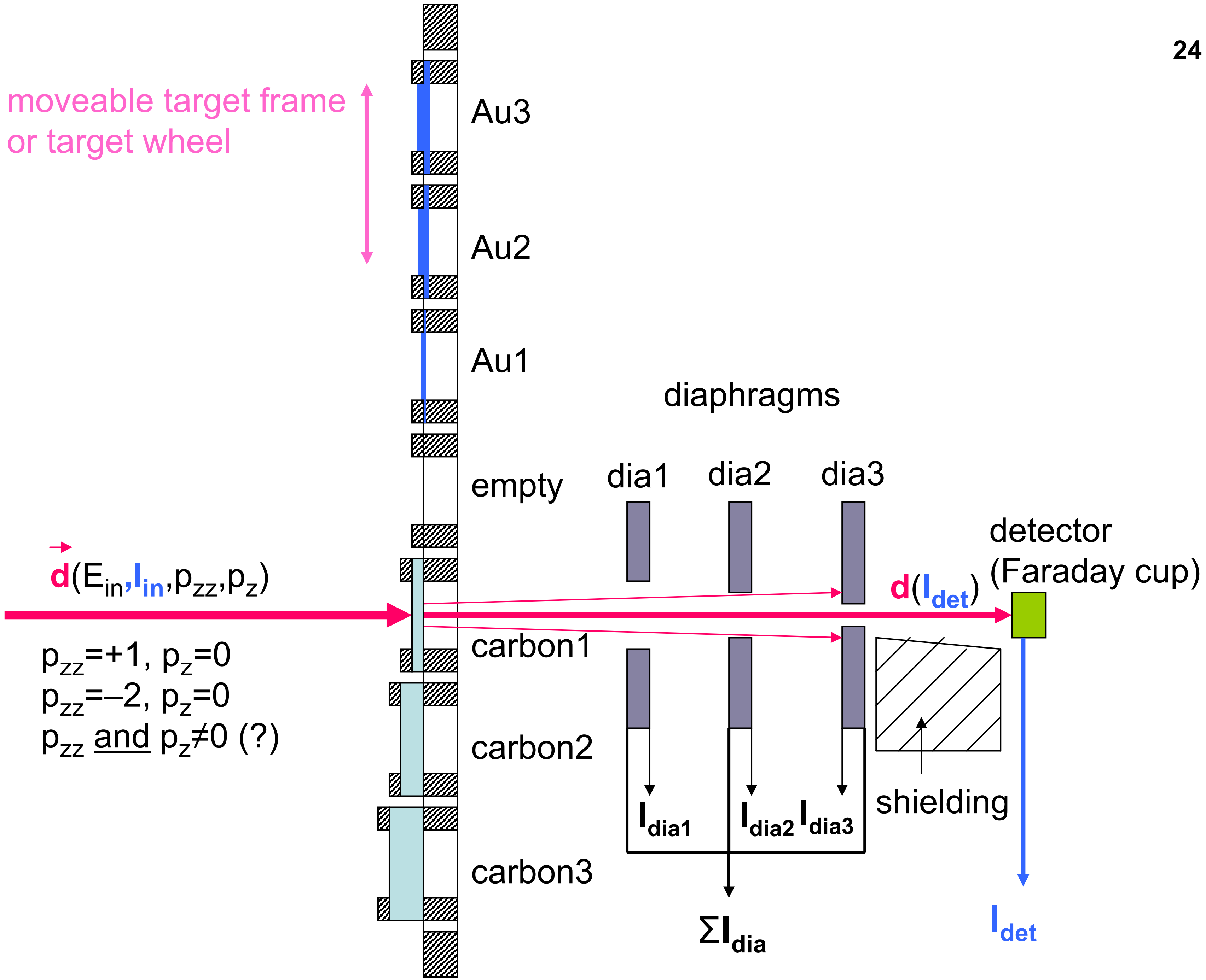
p_{zz}= – 2, p_z = 0 (100% m=0)

