

# Physics of proton and deuteron polarimeters

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Physics of protons and deuterons incident on nuclei involves mostly elastic scattering and single- or few-nucleon transfer. This topic was investigated thoroughly in 1970s and 1980s.

Replace protons and neutrons in nucleus with average field. (optical model)  
Problem reduces to single point projectile traveling in a central potential.

Early efforts used Schrödinger Equation:  $(H + \underline{V})\Psi = E\Psi$

The potential properties are: complex (to include absorption)  
central similar to matter distribution  
spin-orbit term at surface

In 1980s, people switched to Dirac Equation  
Potential had to be relativistic invariant.

Central and spin-orbit replaced with attractive scalar (from “ $\sigma$ ” meson) and repulsive time-like vector (from  $\omega$  meson) meson. Both potentials are large (300 to 400 MeV), thus motion inside nucleus is always relativistic.

Spin-orbit effects arise, as they do in atoms, from the derivative of the potential considered relativistically.

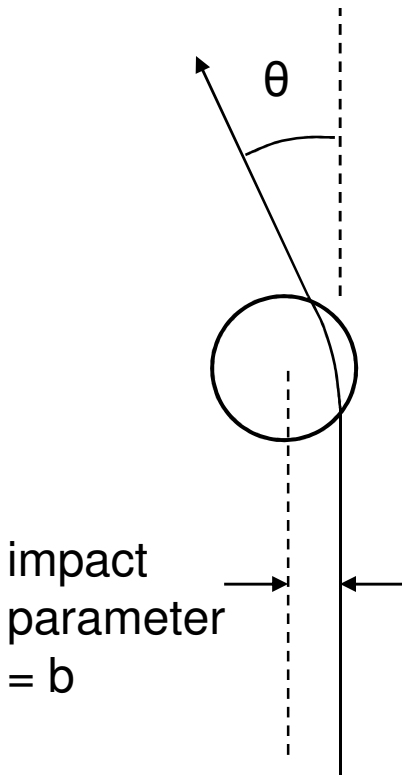
A large body of elastic scattering data was treated with optical potentials. Systematic studies made of the potential shapes, etc.

To gain some intuition about the physics, I prefer to think of the scattering semi-classically. Some quantum aspects will be included as needed.

