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Survey of Measurements in Stripping Reactions

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I want first to state some rules which current stripping theories provide before I describe the measurements so that I can make comparisons as I go along.

The simplest stripping theory, BUTLER's or BORN Approximation, the one often used by nuclear spectroscopists to find spins and parities, gives always zero polarization, so polarization measures the inadequacies of this theory directly.

The next lowest order approximation, and one which has received extensive theoretical treatment supposes the incoming deuteron and emitted nucleon to pass through a distorting potential which is purely central. The emitted nucleon polarization then obeys the following rules:—

$$P \leqslant \frac{1}{3}$$

$$P_{l=0} = 0$$

$$\left[\left(j+\frac{1}{2}\right) P\right]_{j=l+1/2} = -\left[\left(j+\frac{1}{2}\right) P\right]_{j=l-1/2} = \left[\frac{1}{3}\left(j+\frac{1}{2}\right) P_{nucl}\right]_{j=l-1/2} =$$

$$= \left[\frac{j\,(j+1/2)}{3\,(j+1)}\, P_{nucl}\right]_{j=l+1/2}$$

$$A = 3\, P \cdot P_d$$

for reactions with the same l and the same distorting potentials. here j and l refer to the captured nucleon, the parameters which spectroscopists are finding when they do stripping. The relations involving P_{nucl}, the polarization of the final nucleus, are restricted to spin zero target reactions. The last formula relates the asymmetry A in stripping with polarized deuterons which have vector polarization P_d to the emitted nucleon polarization produced by the same reaction with unpolarized deuterons. It also seems from semiclassical pictures and actual calculations that the deuteron and emitted nucleon distortions each give opposite signs of polarization, and the resulting sign is to some extent a measure of their relative importance.

Spin dependence in the deuteron, or emitted nucleon distorting potential, invalidates all these relations and there then seem to be no general rules, except perhaps for $P_{l=0}$ reactions when we have rules which are effectively extensions of those for scattering processes, with the polarization coming from the spin dependence of the distorting potentials and not depending directly on the properties of the captured nucleon.

The measurements fall into three distinct energy regions, which I will discuss separately starting at the lowest energies.

JURIĆ and ĆIRILOV [1][1]) have measured the energy dependence of the C^{12} (d, p) C^{13} polarization around 1 MeV (figure 1). The differential cross section at these energies shows strong resonances and its angular variation is completely different from a Butler type curve, showing a forward and backward peak. JURIĆ and ĆIRILOV measured near these peaks, at 20° and 140°. There is a resonance at 1.16 MeV and they varied the bombarding energy across it.

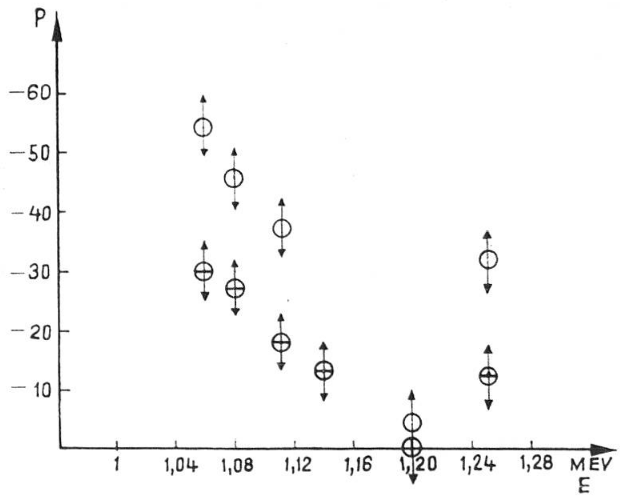

Figure 1

Their experimental method was to analyse the polarization of the protons by scattering them from carbon. The phase shifts for this are known in the appropriate energy region. Carbon offers obvious experimental advantages over helium as an analyser, but the phase shift analysis is yet not as accurate (EVANS and GRACE [2]). It is quite

[1]) Numbers in brackets refer to References, page 200.

obvious that here resonance effects predominate, and it may not be valid to consider this with a direct interaction theory at all. However quite good theoretical fits to the differential cross section have been made by including the Coulomb distortions in the deuteron and proton interactions and assuming the resonance to occur in the orbital angular momentum 2 partial wave of the emitted protons. Perhaps this theoretical approach will also succeed in fitting the polarization if some appropriate total spin for the partial wave is assumed.

Most polarizations have been measured at somewhat higher energies where stripping is well established as the main mechanism and the differential cross sections show in most cases clearly defined stripping peaks.

With one exception, all measurements in this medium energy region have been made by substantially the same method, differing only in details. I will show one particular arrangement as typical. Figure 2 shows the apparatus of JUVELAND and JENTSCHKE [3]. Some workers include a strong focussing magnet to focus the protons into the helium analyser, this seems worthwhile doing because it can give a factor 50 increase in the proton to background ratio. The helium analysers vary in detail. Sometimes a venetian blind slit system is used to define the scattered proton direction, and sometimes this is deduced from the directions of the emulsion tracks. The phase shifts for the helium scattering are now known sufficiently well over all this energy region to predict its analysing power to perhaps a few percent.