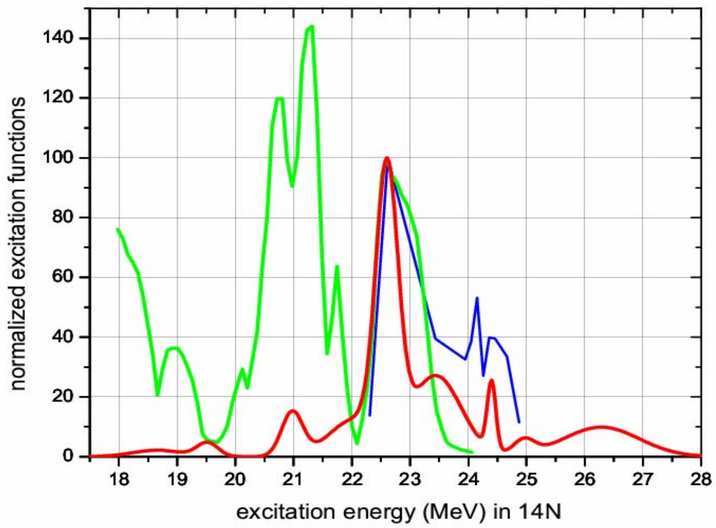
dashed lines: with the possibly artificial resonance at 16.1 MeV

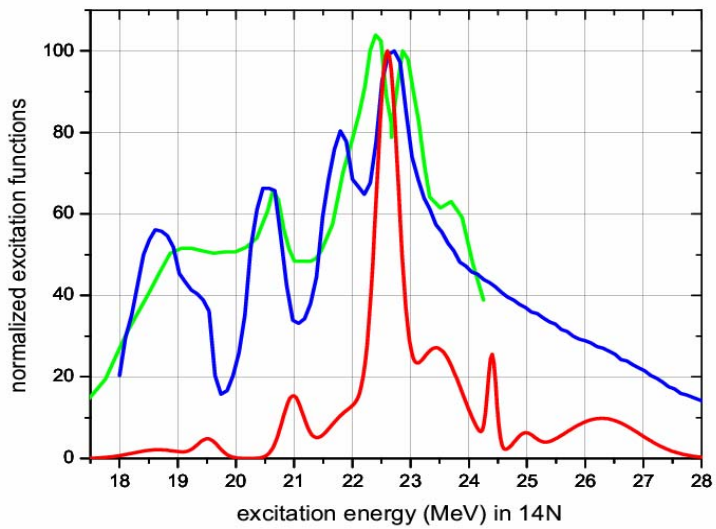


! → **Calculated with either σ_0 or $\sigma_{\pm 1}$ equal to zero**

13.75	**14.4**	**15.4** MeV	resonance **removes**
m=0	**m=±1**	**m=0**	deuterons from the beam


moveable target frame
or target wheel
Au3
Au2
Au1
empty
carbon1
carbon2
carbon3
diaphragms
dia1
dia2
dia3
detector
(Faraday cup)
$\vec{d}(E_{in}, I_{in}, p_{zz}, p_z)$
$d(I_{det})$
$p_{zz}=+1$, $p_z=0$
$p_{zz}=-2$, $p_z=0$
p_{zz} and $p_z \neq 0$ (?)
I_{dia1}
I_{dia2}
I_{dia3}
shielding
ΣI_{dia}
I_{det}





$^{12}\mathrm{C}(\mathrm{d},\alpha)^{10}\mathrm{B}^*(1.74\mathrm{MeV}, \mathrm{J}^\pi = 0^+, \mathrm{T} = 1)$

α emission forward

L. Meyer-Schützmeister et al.,Phys. Rev. **147**, 743 (1966); H. Vernon Smith, Jr., and H.T. Richards, Phys. Rev. Lett. **23**, 1409 (1969); P.L. Jolivette, Phys. Rev. **C 9**, 16 (1974)

α emission backward

D. von Ehrenstein et al., Phys. Rev. Lett. **27**, 107 (1971)

peaks of the present fit without the possibly artificial resonances at 16.1, 16.7, and 17.5 MeV

