Experimental observation of deuteron spin dichroism

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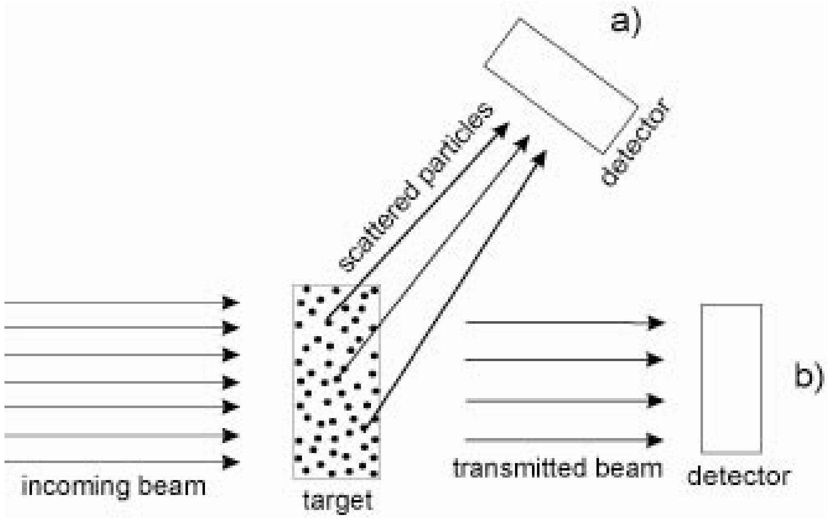
Scattering vs. Transmission Experiment



a) scattering experiment ⟹ incoherently scattered articles detecting

b) transmission experiment ⟹ coherently scattered particles are detected in forward direction.

Spin rotation of high-energy particles in polarized targets

- As a result of numerous studies (*M.Lax, Rev.Mod.Phys. 23 (1951) 287*), a close connection between the amplitude *f(0)* of coherent elastic scattering at zero angle and the refraction index of a medium *N* has been established

$$N = 1 + \frac{2\pi\rho}{k^2} f(0)$$ *k is wave number of a particle*

- When slow neutrons pass through the target with polarized nuclei a new effect of nucleon spin precession occurred. This effect is similar to Faraday effect.

V.G. Baryshevsky and M.I. Podgoretsky, Zh. Eksp.Teor. Fiz. 47 (1964) 1050 [Sov. Phys. JETP 20 (1965) 704]

- In a polarized target neutrons are characterized by two refraction indices $N_{\uparrow\uparrow} \neq N_{\uparrow\downarrow}$

$N_{\uparrow\uparrow}$ for neutrons with the spin parallel to the target polarization vector

$N_{\uparrow\downarrow}$ for neutrons with the opposite spin orientation

The experiments which proved the existence of this effect was done by

A. Abragam et al., C.R. Acad. Sci. 274 (1972) 423

M. Forte, Nuovo Cimento A 18 (1973) 727

A. Abragam and M. Goldman, Nuclear magnetism: order and disorder (Oxford Univ. Press, Oxford, 1982).

Deuteron spin rotation and oscillations in an unpolarized target (I)

The refractive index of neutral and charged particles of spin S

$$\widehat{N} = 1 + \frac{2\pi\rho}{k^2}\hat{f}(0)\,, \;\; \hat{f}(0) = Sp\,\hat{\rho}_J \widehat{F}(0)$$

If the wave function of the particle entering a target is ψ_0, then after travelling a distance *z* in the target it is

$$\psi(z) = \exp\left(i\,k\,\widehat{N}\,z\right)\psi_0$$

The explicit form of the amplitude $\hat{f}(0)$ for particles with arbitrary spin *S* has been obtained in *V. G. Baryshevsky, J. Phys.G 19, 273 (1993).*

Consider a specific case of strong interactions invariant under space and time reflections. Even for an unpolarized target, $\hat{f}(0)$ is a function of the incident particle spin operator

$$\hat{f}(0) = d + d_1 S_z^{\,2} + d_2 S_z^{\,4} + \ldots + d_s S_z^{\,2S}$$

for deuterons

$$\hat{f}(0) = d + d_1 S^2$$

In this case the terms containing odd powers of S are neglected and the refractive index is:

$$\hat{N} = 1 + \frac{2\pi\rho}{k^2}\left(d + d_1 S_z^{\,2} + d_2 S_z^{\,4} + \ldots + d_s S_z^{\,2S}\right)$$

for deuterons

$$\hat{N} = 1 + \frac{2\pi\rho}{k^2}\left(d + d_1 S_z^{\,2}\right)$$

Deuteron spin rotation and oscillations in an unpolarized target (II)

The refractive index depends on orientation of the spin with respect to the momentum *even for unpolarized media*. As a result, a new phenomenon of spin rotation and oscillation appears for deuteron (or particle with spin ≥ 1) passing through an unpolarized medium.

- magnitude of the effect increases with the growth of particle energy !

These phenomena are similar to the well-known birefringence optical effect in Iceland spar.

Let me denotes a magnetic quantum number, then for a deuteron in a state that is an eigenstate of the spin projection operator onto the z axis (S_z) the refractive index

$$N(m) = 1 + \frac{2\pi\rho}{k^2}\left(d + d_1 m^2\right)$$

Particle states with quantum numbers m and -m have the same refractive indices.

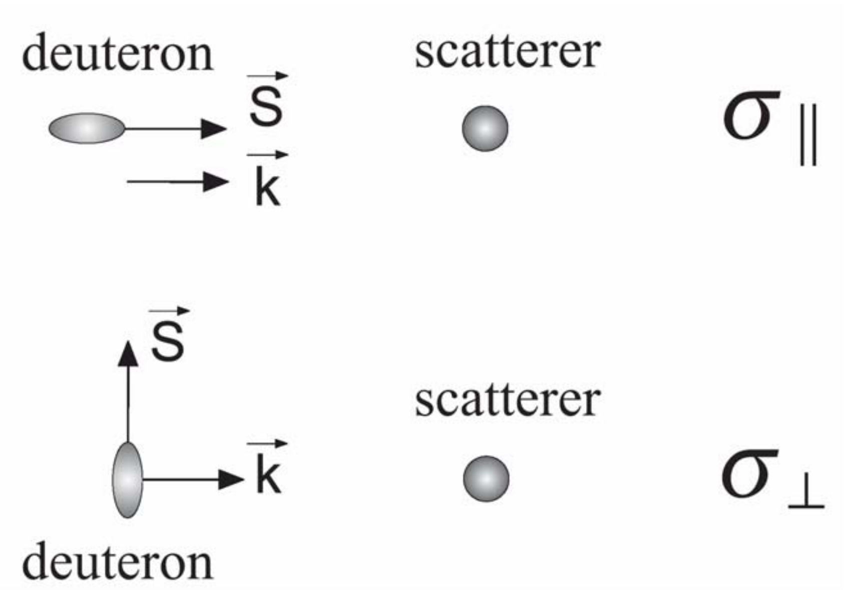
For deuteron:

$$\operatorname{Re} N(\pm 1) \neq \operatorname{Re} N(0)$$

$$\operatorname{Im} N(\pm 1) \neq \operatorname{Im} N(0)$$

Deuteron (spin = 1) passing through an unpolarized target (I)