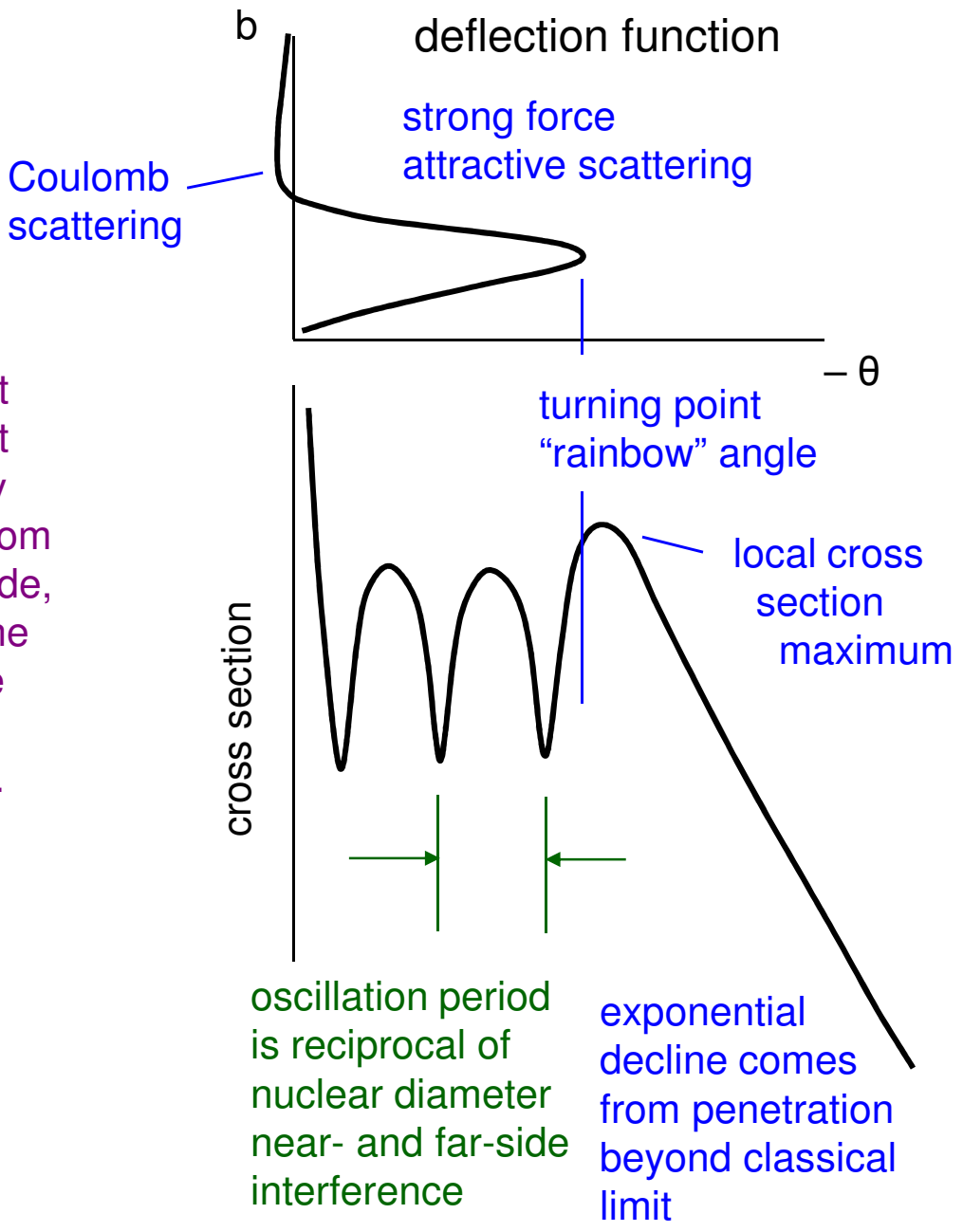
The essential classical features have been verified using full quantum mechanical calculations. The classical limit is approached as  $1/L$ , where  $L$  is the angular momentum of the partial waves contributing to the effect. In these cases  $L$  is typically 10 to 20  $\hbar$ .

I start with the deuteron, treating it as a point particle. Studies involving “adiabatic” potentials and coupled-channel bases have demonstrated that only “small” deuterons scatter or undergo reactions. “Large” deuterons break up and generally do not enter into subsequent considerations.

Classical description of the deuteron trajectory

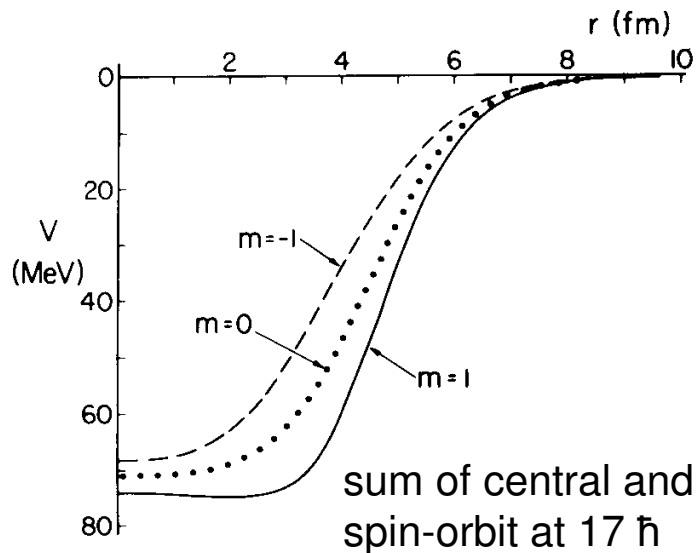


The most important trajectory comes from the far side, bent in the attractive nuclear potential.