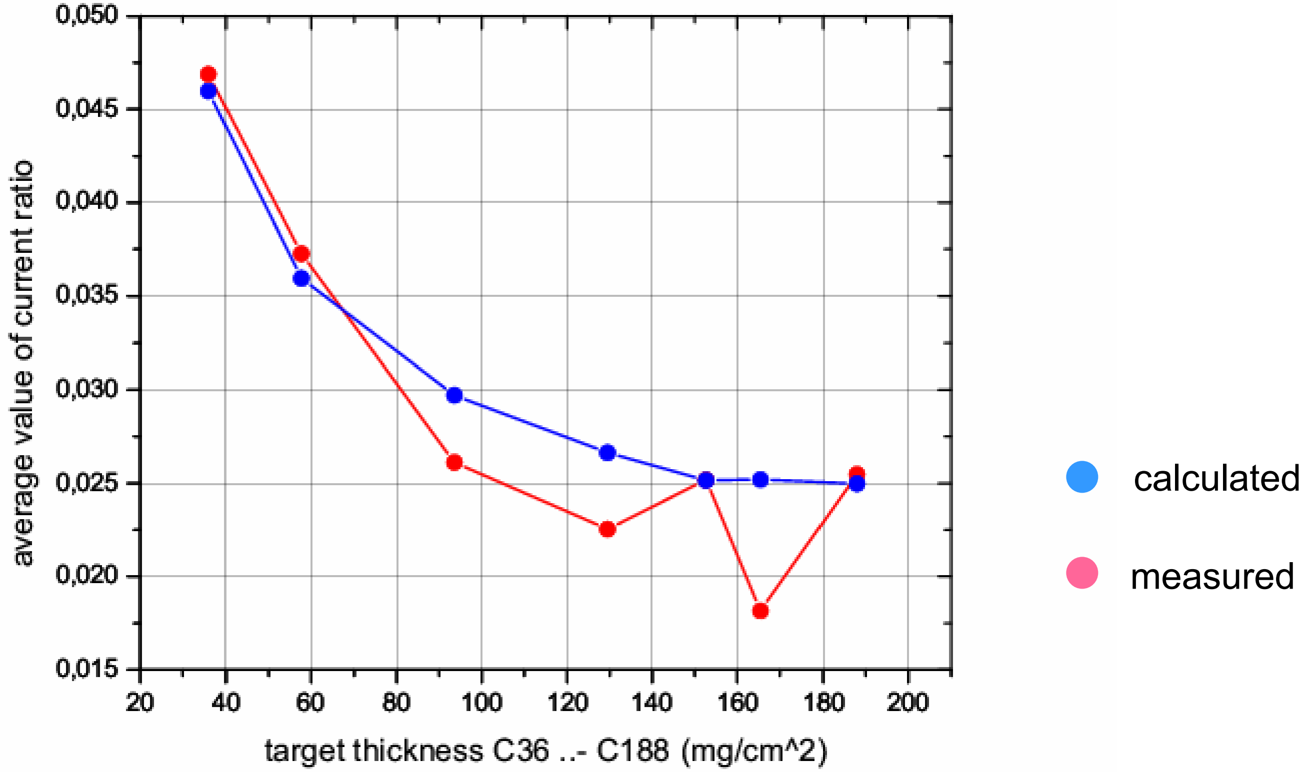
$^{13}C(p,\gamma)^{14}N$

F. Riess et al., Nucl. Phys. A175, 462 (1971)

$^{14}N(\gamma,p)^{13}C$