Appearance of two refraction indices of the deuterons can be easily explained



The ground state of a deuteron is non-spherical ⇒ the scattering cross-section depends on the angle between the spin and momentum of the deuteron

$$\mathrm{Im} f_{\parallel}(0) = \frac{k}{4\pi}\sigma_{\parallel} \neq \mathrm{Im} f_{\perp}(0) = \frac{k}{4\pi}\sigma_{\perp}$$

According to the dispersion relation *Re f(0) ~ Φ (Im f(0))*

$$Re\ f_{\perp}(0) \neq Re\ f_{\parallel}(0)$$

Deuteron (spin = 1) passing through an unpolarized target (II)

The deuteron spin wave function can be represented as a superposition of basis spin wave functions χ_m that are eigenfunctions of the operators $\hat{S}^2$ and $\hat{S}_z$, $\hat{S}_z \chi_m = m \chi_m$

$$\psi = \sum_{m=\pm 1,0} a^m \chi_m$$

Suppose the particle enter the target at *z=0*. Wave function of the particle inside the target at the depth *z* *(* $N_1 = N_{-1}$*)*:

$$\Psi = \begin{Bmatrix} a^1 \\ a^0 \\ a^{-1} \end{Bmatrix} = \begin{Bmatrix} a\, e^{i\delta_1} e^{ikN_1 z} \\ b\, e^{i\delta_0} e^{ikN_0 z} \\ c\, e^{i\delta_{-1}} e^{ikN_{-1} z} \end{Bmatrix} = \begin{Bmatrix} a\, e^{i\delta_1} e^{ikN_1 z} \\ b\, e^{i\delta_0} e^{ikN_0 z} \\ c\, e^{i\delta_{-1}} e^{ikN_1 z} \end{Bmatrix}$$

Deuteron (spin = 1) passing through an unpolarized target (III)

The cartesian spin-tensor moment expansion of the density matrix for the deuteron beam before the target is written as

$$\hat{\rho}_0 = \frac{\hat{I}}{3} + \frac{1}{2}\left(\vec{p}_x \hat{\vec{S}}_x + \vec{p}_y \hat{\vec{S}}_y + \vec{p}_z \hat{\vec{S}}_z\right) + \frac{2}{9}\left(p_{xy}\hat{Q}_{xy} + p_{xz}\hat{Q}_{xz} + p_{yz}\hat{Q}_{yz}\right) + \frac{1}{9}\left(p_{xx}\hat{Q}_{xx} + p_{yy}\hat{Q}_{yy} + p_{zz}\hat{Q}\right)$$

The density matrix of the deuteron beam in the target can be written as

$$\hat{\rho} = \begin{pmatrix} e^{ikN_1 z} & 0 & 0 \\ 0 & e^{ikN_0 z} & 0 \\ 0 & 0 & e^{ikN_1 z} \end{pmatrix} \hat{\rho}_0 \begin{pmatrix} e^{-ikzN_1^* z} & 0 & 0 \\ 0 & e^{-ikN_0^* z} & 0 \\ 0 & 0 & e^{-ikN_1^* z} \end{pmatrix}$$

$$\vec{p} = \langle \vec{S} \rangle = \frac{Tr(\hat{\rho}\hat{\vec{S}})}{Tr\hat{\rho}} \qquad p_{ik} = \langle Q_{ik} \rangle = \frac{Tr\hat{\rho}\hat{Q}_{ik}}{Tr\hat{\rho}} \qquad \text{where } i,k=x,y,z$$

With the initial parameters of the beam at z = 0, $p_{x0}, p_{y0}, p_{z0}, p_{xx0}, p_{yy0}, p_{zz0}, p_{xy0}, p_{xz0}, p_{yz0}$

For deuteron energy up to 20 MeV → $e^{ikz(N_1 - N_1^*)} \approx 1 + ikz(N_1 - N_1^*)$

Deuteron (spin = 1) passing through an unpolarized target (IV)

$$p_x = \frac{\left(1 - \frac{1}{2}\rho z(\sigma_0 + \sigma_1)\right)p_{x0} + \frac{4}{3}\frac{\pi\rho z}{k}\mathrm{Re}\, d_1 p_{zy0}}{Tr\hat{\rho}} \quad \Leftrightarrow \quad p_{yz} = \frac{\left(1 - \frac{1}{2}\rho z(\sigma_0 + \sigma_1)\right)p_{yz0} - \frac{3\pi\rho z}{k}\mathrm{Re}\, d_1 p_{x0}}{Tr\hat{\rho}}$$

$$p_y = \frac{\left(1 - \frac{1}{2}\rho z(\sigma_0 + \sigma_1)\right)p_{y0} - \frac{4}{3}\frac{\pi\rho z}{k}\mathrm{Re}\, d_1 p_{zx0}}{Tr\hat{\rho}} \quad \Leftrightarrow \quad p_{xz} = \frac{\left(1 - \frac{1}{2}\rho z(\sigma_0 + \sigma_1)\right)p_{xz0} + \frac{3\pi\rho z}{k}\mathrm{Re}\, d_1 p_{y0}}{Tr\hat{\rho}}$$

$$p_z = \frac{(1 - \rho\sigma_1 z)p_{z0}}{Tr\hat{\rho}} \qquad p_{xy} = \frac{(1 - \rho\sigma_1 z)p_{xy0}}{Tr\hat{\rho}}$$

$$p_{xx} = \frac{(1 - \rho\sigma_1 z)p_{xx0} + \frac{1}{3}\rho z(\sigma_1 - \sigma_0) - \frac{1}{3}\rho z(\sigma_1 - \sigma_0)p_{zz0}}{Tr\hat{\rho}}$$

$$p_{yy} = \frac{(1 - \rho\sigma_1 z)p_{yy0} + \frac{1}{3}\rho z(\sigma_1 - \sigma_0) - \frac{1}{3}\rho z(\sigma_1 - \sigma_0)p_{zz0}}{Tr\hat{\rho}}$$

$$p_{zz} = \frac{\left(1 - \frac{1}{3}\rho z(2\sigma_0 + \sigma_1)\right)p_{zz0} - \frac{2}{3}\rho z(\sigma_1 - \sigma_0)}{Tr\hat{\rho}}$$

where $$Tr\hat{\rho} = 1 - \frac{\rho z}{3}(2\sigma_1 + \sigma_0) - \rho z(\sigma_1 - \sigma_0)\langle Q_{zz0}\rangle$$

Deuteron (spin = 1) passing through an unpolarized target (V)

For initially unpolarized beam $p_{x0} = p_{y0} = p_{z0} = p_{xx0} = p_{yy0} = p_{zz0} = p_{xy0} = p_{xz0} = p_{yz0} = 0$

