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Production of Polarized Neutron Beams by (p, n) Reactions in Various Nuclei

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Introduction

The work that is the subject of this talk was carried out at the Atomic Energy Research Establishment, Harwell, by a team consisting of the following people,

P. H. BOWEN, G. C. COX, G. B. HUXTABLE, J. P. SCANLON, J. J. THRESHER, A. E. R. E., Harwell;
A. LANGSFORD, Clarendon Laboratory, Oxford,

and we were also assisted for some time by H. APPEL, on leave from the University of Mainz.

The production and measurement of high energy polarized neutron beams was part of a programme of research carried out using a neutron time-of-flight spectrometer in conjunction with the Harwell cyclotron. Using this equipment, measurements had previously been made with unpolarized neutrons, including the determination of neutron total cross-sections in the energy range 15–125 MeV for a wide range of elements, and the angular distribution of neutron-proton scattering in the range 30–120 MeV. A source of polarized neutrons covering a similar energy range was needed in order to extend this work.

Neutron Time-of-Flight Spectrometer

The apparatus has been described in detail (SCANLON, STAFFORD, THRESHER and BOWEN [1][1]), so the remarks here will be confined to a brief outline.

Neutrons are produced by allowing 143 MeV protons to strike an internal target in the cyclotron (figure 1). As each accelerated proton bunch reaches a mean radius of 112 cm it is deflected electrostatically onto a target which is placed above the magnetic median plane and hence

[1]) Numbers in brackets refer to References, page 192.

is not in the path of the undeflected protons. In this way, 200 bursts of neutrons are produced per s at the target, and the duration of each burst is 9 ns measured as a full width at half height.

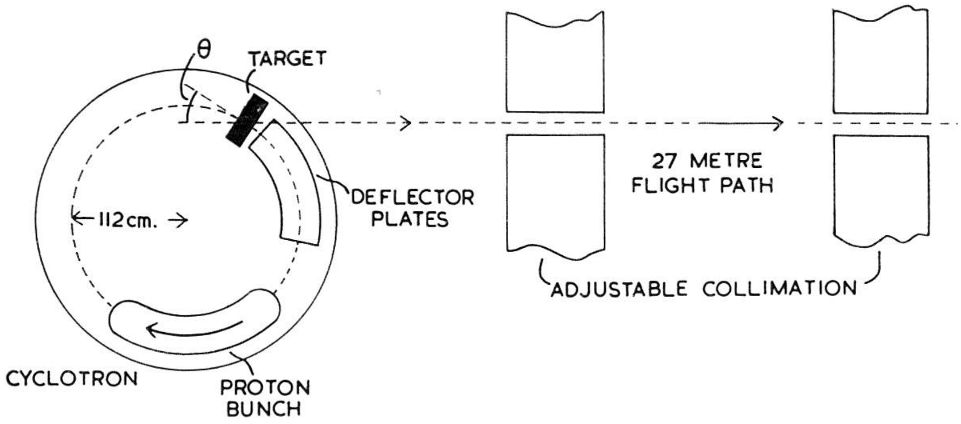

Figure 1

The collimated flight path is 27 m long, and the energy of any neutron which is detected at the end of the flight path is determined by measuring its time of flight over the known distance from the target. This time is obtained from the interval between two pulses, the first corresponding to the deflection of the proton bunch, and the second to the detection of the neutron. The energy resolution depends on the duration of the neutron burst and the length of the flight path. The figures quoted above correspond to $13^1/_2\%$ at 130 MeV and $3^1/_2\%$ at 30 MeV.

One big advantage of this technique is that providing the necessary neutrons come along the flight path and that suitable neutron detectors are used, one can cover a large range of neutron energies in a single experiment.