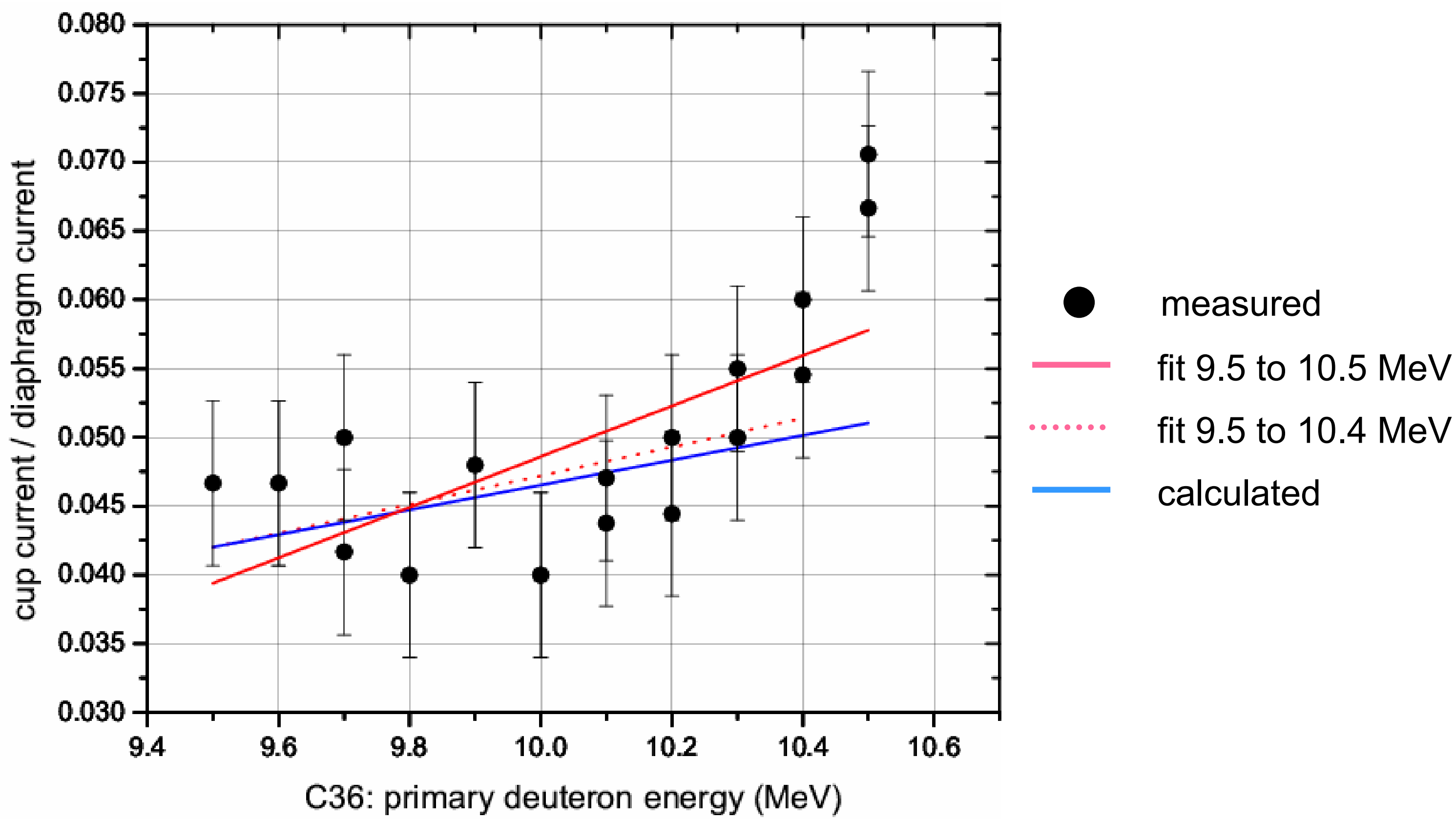
R. Kosiek, K. Maier, and K Schlüpmann, Phys. Lett. 9, 260 (1964)

Agreement in the peak positions accidental?