After a target

$$p_{zz} \approx -\frac{2}{3}\rho z(\sigma_1 - \sigma_0)$$

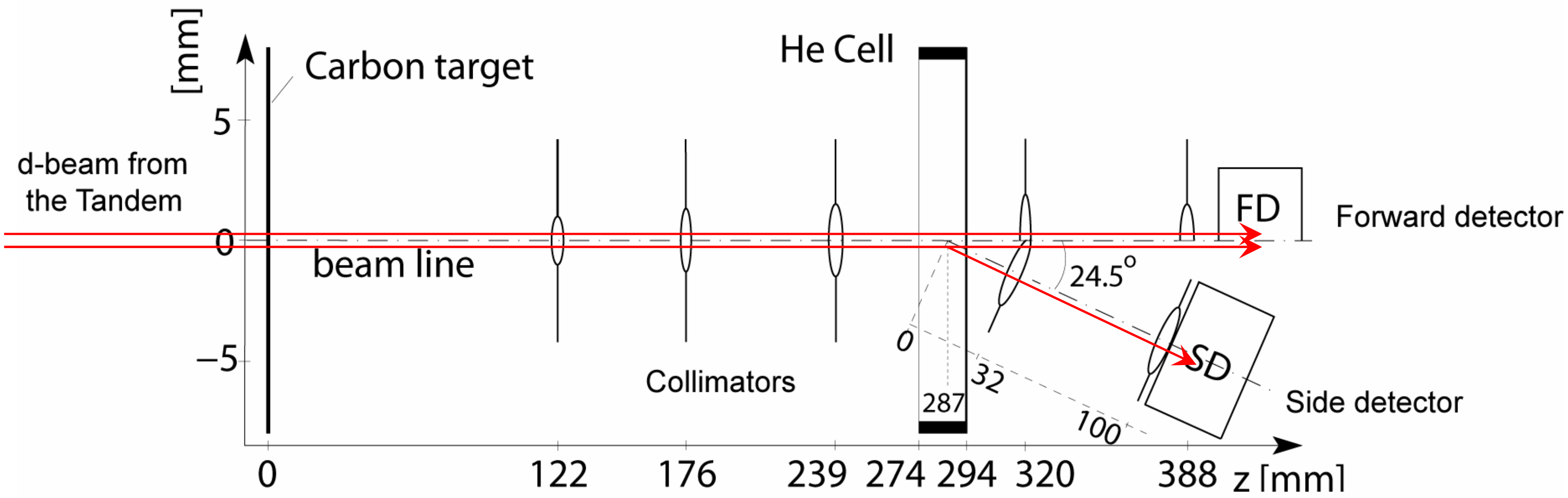
$$p_{xx} = p_{yy} \approx \frac{1}{3}\rho z(\sigma_1 - \sigma_0)$$

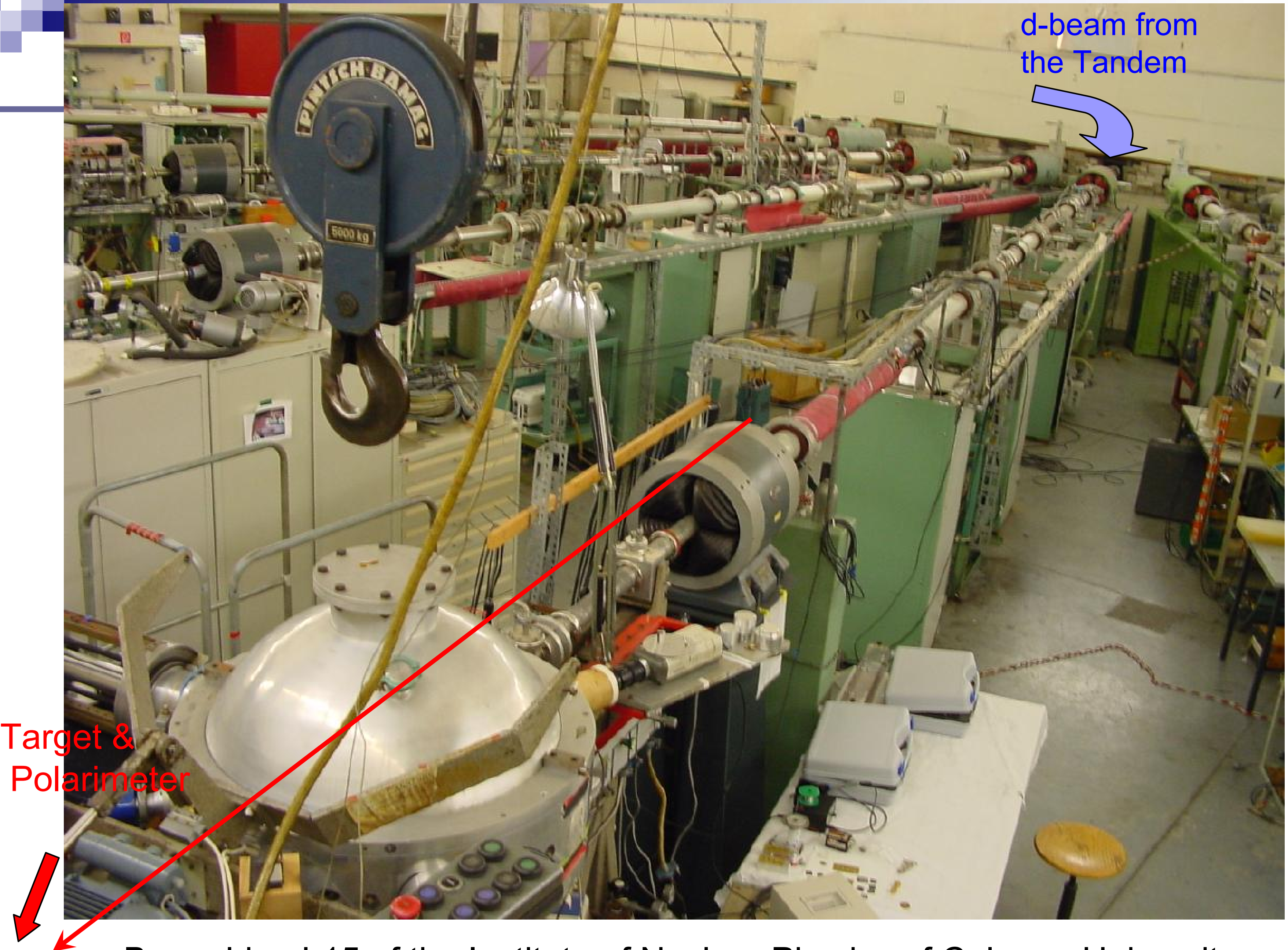
Dicroism is $A = \frac{I_0 - I_\pm}{I_0 + I_\pm} = \frac{\rho z}{2}(\sigma_1 - \sigma_0)$ where I_o and $I_\pm$ are the deuteron occupation numbers with a spin projection m=0 and m=±1, respectively