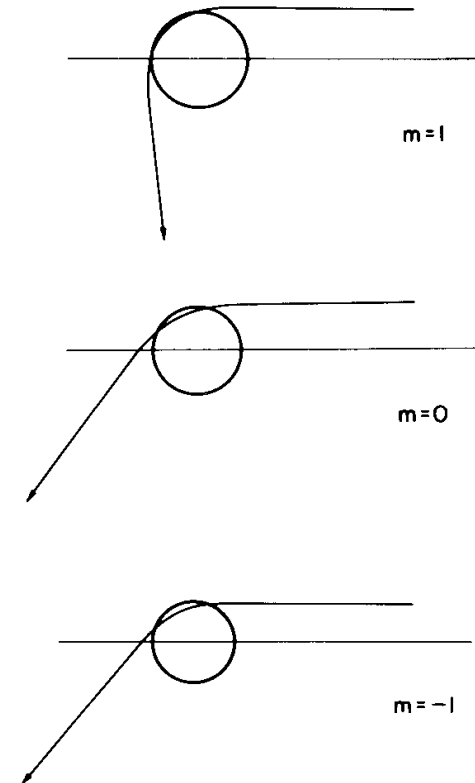


Quantize the deuteron spin = 1 along the perpendicular to the scattering plane.

In this representation, the three spin projections decouple to the level of  $1/L$ , and the scattering can be regarded as three independent beams, each with its own scattering cross section.

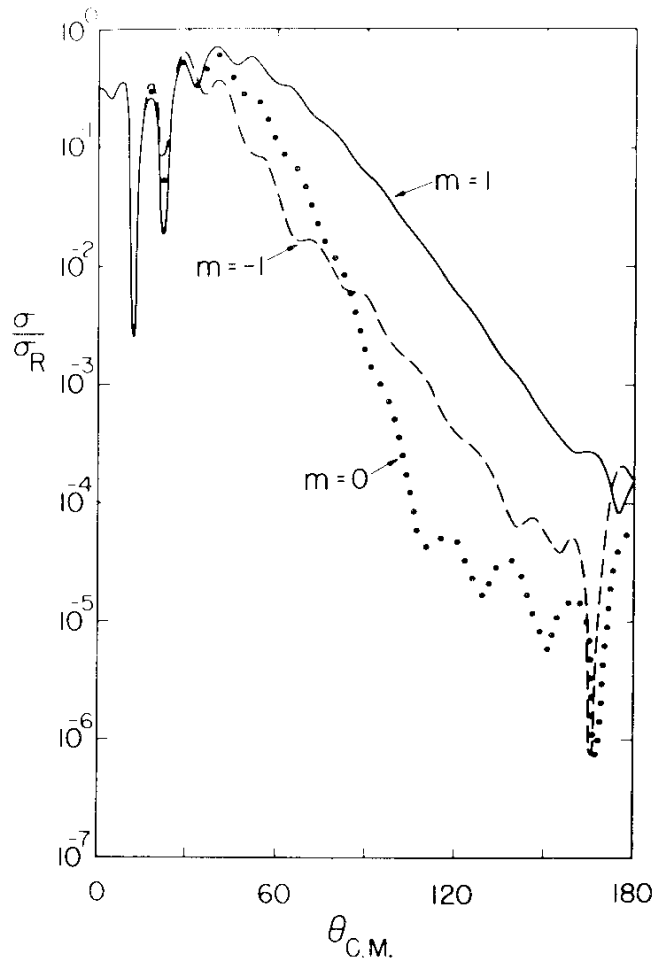


trajectories at the classical rainbow angle for each spin projection



Behavior is analogous to a spin-dependent index of refraction in the nuclear medium. Thus spin is the “color” in the nuclear rainbow.

cross sections for the three spin states based on optical potential for  $^{58}\text{Ni}$  at 80 MeV deuteron energy