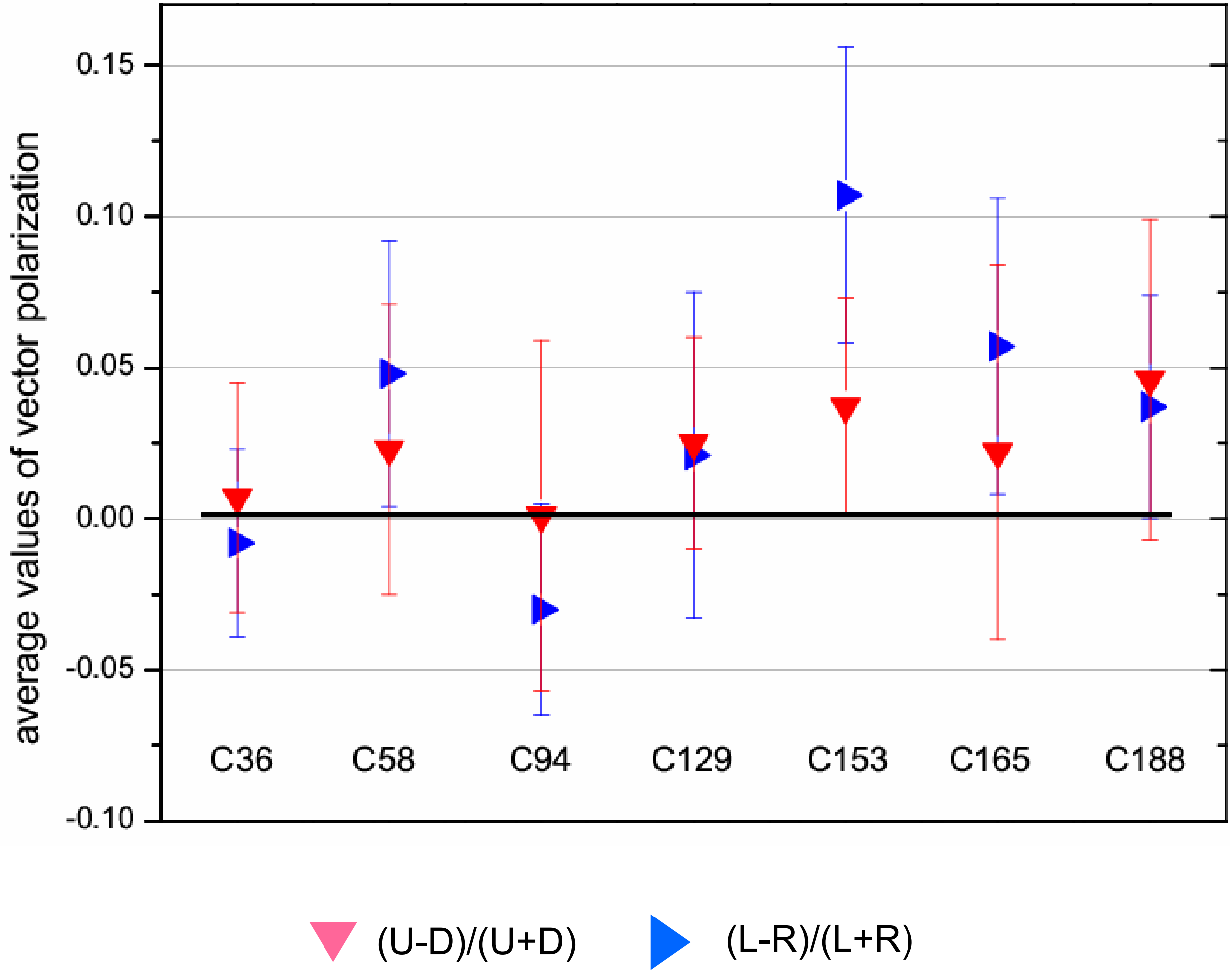
Average values of the ratio $\mathbf{I_{cup}/I_{diaphragams}}$ for the 7 carbon targets

Width of the angular distribution $\sim \frac{1}{vp}\sqrt{d_{target}} \rightarrow$ ratio decreases with d_{target}