$$p_{zz} = -\frac{4}{3}A,$$

$$p_{xx} = p_{yy} \approx \frac{2}{3}A$$

Setup of the experimental arrangement



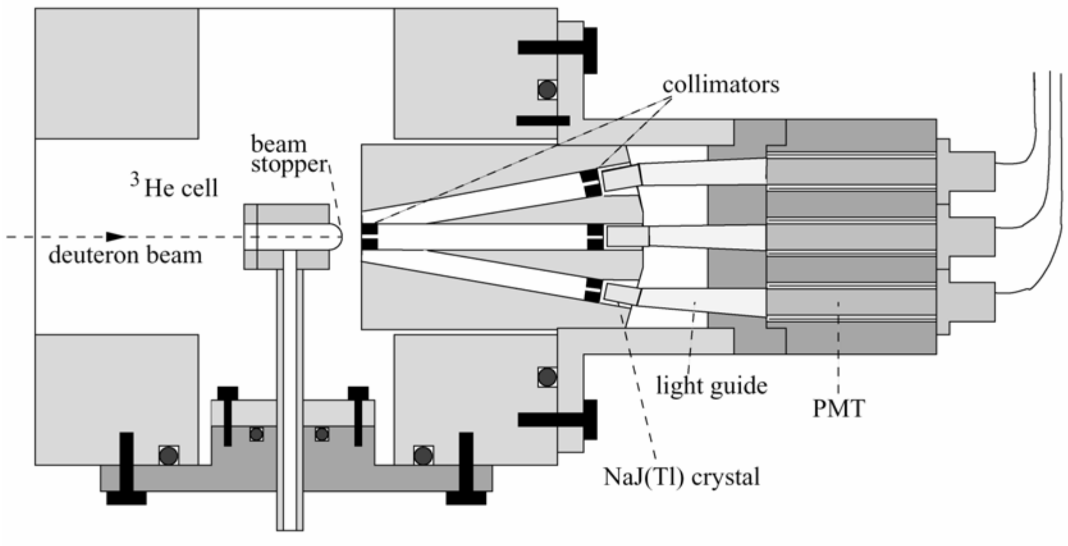


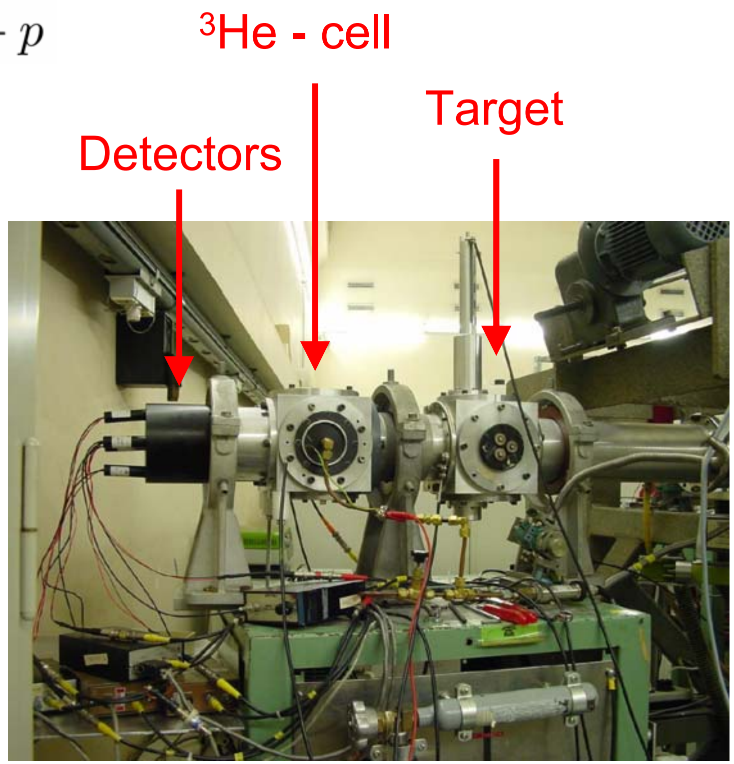
Beam Line L15 of the Institute of Nuclear Physics of Cologne University

Detection Of Deuteron Spin Dichroism With A ^3He - Polarimeter

The existing ^3He polarimeter of the experimental installation was used to measure all components of the deuteron vector and tensor polarization via anisotropies of the outgoing protons from the nuclear reaction

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





$$L = Nn\Omega_L EI(24.5^\circ)_0 \left\{1 + \frac{3}{2}p_{y'}A_y(24.5^\circ) + \frac{2}{3}p'_x z' A_{xz}(24.5^\circ) + \right.$$
$$\left. + \frac{1}{6}(p_{x'z'} - p_{y'y'})\left[A_{xx}(24.5^\circ) - A_{yy}(24.5^\circ)\right] + \frac{1}{2}p_{z'z'}A_{zz}(24.5^\circ)\right\}$$

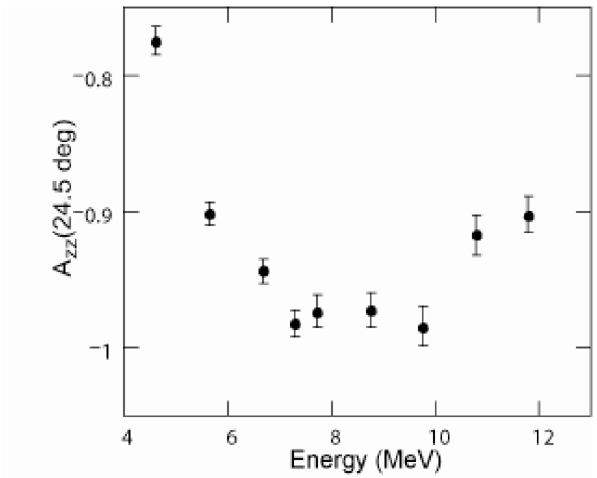
$$R = Nn\Omega_R EI(24.5^\circ)_0 \left\{1 - \frac{3}{2}p_{y'}A_y(24.5^\circ) - \frac{2}{3}p'_x z' A_{xz}(24.5^\circ) + \right.$$
$$\left. + \frac{1}{6}(p_{x'z'} - p_{y'y'})\left[A_{xx}(24.5^\circ) - A_{yy}(24.5^\circ)\right] + \frac{1}{2}p_{z'z'}A_{zz}(24.5^\circ)\right\}$$

$$U = Nn\Omega_U EI(24.5^\circ)_0 \left\{1 - \frac{3}{2}p_{y'}A_y(24.5^\circ) + \frac{2}{3}p'_x z' A_{xz}(24.5^\circ) - \right.$$
$$\left. + \frac{1}{6}(p_{x'z'} - p_{y'y'})\left[A_{xx}(24.5^\circ) - A_{yy}(24.5^\circ)\right] + \frac{1}{2}p_{z'z'}A_{zz}(24.5^\circ)\right\}$$