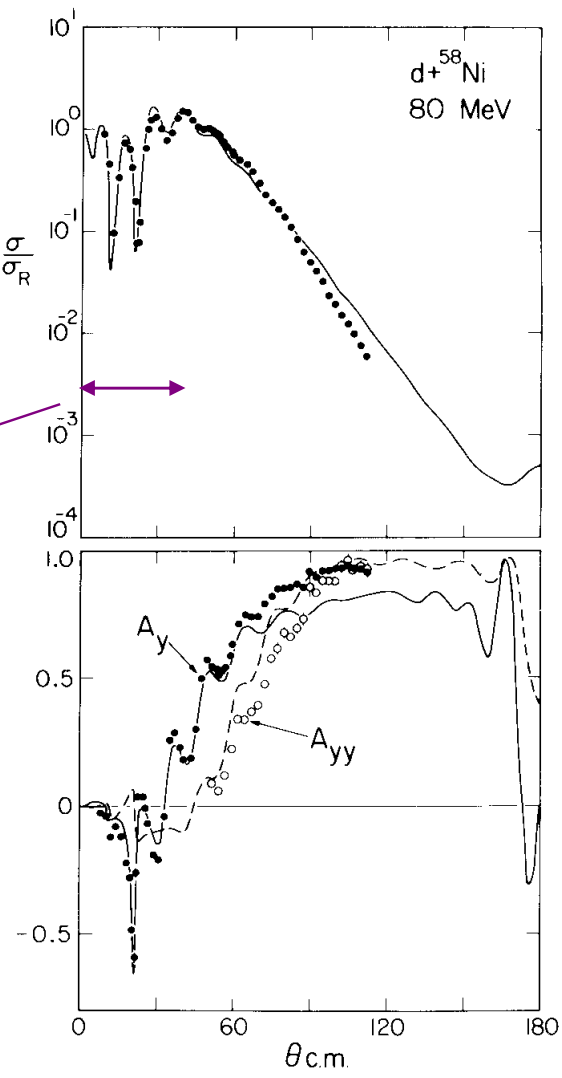
$\sigma_{-1}$  falls away first, causing  $A_y$  to rise to large positive values.

$$A_y = \frac{\sigma_1 - \sigma_{-1}}{\sigma_1 + \sigma_0 + \sigma_{-1}}$$

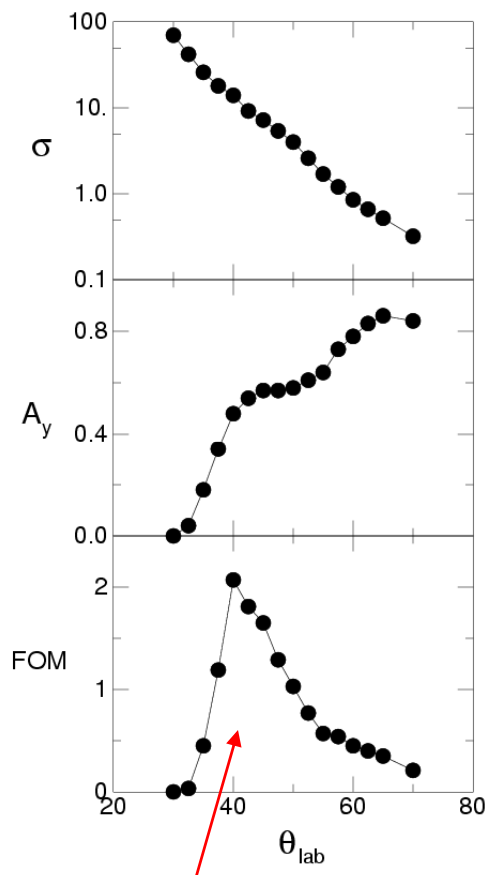
$$A_{yy} = \frac{\sigma_1 + \sigma_{-1} - 2\sigma_0}{\sigma_1 + \sigma_0 + \sigma_{-1}}$$

$\sigma_0$  falls away second, causing a later rise for  $A_{yy}$  to positive values, after a small negative dip from  $\sigma_{-1}$ .