Production of a Polarized Neutron Beam

In general, some degree of polarization will be expected in the neutrons scattered at angles other than 0° from targets bombarded by high energy protons. However, to achieve the most useful beam it is necessary to maximize the quantity $P_1{}^2N$, where P_1 is the polarization of the beam and N the intensity. For doing this with a given geometry, three possible variable parameters were target material, target thickness and angle of scattering. On the basis of previous work one could say that in the range of scattering angles $\theta = 0 - 45°$, N might be expected to decrease and P to increase as θ increased.

The first target material to be tried was lithium deuteride, as this had given the largest neutron yield for 0° scattering of all materials used.

Furthermore it was hoped that a reasonable degree of polarization might result from 'quasi-free' $p-n$ scattering in deuterium. The target thickness was 28 MeV, and scattering angles of 25°, 35°, and 45° were used. A similar set of measurements was made with an aluminium target of 55 MeV thickness, and one thick enough to stop the incident protons completely was tried at 35°. Finally, to try to gain a little more insight into the physical processes involved, some measurements were made of the neutrons produced from thin ($\sim$ 3 MeV) targets of lithium hydride, lithium deuteride and aluminium.

The Polarization Analyser

The technique used was that suggested by SCHWINGER [2]. It depends on the fact that the small angle scattering of neutrons by nuclei is polarized due to the interaction of the magnetic moment of the neutron with the Coulomb field of the target nucleus. The magnitude of the effect can be estimated with reasonable accuracy, and it occurs at scattering angles small enough for the polarization from nuclear interactions to be negligible. The basic principle was therefore to measure the asymmetry between left and right scattering through an angle θ of the polarized beam by a suitable target (figure 2).

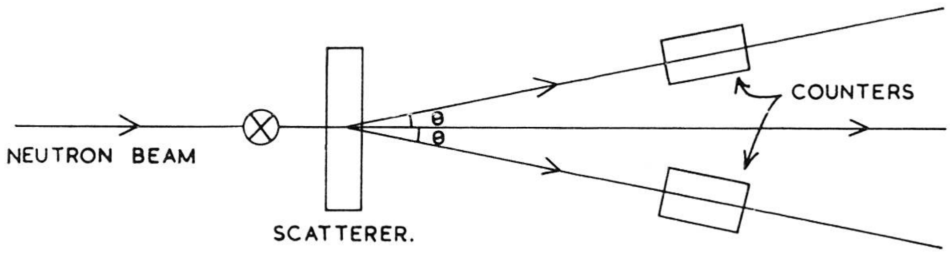

Figure 2

In order to find out the best conditions for doing this, the scattering process must be considered in rather more detail. The neutron will see an effective magnetic field as it rushes past the electric charge of the nucleus, so that its magnetic dipole will have a potential energy $V = -\boldsymbol{\mu} \cdot \boldsymbol{H}$. This can be regarded as a small perturbation to the specifically nuclear interaction, and assuming the nuclear part of the scattering amplitude to be unpolarized, a plane wave Born approximation calculation gives the differential cross-section at angle θ as

$$\sigma(\theta) = \left[| f_0(\theta) |^2 + \gamma^2 \cot^2 \frac{\theta}{2} \right] - 2 \operatorname{Im} \{f_0(\theta)\} \gamma \cot \frac{\theta}{2} \cdot \boldsymbol{n} \cdot \boldsymbol{P}_1 \qquad (1)$$

where θ is the C of M scattering angle, $f_0(\theta)$ is the nuclear scattering amplitude, $\boldsymbol{n}$ is the unit vector defining the plane of scattering, $\boldsymbol{P}_1$ is the polarization vector of the incident beam, and $\gamma = {}^1/_2\,|\mu_n|\,Z\,e^2/M\,c^2$ where the intrinsic magnetic moment $\boldsymbol{\mu}$ of the neutron is defined as $\boldsymbol{\mu} = -\,|\mu_n|\,\boldsymbol{\sigma}\,e\,\hbar/2\,M\,c$, $\boldsymbol{\sigma}$ being the Pauli spin matrix. The asymmetry for left-right scattering is

$$A = \frac{-\,2\,\mathrm{Im}\,\{f_0(\theta)\}\,\gamma\cot\frac{\theta}{2}\cdot\boldsymbol{n}\cdot\boldsymbol{P}_1}{\left[|f_0(\theta)|^2+\gamma^2\cot^2\frac{\theta}{2}\right]} = P_2\,(\boldsymbol{n}\cdot\boldsymbol{P}_1)\,. \tag{2}$$