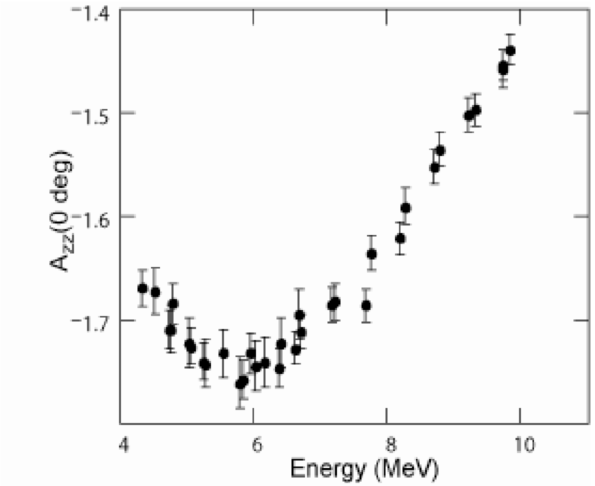
$$D = Nn\Omega_D EI(24.5^\circ)_0 \left\{1 + \frac{3}{2}p_{y'}A_y(24.5^\circ) - \frac{2}{3}p'_x z' A_{xz}(24.5^\circ) - \right.$$
$$\left. + \frac{1}{6}(p_{x'z'} - p_{y'y'})\left[A_{xx}(24.5^\circ) - A_{yy}(24.5^\circ)\right] + \frac{1}{2}p_{z'z'}A_{zz}(24.5^\circ)\right\}$$

$$F = Nn\Omega_F EI(0^\circ)_0 \left[1 + \frac{1}{2}p_{z'z'}A_{zz}(0^\circ)\right]$$

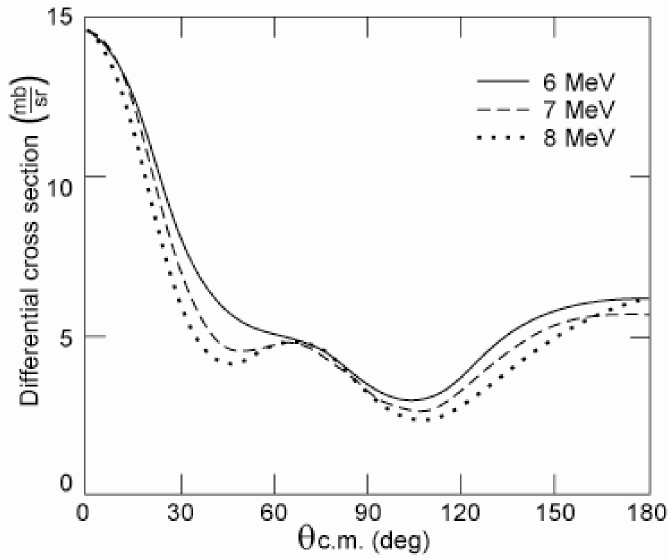
^{3}He - Polarimeter



Analyzing power for the side detectors



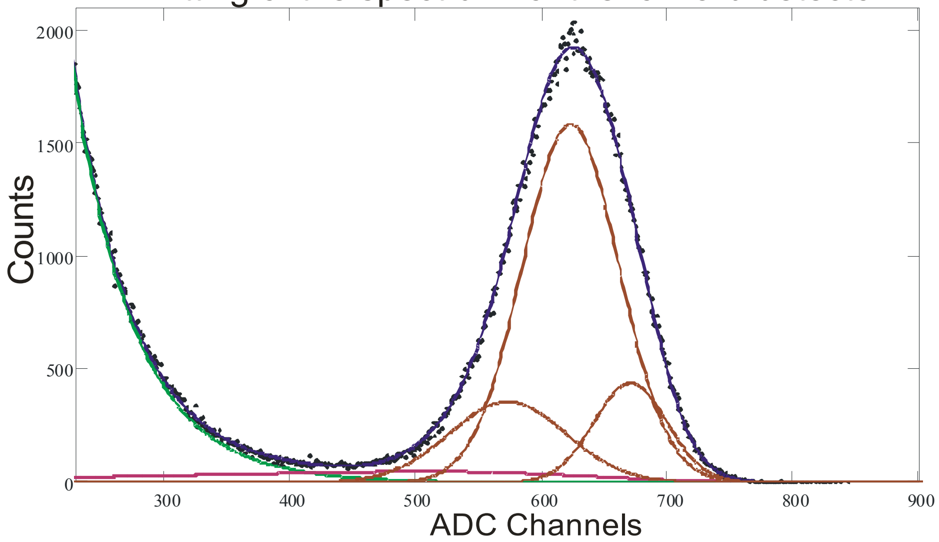
Analyzing power for the forward detector



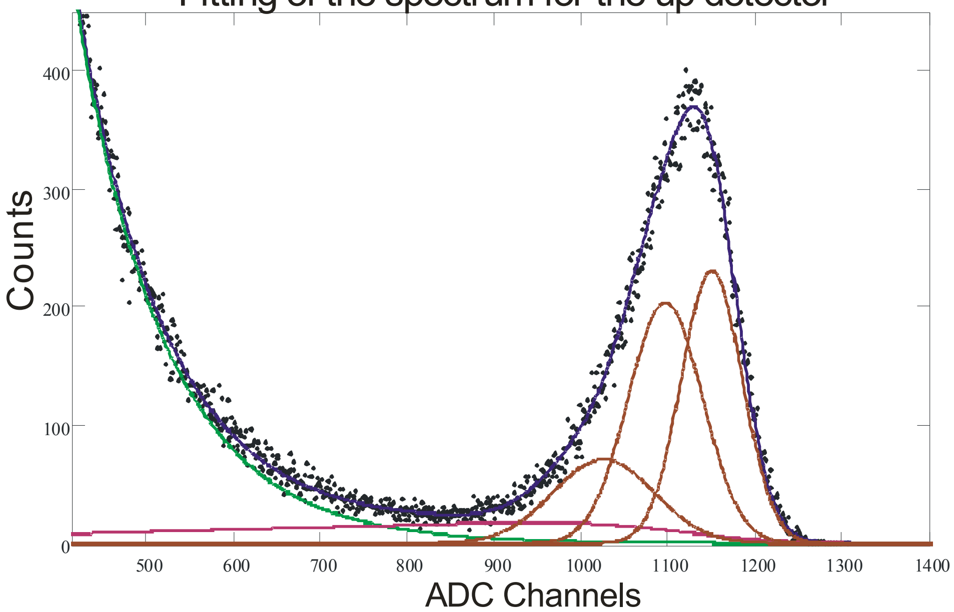
Differential cross section of the ^{3}He(d,p)^{4}He at 6, 7 and 8 MeV

Fitting of spectra

Fitting of the spectrum for the forward detector



Fitting of the spectrum for the up detector



Elements of spectra analysis:

- rebinning
- proton peaks: 2 or 3 Gaussians
- background: exponential + step functions
- forming the error matrix
- χ^2-test