region of comparable near and far side amplitudes

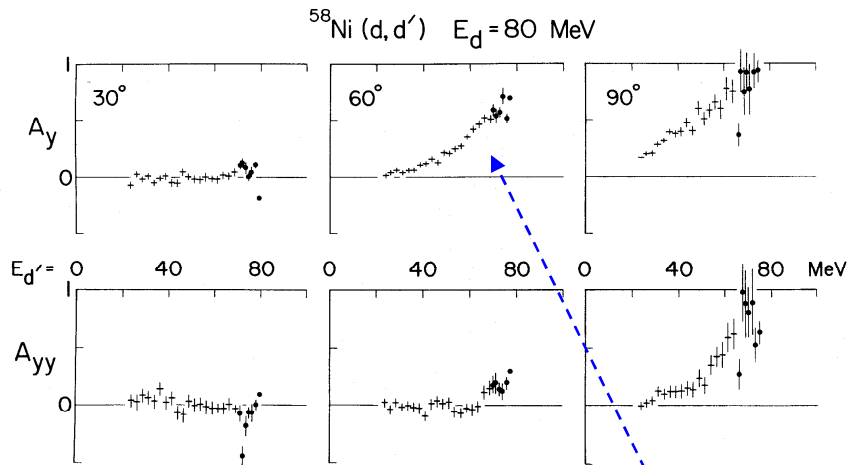


data from Kato, d+C, 70 MeV



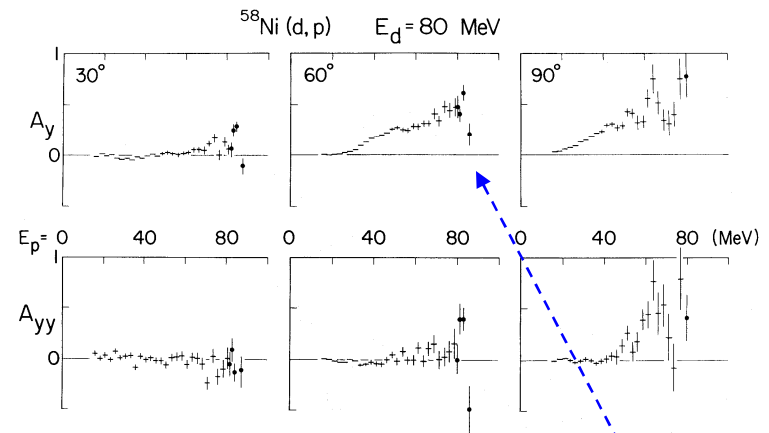
Build polarimeter here.

The extra bonus for deuterons is that inelastic scattering and the major reaction channels have, for low Q-values, spin dependence similar to elastic scattering.



← inelastic scattering

single-nucleon transfer →

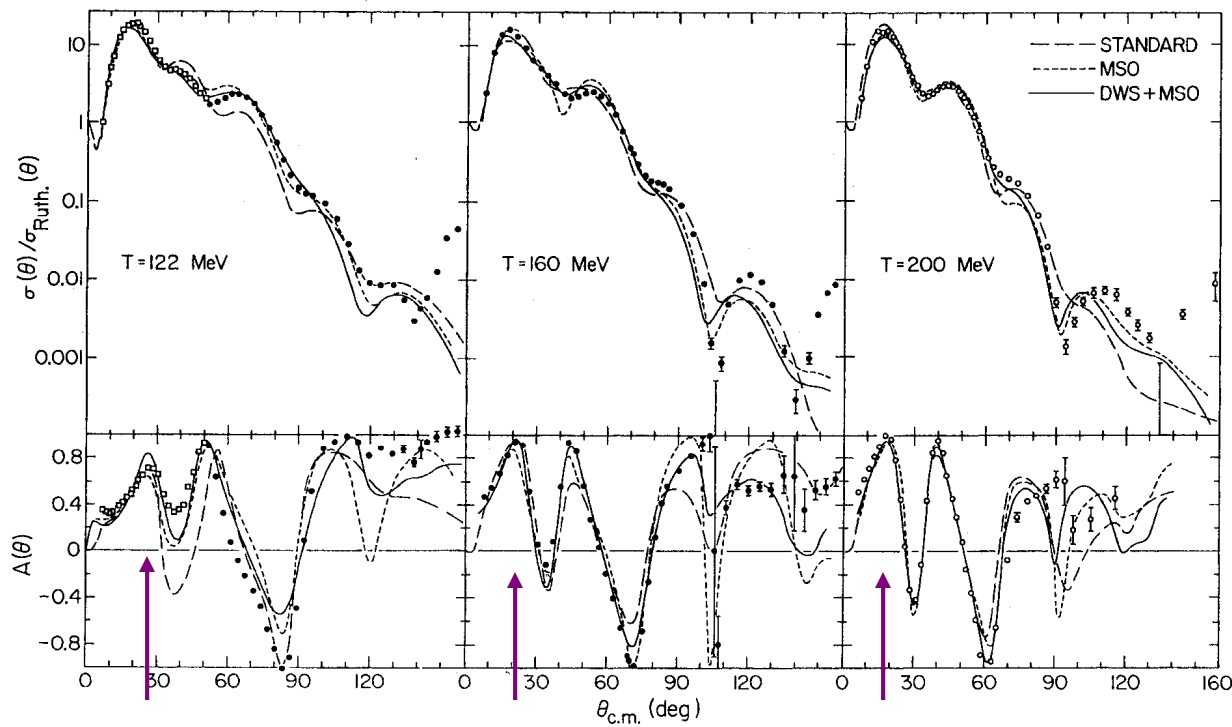


Include this in polarimeter acceptance.