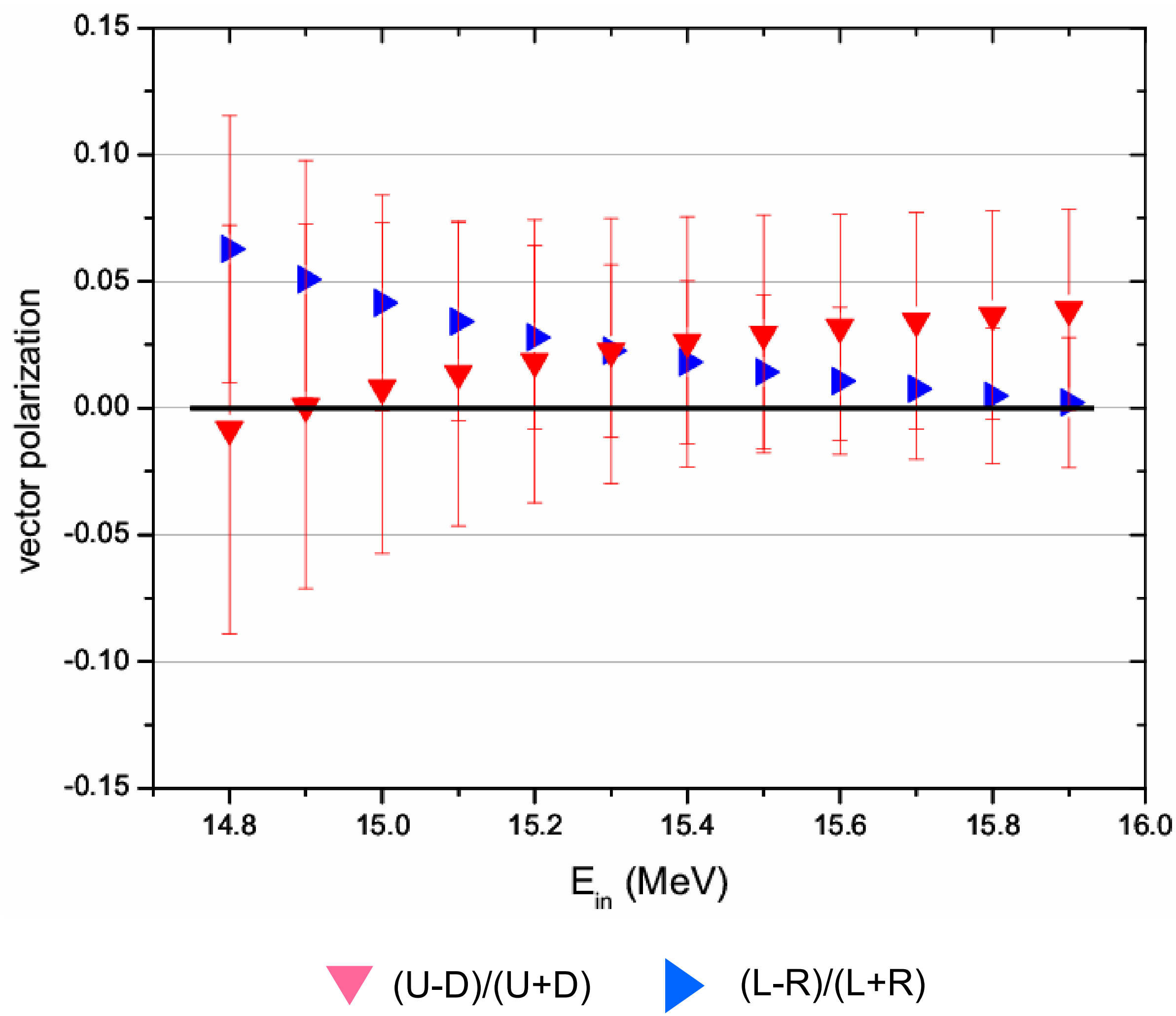


Energy dependence of the ratio $\mathbf{I_{cup}/I_{diaphragams}}$ for the C36 carbon target

Width of the angular distribution ~ $(vp)^{-1}$→ ratio increases with energy



0.15
0.10
0.05
0.00
-0.05
-0.10
average values of vector polarization
C36
C58
C94
C129
C153
C165
C188
(U-D)/(U+D)
(L-R)/(L+R)


0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
vector polarization
14.8
15.0
15.2
15.4
15.6
15.8
16.0
E_in (MeV)
(U-D)/(U+D)
(L-R)/(L+R)