The methodology of experiments

- Without a target

$$L = Nn\Omega_L E_L I(24{,}5^\circ)_0$$

$$R = Nn\Omega_R E_R I(24{,}5^\circ)_0$$

$$U = Nn\Omega_U E_U I(24{,}5^\circ)_0$$

$$D = Nn\Omega_D E_D I(24{,}5^\circ)_0$$

$$F = Nn\Omega_F E_F I(0^\circ)_0$$

$$\frac{L+R+U+D}{F} = \frac{I(24{,}5^\circ)_0\left[\Omega_L E_L + \Omega_R E_R + \Omega_U E_U + \Omega_D E_D\right]}{I(0^\circ)\Omega_F E_F}$$

- With a target

$$L_t = N_t n_t \Omega_L E_L I(24{,}5^\circ)_0\left[1+\tfrac{1}{2}P_{z'z'}A_{zz}(24{,}5^\circ)\right]$$

$$R_t = N_t n_t \Omega_R E_R I(24{,}5^\circ)_0\left[1+\tfrac{1}{2}P_{z'z'}A_{zz}(24{,}5^\circ)\right]$$

$$U_t = N_t n_t \Omega_U E_U I(24{,}5^\circ)_0\left[1+\tfrac{1}{2}P_{z'z'}A_{zz}(24{,}5^\circ)\right]$$

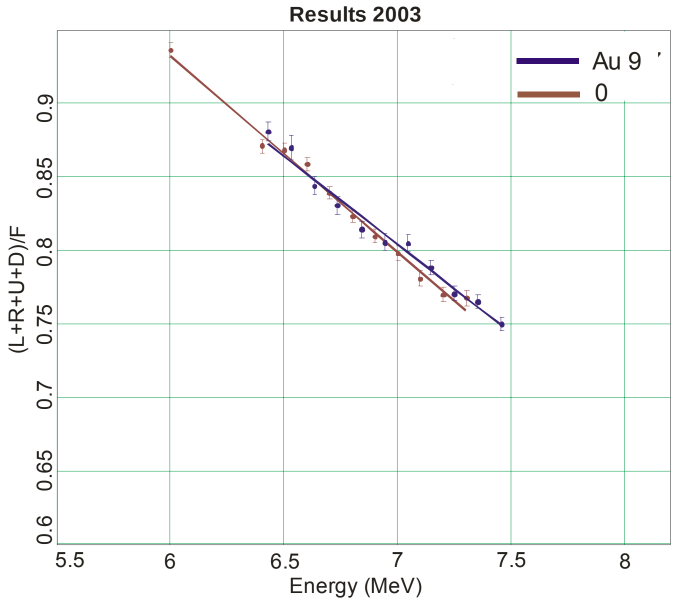
$$D_t = N_t n_t \Omega_D E_D I(24{,}5^\circ)_0\left[1+\tfrac{1}{2}P_{z'z'}A_{zz}(24{,}5^\circ)\right]$$

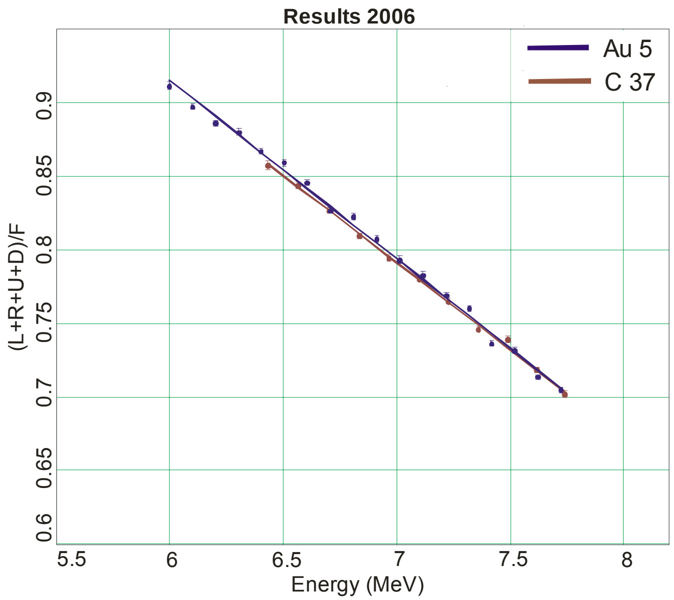
$$F_t = N_t n_t \Omega_F E_F I(0^\circ)_0\left[1+\tfrac{1}{2}P_{z'z'}A_{zz}(0^\circ)\right]$$

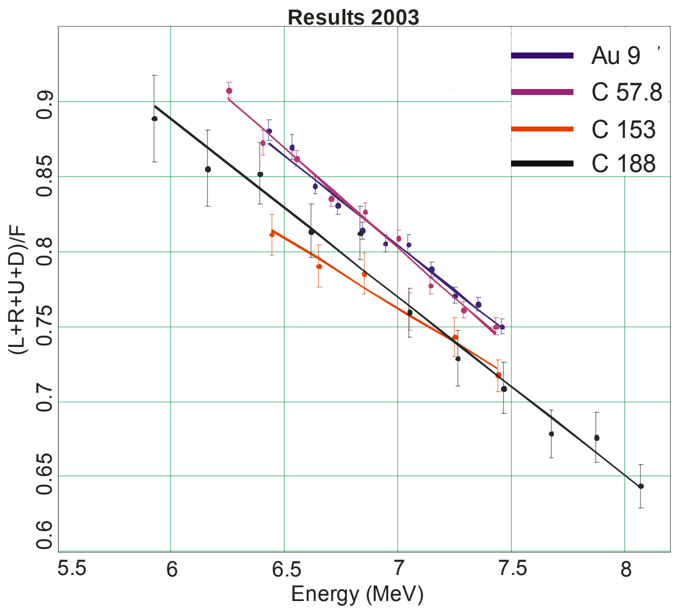
$$\frac{L_t+R_t+U_t+D_t}{F_t} = \frac{I(24{,}5^\circ)_0\left[\Omega_L E_L + \Omega_R E_R + \Omega_U E_U + \Omega_D E_D\right]}{I(0^\circ)\Omega_F E_F}\cdot\frac{\left[1+\frac{1}{2}P_{z'z'}A_{zz}(24{,}5^\circ)\right]}{\left[1+\frac{1}{2}P_{z'z'}A_{zz}(0^\circ)\right]}$$