Protons fall in between deuterons (rainbow projectiles) and purely diffractive scattering (where the near and far side amplitudes are essentially equal).

The proton analyzing power is mostly positive. Finding a suitable angle and energy range for polarimetry depends on the details of the diffraction pattern.

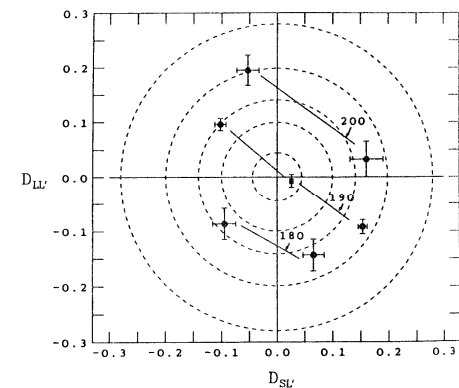
### The proton + carbon maximum



The analyzing power goes through an  $A=1$  point at  $\sim 189$  MeV.

The proof requires:

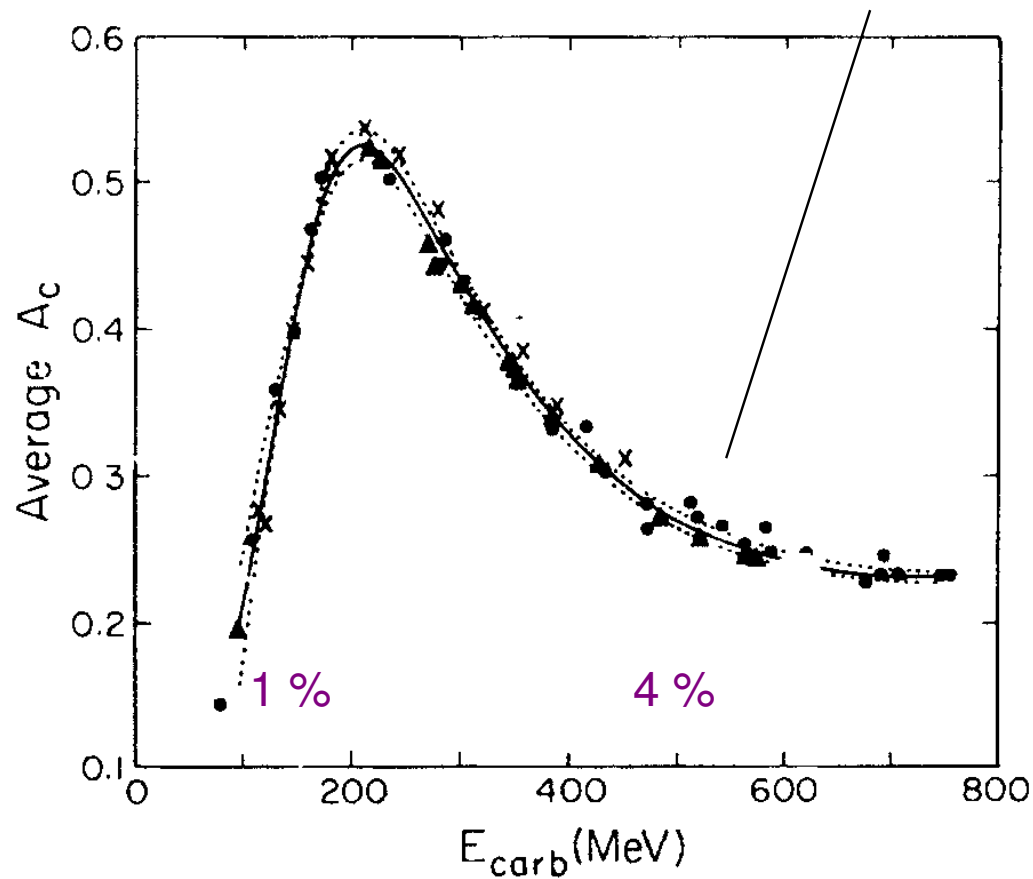
$$D_{LL'}^2 + D_{LS'}^2 + A^2 = 1$$



## McNaughton analysis from LANL

“Polarimeter” used thick carbon target and recorded all forward angle protons, which are mostly elastic.