The denominator is the unpolarized differential cross-section, which can be measured. Also, for sufficiently small angles ($\sim 1°$) we may say

$$\mathrm{Im}\,\{f_0(\theta)\} \simeq \mathrm{Im}\,\{f_0(0)\} \simeq \frac{K\sigma_T}{4\,\pi}$$

by the optical theorem. We can measure σ_T.

P_2 which may be called the analysing efficiency of the system, varies as shown in figure 3, having a maximum amplitude in the neighbourhood of 1/4°. This is not necessarily the best angle at which to measure the scattering however, from the following considerations. Suppose a counter of finite size is placed as close as possible to the transmitted beam, also of finite size (figure 4); the optimum position for the counter will be that which gives the maximum value of the quantity $P_2^2\Omega\cdot\sigma(\theta)$ where Ω is the solid angle subtended at the scatterer by the counter. If θ is varied by changing the distance between the counter and scatterer the following type of curve is obtained (figure 5). Substantial gains can be made by moving out as far as 2° or so. There are still several reasons why θ should be kept as small as possible however.

a) The approximation $\mathrm{Im} f_0(\theta) = \mathrm{Im} f_0(0)$ will break down at larger angles.

b) Nuclear polarization will cease to be negligible as θ increases.

c) The effect of false asymmetries is reduced by keeping P_2 as large as possible.

d) The plane wave Born approximation calculation becomes less valid as θ is increased.

e) The calculation of P_2 assumes a point nucleus. The error in this assumption increases rapidly as θ is increased.

From these considerations it was decided to use a scattering angle of 1°, and because $P_2 \propto \gamma \propto Z$, Uranium was used as the scattering material.

The experimental arrangement is shown schematically in figure 6. The beam was approximately 2 cm by 5 cm in cross-section and the Uranium scatterer was 2.5 cm thick. The scattering was measured simultaneously on both sides of the beam by two liquid scintillation counters 48 cm long 2.5, cm thick and 7.5 cm wide. In addition, the magnetic field from a solenoid was used to reverse the polarization direction of the neutron beam. As the angle through which the neutron spin precesses in a given integrated magnetic field depends upon the neutron velocity, it was possible to turn it through + and − 90° for only one energy. This was chosen to correspond to the mean velocity of the spectrum between 20 and 120 MeV, which corresponded to 42 MeV. For other energies, if $\pm\alpha$ is the angle of precession of the neutron spin, the value of P_1 calculated from the measured asymmetry has to be multiplied by cosec α. The correction amounts to about 25% at 120 MeV and 20% at 20 MeV.