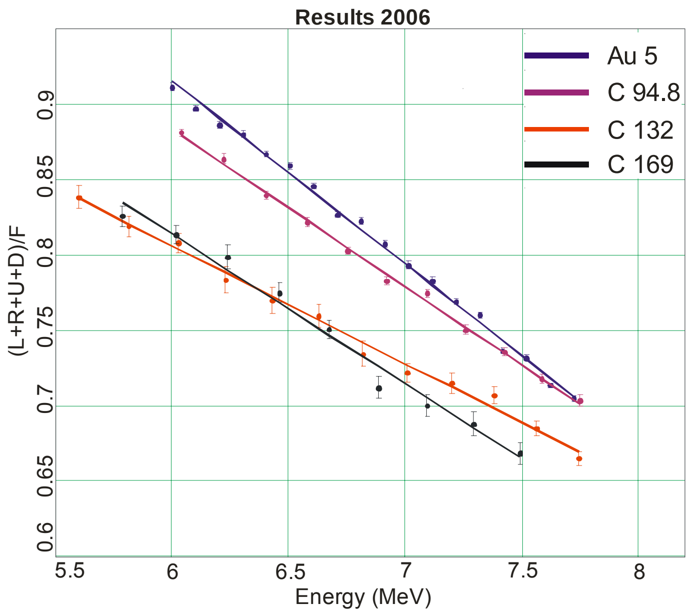
$$\frac{\dfrac{L_t+R_t+U_t+D_t}{F_t}}{\dfrac{L+R+U+D}{F}} = \frac{\left[1+\frac{1}{2}P_{z'z'}A_{zz}(24{,}5^\circ)\right]}{\left[1+\frac{1}{2}P_{z'z'}A_{zz}(0^\circ)\right]}$$

Results of measurement of ratio (L+R+U+D)/F in 2003 and 2006 (I)

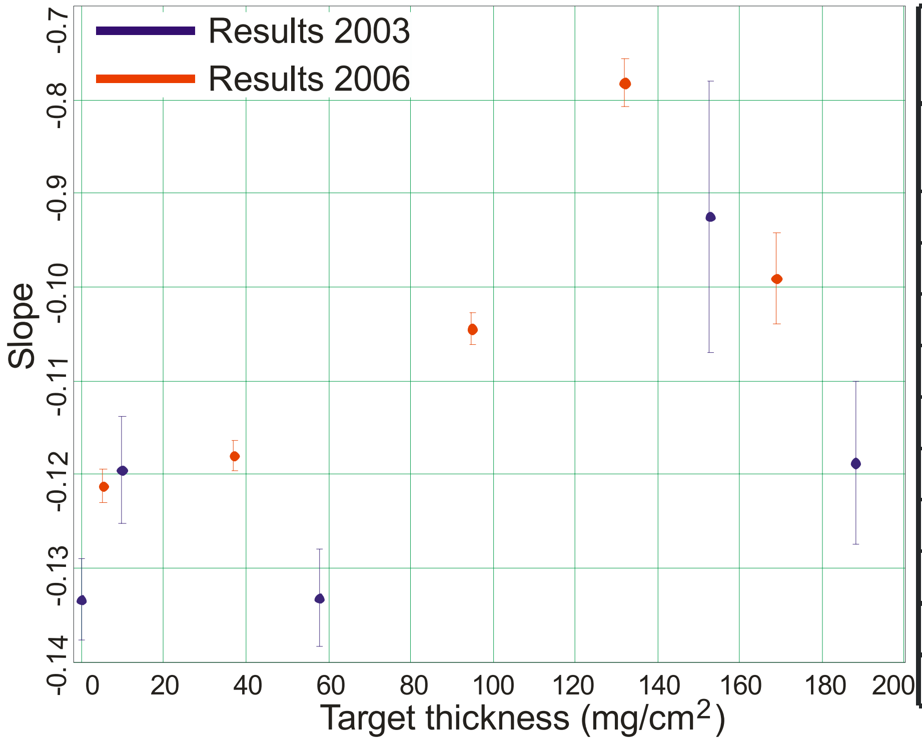






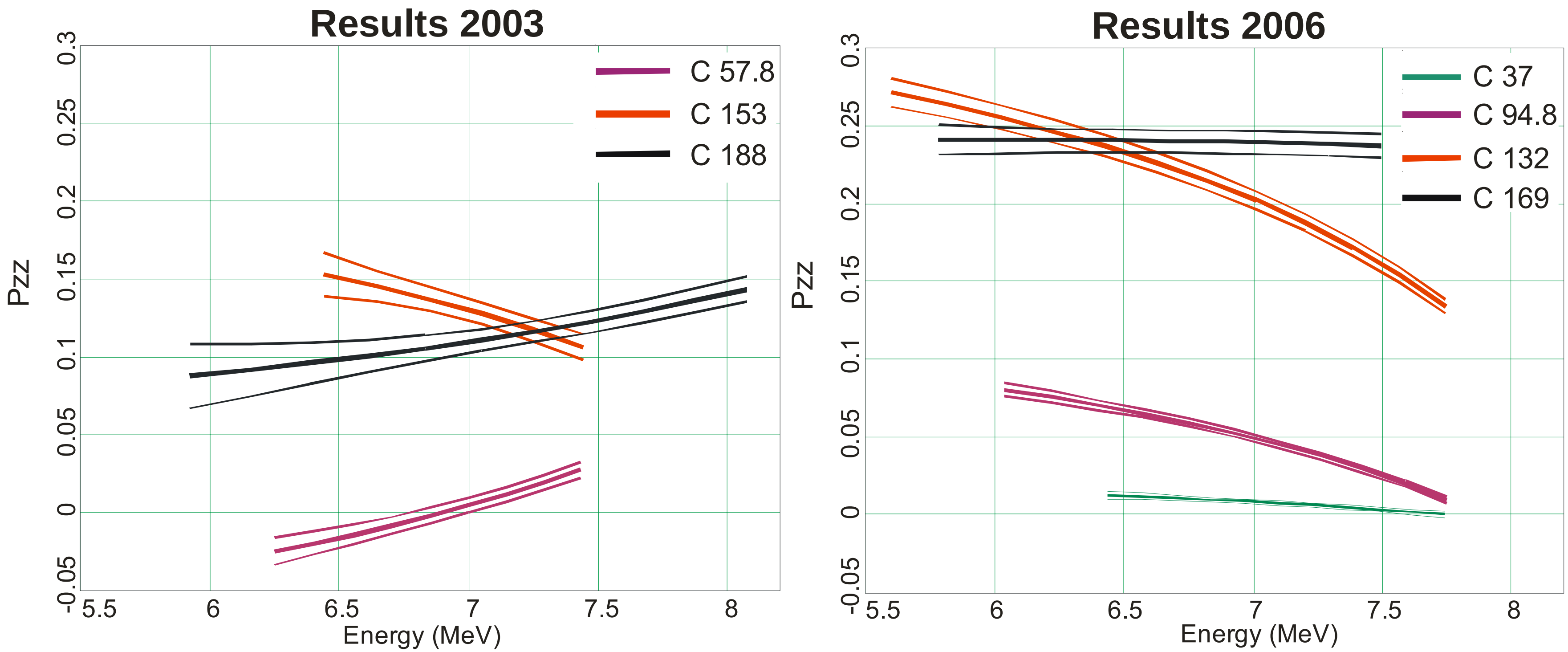


Results of measurement of ratio (L+R+U+D)/F in 2003 and 2006 (II)