rough efficiencies  
(defined as the number of protons used for a polarization measurement divided by the number of protons hitting the target)



The improvement is due mostly to the increased target thickness.

# The Indiana data between 100 and 200 MeV

This polarimeter selected for elastic scattering.

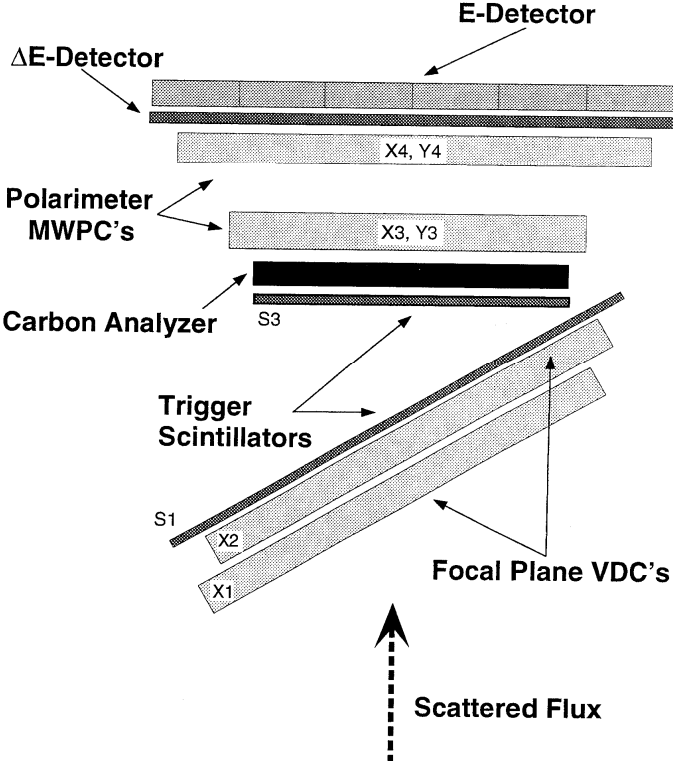
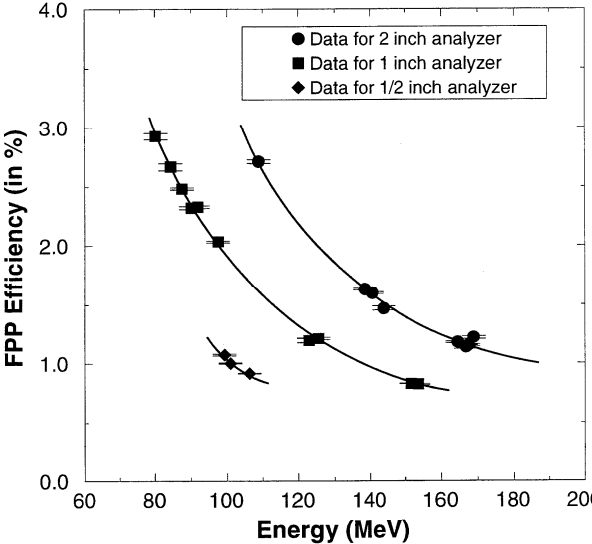
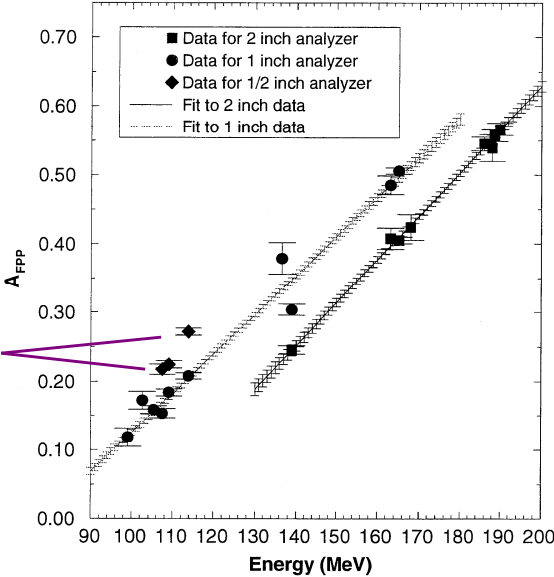