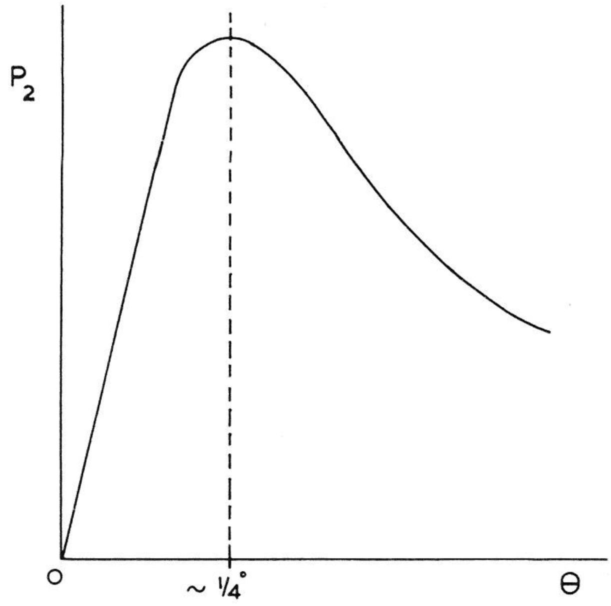

Figure 3

To minimize scattering from the 'straight through' beam into the counters, a hydrogen path was used, and the neutrons travelled a further 6 m into a beam trap. The residual background rates, which amounted to about 25% of the total counting rates were determined by putting 40 cm of steel directly in front of the counters to block the neutrons scattered from the uranium.

There are a number of advantages in using the system of two counters together with a solenoid. If the counter efficiencies are defined as ε_1 and ε_2, the number of neutrons scattered left and right per unit incident flux as L and R, and I^+ and I^- the incident fluxes for measurements made with clockwise and anti-clockwise precession, the ratio of neutrons detected in the two counters is $I^+ L \varepsilon_1 / I^+ R \varepsilon_2$, and for anti-clockwise precession $I^- R \varepsilon_1 / I^- L \varepsilon_2$. Dividing these two ratios together gives L^2/R^2 from which

A can be calculated. The result is independent of changes in beam intensity, so that the system is self-monitoring, and also independent of the counter efficiencies, so long as they remain constant.

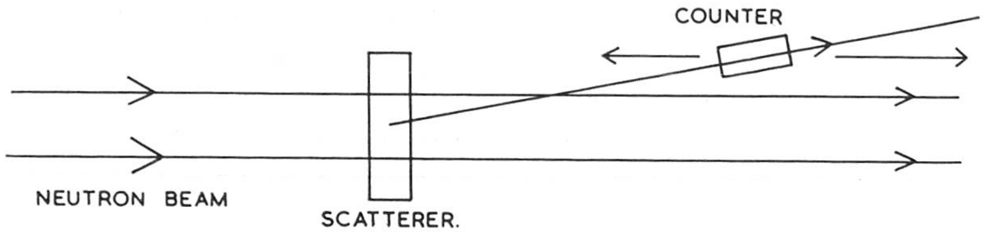

Figure 4

A monitor is still needed to normalize the measurements of backgrounds, but as this is only some 25% of the total, the monitoring can be proportionately less accurate.