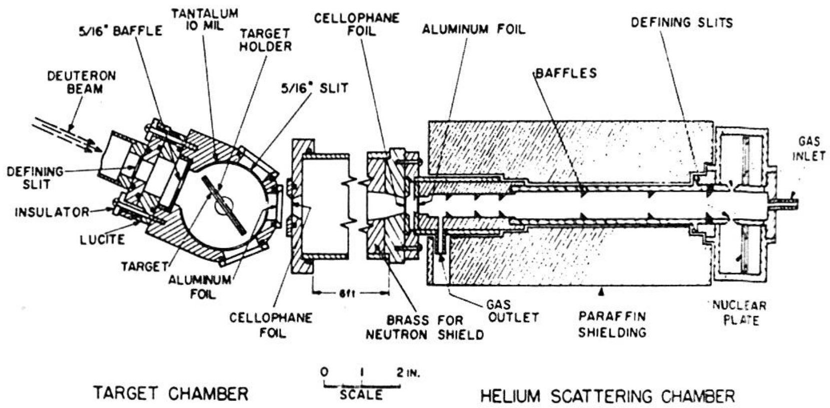

Figure 2

Schematic diagram of the apparatus

The reaction most investigated is $C^{12}(d, p)C^{13}$. Figure 3 shows a combined plot of all measurements on the ground state proton polarization. Ignoring the 1.06 MeV points which are from JURIĆ and ĆIRILOV data, the only evidence of resonance behaviour is the 4 MeV point obtained by HILMAN otherwise the energy variation seems to be too slight to identify clearly from these results. Obvious features of the polarization are that it is fairly small near the stripping peak which is somewhere near 20 to 30° at these energies, and then a rise to a magnitude which is definitely more than the 1/3 predicted by the central distortion theory. At larger angles still we have only one point to indicate the change of sign which is expected theoretically at some angle near to the minimum of the differential cross section. This sign change comes from assuming that the distortion effects provide a small perturbation to the simple stripping, so that the sign of the polarization changes with the sign of the simple stripping amplitude.

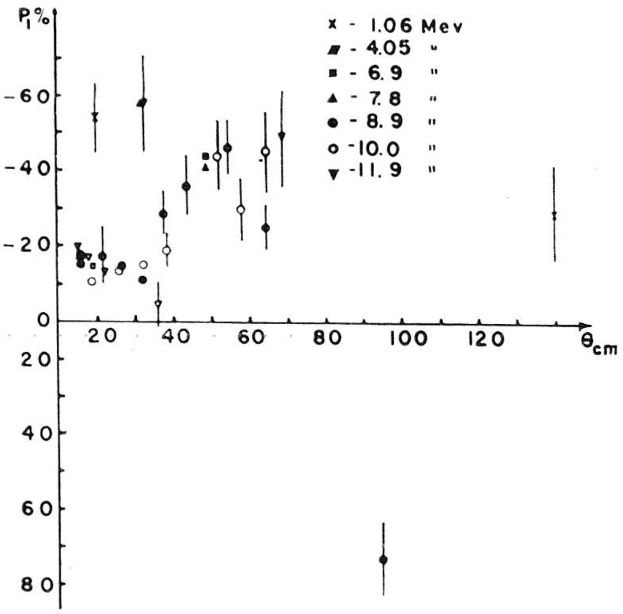

Figure 3

All known polarization measurements on $C^{12}(d, p)C^{13}$

The overall experimental sign of the polarization indicates that the deuteron central distortion effects predominate over the proton distortion effects in producing this polarization.

There is rather fragmentary experimental data on a range of other reactions in this energy region, mostly obtained by the same experimental system as for the carbon measurements. An exception to this is the method used by CHASE and IGO [6] to find the sign of the B^{12} polarization from the $B^{11}(d,p)B^{12}$ reaction. They looked at the forward-backward asymmetry of the β decay of the B^{12} final nucleus. On the central force distortion theory, the final nucleus has the same sign polarization as the outgoing protons when $j = l + 1/2$ and the opposite sign when $j = l - 1/2$.

The results in the medium energy range can be summarised by saying that, apart from two reactions, the sign of the polarization has always been found to indicate predominating deuteron distortions. One of the exceptions is $B^{10}(d,p)B^{11}$ to the first excited state. HENSEL and PARKINSON [7] showed that this has opposite sign to the ground state. This reaction has an $l = 1$ angular distribution but a spin change of 5/2 is required to fit the energy level spins. Two theories have been suggested for this reaction, both of which would predict the anomalous proton polarization. One is that a normal $l = 1$ transition is followed by spin flip of the emitted proton interacting with the final nucleus. This process would of course require a noncentral proton interaction. The other suggestion is exchange stripping, where the two nucleons from the deuteron are both absorbed and the emitted proton, with opposite spin direction, comes from the initial nucleus.