figure of merit is better with thinner target:  $\sigma A^2$

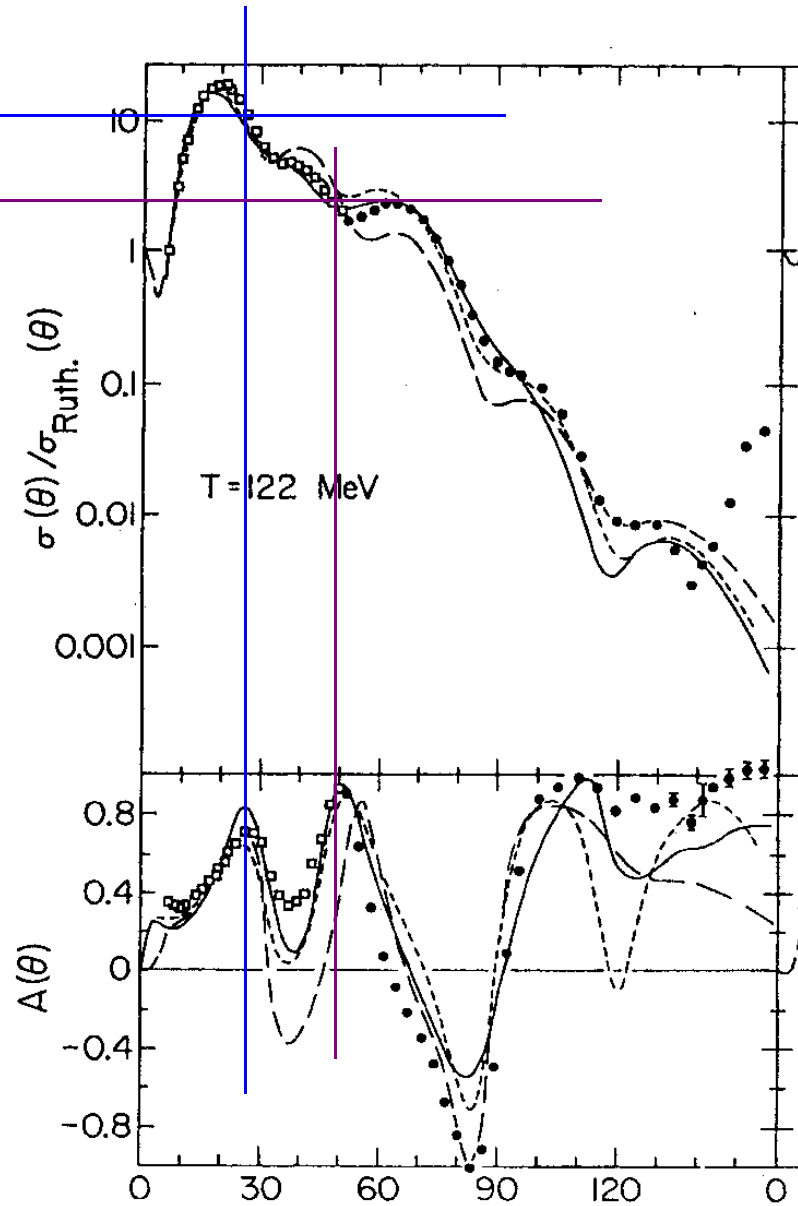


Below 100 MeV, the forward peak in the analyzing power fades. You then have to go to larger angles.

factor between 4 and 5

multiply by  $1/\sin^4(\theta/2) = 9.3$

You lose about a factor of 40 in cross section. The solid angle can recover about a factor of two.



Osaka built a polarimeter for 65 MeV  
(based on the Kato data)