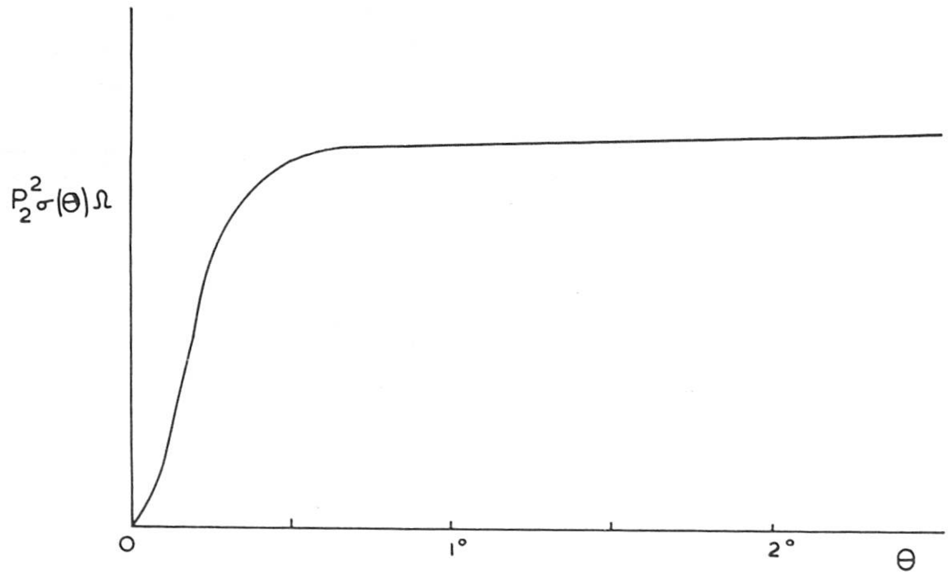

Figure 5

An even more important advantage lies in the greater precision with which the geometry may be defined. The centre line of the neutron beam can certainly not be defined to better than 1 mm, so this limits the accuracy to which the angle of a single counter can be set. However, when two counters are used, the angle between them can be set to a much greater accuracy, and any false asymmetries which result if they are not placed symmetrically about the beam line cancel out to first order when measurements are made with the polarization vector reversed. For conditions which would give a 5% false asymmetry using a single counter, the error is reduced to 0.1% for a double counter system.

Finally, by using two counters the information is obtained in half the time that would be taken using a single counter.

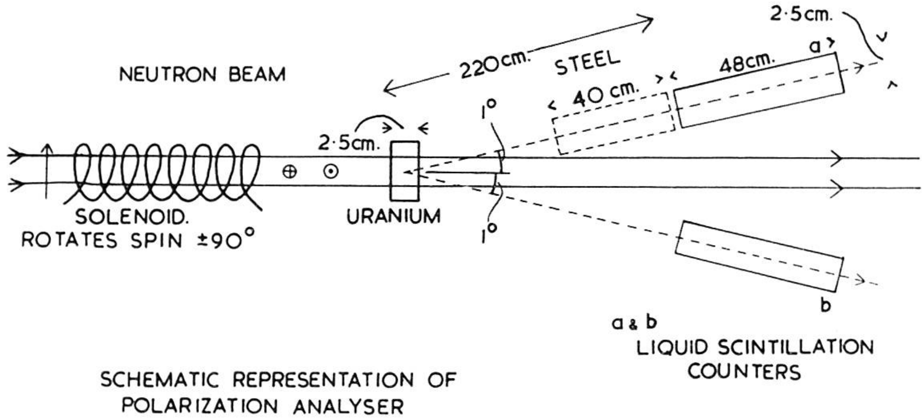

Figure 6

The total neutron cross-section of Uranium was measured over the energy range 15–120 MeV by a transmission experiment in good geometry, and the 1° differential cross-section was determined by comparing the number of neutrons scattered at 1° with the number in the incident beam, using an unpolarized beam and the same experimental arrangement.

Corrections

Eq. (1) and (2) may be expressed more simply as

$$\sigma(\theta) = X(\theta) + Y(\theta)\, P\,, \tag{3}$$

$$P_2 = \frac{Y(\theta)}{X(\theta)} \tag{4}$$

and these relations apply strictly to a point source and scatterer. In practice these conditions were not fullfilled owing to the finite extent of the scatterer and counters, and neutrons were detected which had been scattered over a range of angles in different scattering planes. This was further complicated by the variation in intensity of the neutron beam over its cross-sectional area, and a small variation of efficiency over the area of the counters. The last two effects were determined by subsidiary measurements. There was also a 10% probability that a scattered neutron would be scattered at least once more before leaving the uranium.

However, it is still true to say that

$$\text{(observed scattering)} \quad = x + y\, P_1\,, \tag{5}$$

$$\text{(effective analysing power)} \quad = \frac{y}{x} \tag{6}$$

so that if the cross-section measurement is made in the same geometry as the asymmetry measurements, what actually is measured is x. Thus when calculating the effective analysing efficiency of the system no corrections have to be applied to x, and the only corrections which must be considered are those applying to y. The geometrical effects result in the effective value of P_2 being reduced by about 25%.

The effects of multiple scattering are very difficult to evaluate but the most pessimistic estimate gives a 2% correction.