Target thickness (mg/cm^2)	Parameters of linear fit y=kx+b	
	k $\pm\sigma_{stat}$ $\pm\sigma_{syst}$	b $\pm\sigma_{stat}$ $\pm\sigma_{syst}$
0	**0.133 ±0.004 ±0.000**	**1.73 ±0.03 ±0.00**
Gold 5.2 ± 0.1	**0.121 ±0.002 ±0.000**	**1.64 ±0.01 ±0.00**
Gold 9.6 ±0.1	**0.120 ±0.006 ±0.000**	**1.64 ±0.04 ±0.00**
Carbon 37,0 ± 0.9	**0.118 ±0.002 ±0.001**	**1.62 ±0.01 ±0.02**
Carbon 57.8 ±0.9	**0.133 ±0.005 ±0.001**	**1.73 ±0.04 ±0.02**
Carbon 94.8±1.3	**0.104 ±0.002 ±0.002**	**1.51 ±0.01 ±0.02**
Carbon 131.8±1.6	**0.078 ±0.003 ±0.001**	**1.28 ±0.02 ±0.02**
Carbon 152.6±1.6	**0.092 ±0.015 ±0.002**	**1.41 ±0.10 ±0.03**
Carbon 168.8±1.8	**0.099 ±0.005 ±0.002**	**1.41 ±0.03 ±0.03**
Carbon 187.9±1.8	**0.119 ±0.009 ±0.002**	**1.60 ±0.06 ±0.04**

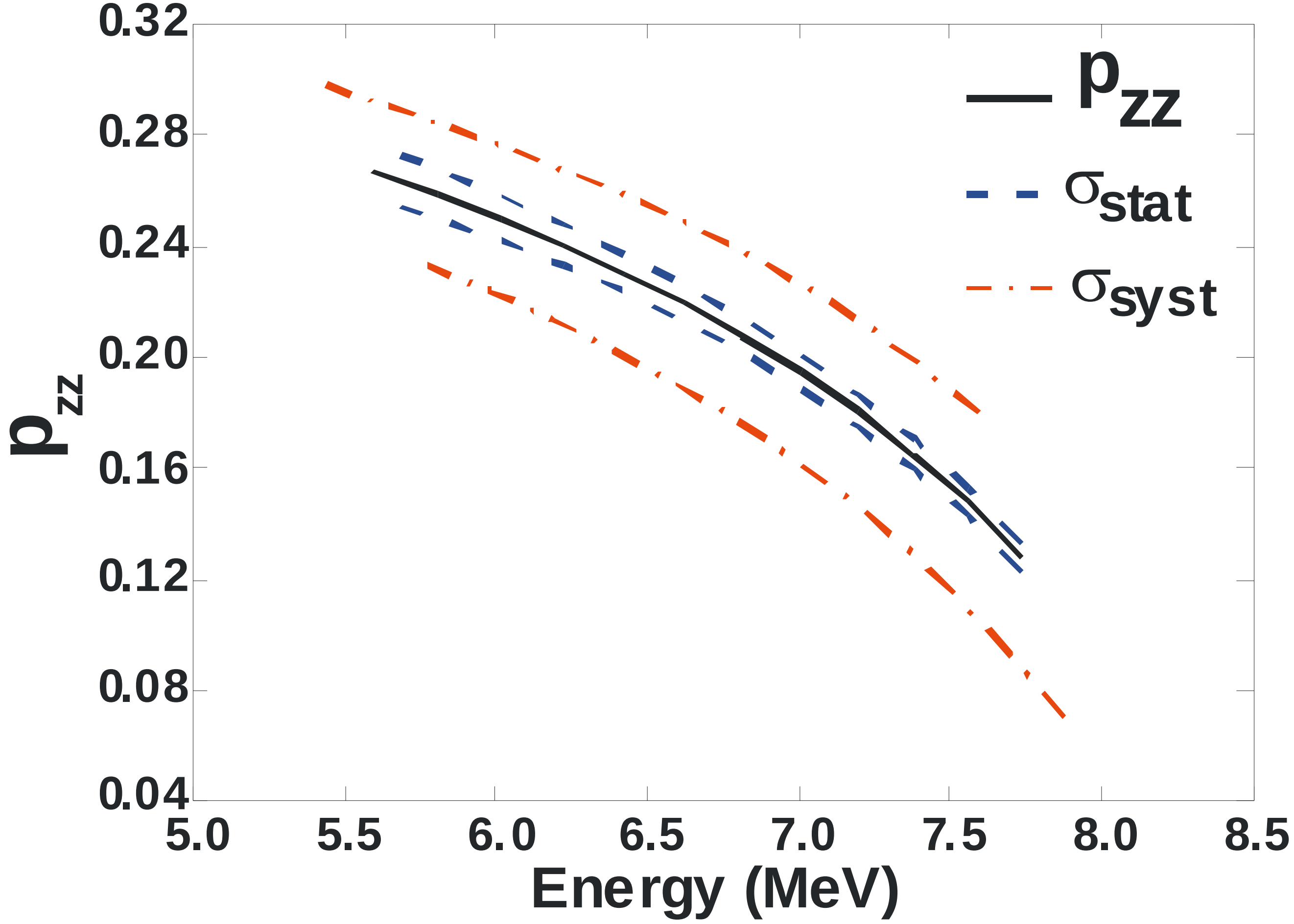
Appearance of tensor polarization in an initially unpolarized deuteron beam after passage through carbon targets of different thickness



Sources of systematic error →

- error of target thickness
- evaluation of energy behind target

Influence of systematical error on result for C 132



Conclusions

Using unpolarized deuteron beam and unpolarized carbon target the changing of asymmetry between forward and side detectors was observed

⇓

appearance of tensor polarization component in the initially unpolarized deuteron beam.

Key publications

❖ V.G. Baryshevsky and M.I. Podgoretsky, Zh. Eksp. Teor. Fiz. 47 (1964) 1050 [Sov. Phys. JETP 20 (1965) 704].

❖ V.G. Baryshevsky, Sov. J. Nucl.Phys. v.38 (1983) 569; V.G.

❖ V.G. Baryshevsky, Phys. Lett. {B} 120 (1983) 267.

❖ V.G. Baryshevsky, I.Ya.Dubovskaya, Yad. Phys. 53 (1991) 1249 [Sov. J. Nucl. Phys. 53, N5 (1991) 770].

❖ V.G. Baryshevsky, I.Ya.Dubovskaya, Phys. Lett. B 256 (1989) 529.

❖ V.G. Baryshevsky, A.G. Shekhtman Phys. Rev. C 53, n.1 (1996) 267.

❖ V. G. Baryshevsky, Phys. Lett. 171A, 431 (1992).

❖ V. G. Baryshevsky, J. Phys.G 19, 273 (1993).

❖ V. G. Baryshevsky, K. G. Batrakov and S. Cherkas J. Phys.G 24, 2049 (1998).

❖ V. Baryshevsky, K. Batrakov, S. Cherkas, LANL e-print archive: hep-ph/9907464 v1 (1999)

❖ V.G. Baryshevsky, Sov. J. Nucl.Phys. v.48 (1988) 1063.

❖ V.G. Baryshevsky LANL e-print archive hep-ph/0109099

❖ V.G. Baryshevsky LANL e-print archive hep-ex/0501045