Experimental Results

Figure 7 shows the values of P_2 obtained as a function of energy. These are fairly constant at a value of about 0.25 for energies down to 80 MeV, and then rise fairly sharply to 0.3 or more. The rise is correlated with a fall in the measured value of the differential scattering cross-section which

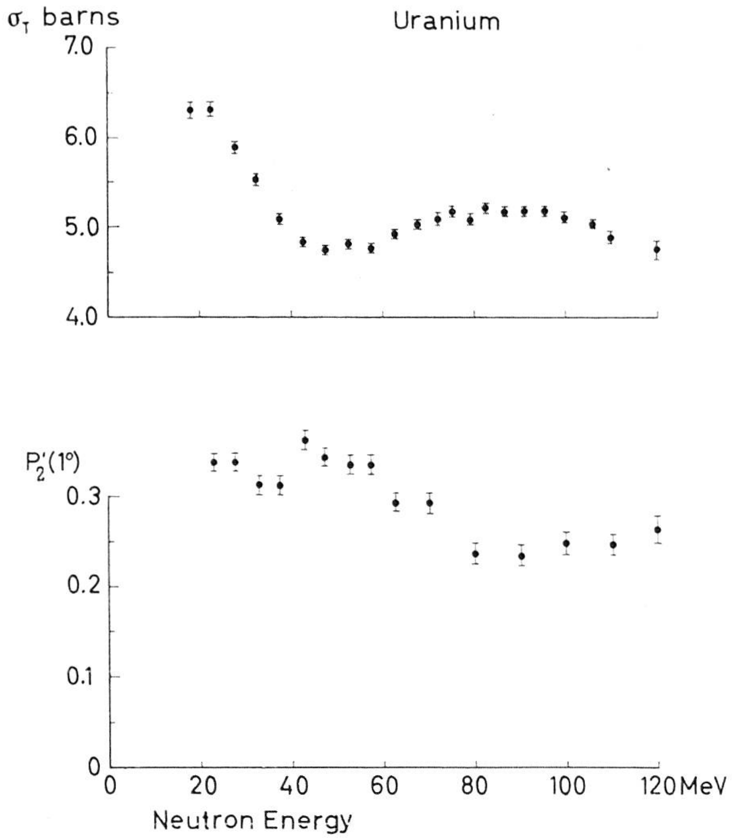

Figure 7

occurs at the energy of the maximum in the total cross-section curve. Such a variation is consistent with the optical model picture of nuclear scattering.

Figure 8 shows values of neutron polarization obtained as a function of energy for 25° scattering from the 28 MeV lithium deuteride target and the 55 MeV aluminium target.

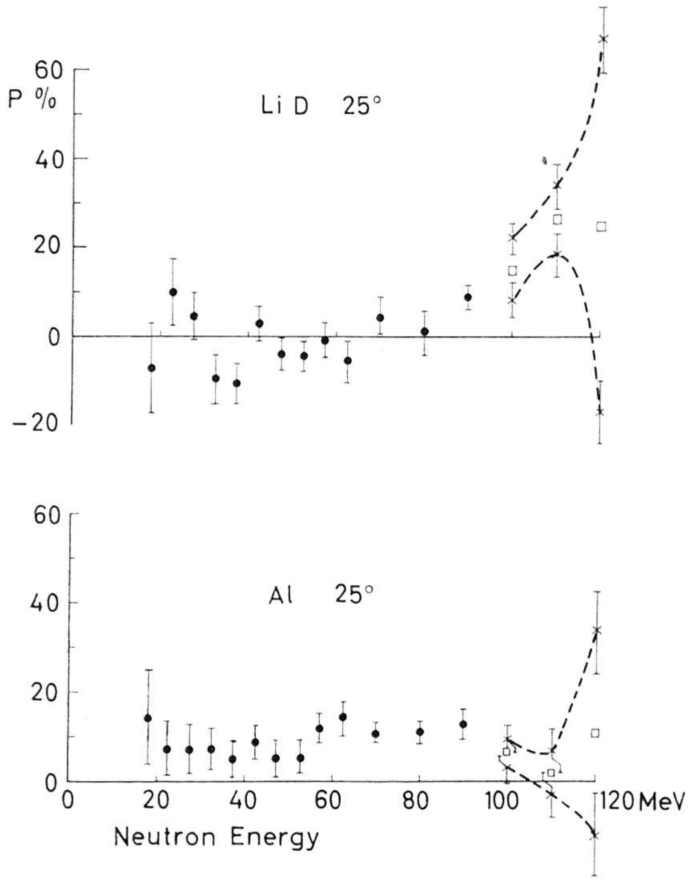

Figure 8

For lithium deuteride the polarization is effectively zero between 20 and 80 MeV, but becomes positive at higher energies. The result for aluminium is rather more encouraging, there being a polarization of about 10% at most energies. The alternative extreme values shown for energies of 100 MeV and above are due to a shortcoming in one of our earlier techniques. The velocities of neutrons detected in the two counters were analysed in separate timing channels, and as the number of neutrons per MeV was a rapidly varying function of energy in this region, a small uncertainty in the lining up of the two timing channels led to a large but systematic uncertainty in the measured asymmetries.

Figure 9 shows results for scattering at 45° from the same targets. Here the polarization of neutrons from lithium deuteride actually changes sign and becomes negative below 55 MeV. From aluminium the polarization is consistently positive, varying smoothly between about 0.15 at 20 MeV and 0.40 at 120 MeV.

The results obtained for a scattering angle of 35° lie in between those shown for 25° and 45°, and the effect of using a thicker aluminium target which completely stops the incident protons is simply to reduce slightly the number of high energy neutrons escaping from the target, and to reduce P_1 slightly at lower energies.

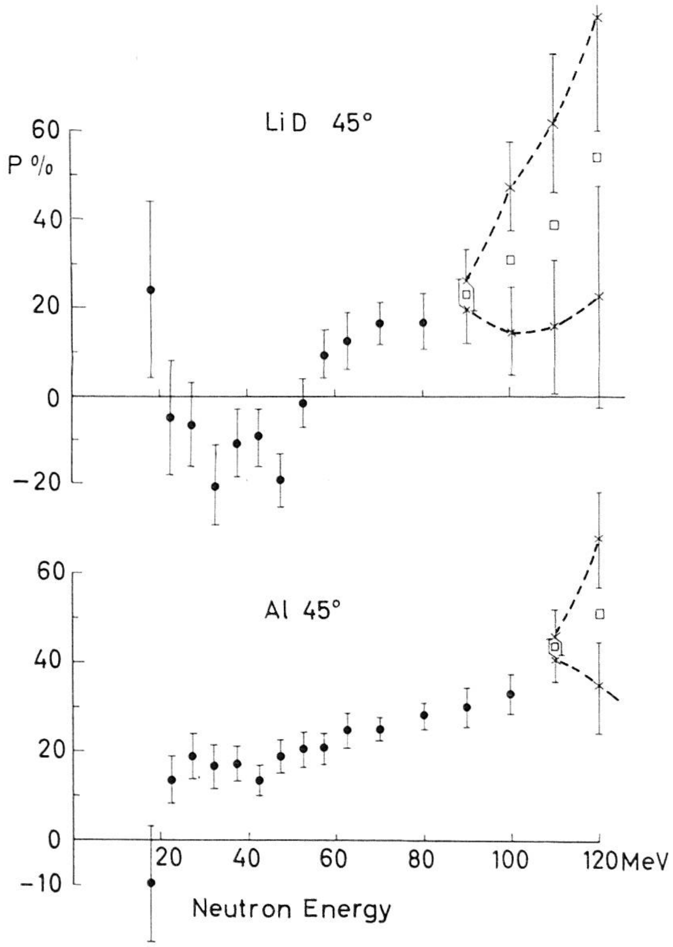

Figure 9

The foregoing results rule out the first choice of lithium deuteride as a polarizing target, and comparing the performance of aluminium at different angles, the most useful beam is obtained at 45°. The fall in intensity between 25° and 45° is more than compensated by the increase in polarization. Some results of CARPENTER and WILSON [3] indicate that a slight further increase of polarization might be obtained by observing scattering at about 55°, but it is doubtful whether this would compensate for the decrease in intensity which would result. Their results also indicate that no significant increase in P_1 would be obtained by using elements heavier than aluminium. It was therefore decided to use a

55 MeV target of Aluminium observed at 45° as the standard polarized neutron source.

Figure 10 shows the results obtained for neutron scattering from thin targets at 45°. The results for deuterium were obtained as the difference between those for lithium, deuteride and lithium.

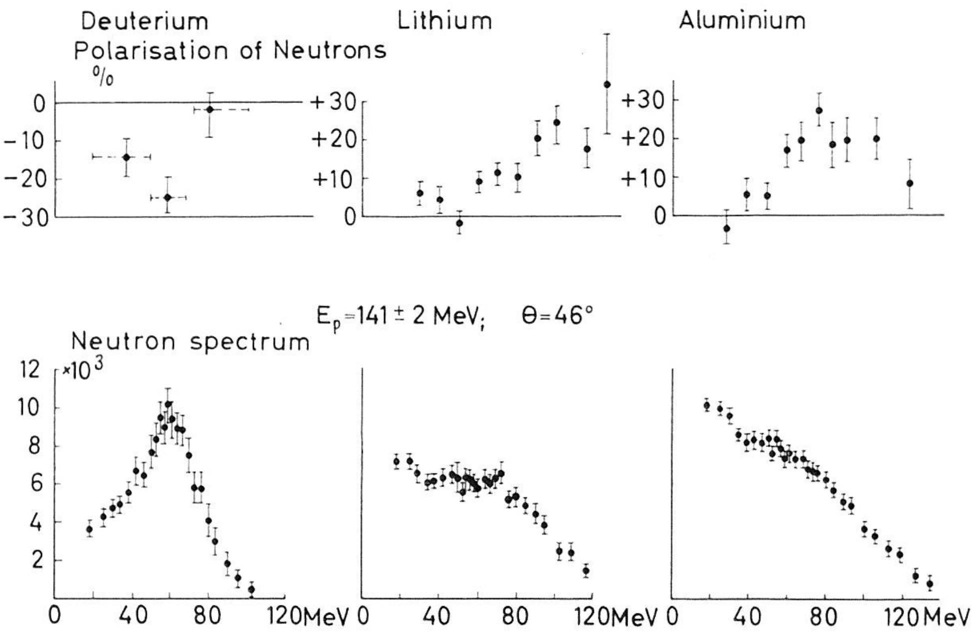

Figure 10

The peak at 60 MeV in the neutron spectrum from deuterium is consistent with quasi-free $p-n$ scattering, as is the sign and magnitude of the corresponding polarization. For lithium and aluminium the expected energy for quasi-free $p-n$ scattering at 45° would be approximately 50 MeV, but at this energy instead of a negative polarization the value is in fact close to zero, while at higher energies both give a large positive polarization.

A qualitative explanation of this has been given by Squires [4]. He regards the scattering process as a quasi-free $p-n$ scattering within the nucleus, and considers the modifications introduced by the nuclear potential and by double and higher order scattering. He concludes that the effect of the nuclear potential could not change the sign of polarization observed, but that multiple scattering within the nucleus is liable to predominate and can easily give the opposite sign. For instance in the present case of $\theta = 45°$, the most likely type of double scattering to give 45° is made up from two single scattering of about $22^1/_2°$ each. At that angle the signs of $p-n$, $p-p$ and $n-n$ polarizations are positive so that the outgoing neutrons produced in this way will have a positive polarization.

The large difference between polarizations produced by deuterium and by heavier elements is explained therefore by the greater likelihood of multiple scattering in the larger nuclei, and the low polarizations from our lithium deuteride target are simply due to the fortuitons cancellation of the effects from deuterium and lithium.

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