The other exception to the polarization sign rule is $Ca^{40}(d,p)Ca^{41}$, which should be $l = 3$ and $j = 7/2$, but has been found to emit protons with positive polarization in the stripping peak. Distorted wave calculations have not yet been made for nuclei as large as calcium. A possible explanation of the sign is that some size resonance effect in the distorted waves could make the polarization produced by the proton distortion the more important in these larger nuclei. It should be possible to investigate this both theoretically and experimentally.

There are some measurements on $l = 0$ reactions. Any polarization here cannot be caused by the central distorting potentials. HENSEL and PARKINSON [7] measured the polarization of the proton group corresponding to stripping to the 3.09 MeV level in C^{13}. At 15° the polarization was found to be zero, but when they measured further away from the forward stripping peak, at 45°, they found + 21% polarization.

Very little has been done on (d,n) stripping polarization. I am excluding consideration here of the $D(d,n)He^3$ reaction which has been discussed by HAEBERLI. There are some measurements in progress by a group in Cracow using a helium counter as a polarization analyser and taking coincidences between the recoil helium and the scattered neutron in a separate counter.

In Liverpool we have been doing some measurements with polarized deuterons of about 6 MeV.

The deuterons were first polarized by scattering them from carbon and we then measured the left-right asymmetry in $Be^9(d,p)Be^{10}$. The angular variation of the ground state and first excited state group asymmetries is shown in figure 4. The ground state polarization angular distribution seems to be quite similar in shape to that found for the proton polarization in $C^{12}(d, p)C^{13}$, as should be expected from the last of the central distortion theory rules, since the stripping peaks and minima of the two reactions occur at roughly similar angles. The opposite signs of the asymmetries of the ground and first excited state groups is also expected from the central distortions because the neutron coupling of one is $j = l + 1/2$, it could be mainly $j = l - 1/2$ in the other. This opposite sign would not be produced by the spin dependent part of the distortions, which ought to be very similar for both proton groups and give similar polarizations. Unfortunately the deuteron vector polarization was not known in these measurements and also tensor polarization have an unknown effect. To make a real test of the last of the central distortion theory rules it will be necessary to measure the asymmetry using deuterons which have known polarization on a reaction where the proton polarization has already been measured. It is possible that the rule might be more generally valid than the central distortion theory but with the factor 3 modified somewhat.

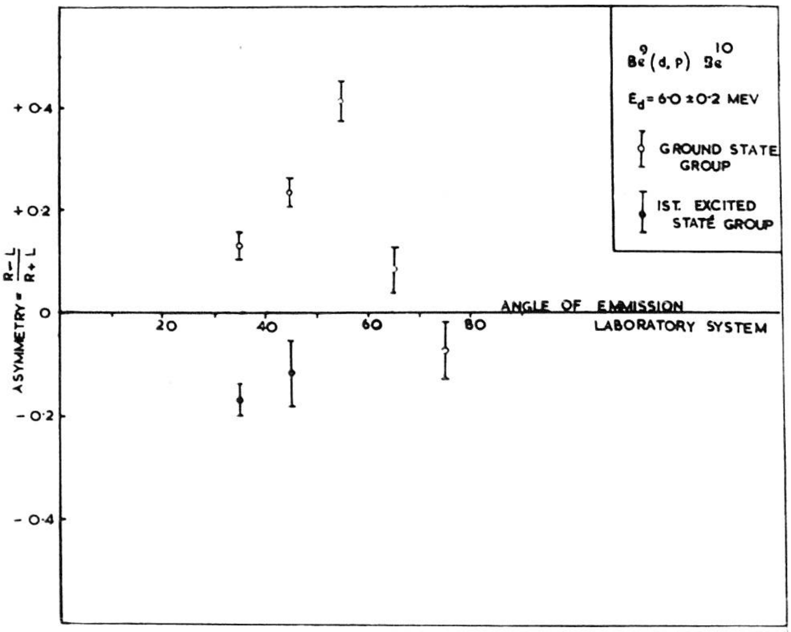

Figure 4
Proton Stripping Asymmetry with Polarized Deuterons

Lastly I want to mention some measurements at much higher energies which I think are relevant. These are (p, d) pick up asymmetry measurements at 145 MeV on carbon by COOPER and WILSON [8] made with a polarized proton beam. They represent the inverse of the stripping polarization measurements. At these energies the energy spectrum of the deuterons shows a peak corresponding to the production of the C^{11} nucleus in its ground state. COOPER and WILSON measured the angular distribution of the asymmetry of these deuterons and their results are shown on figure 5. The line is a theoretical calculation by GREIDER where the neutron spin coupling is entirely neglected and where the asymmetry arises purely through the spin dependence of the proton and deuteron distorting potentials. As is well known from elastic scattering processes the oscillations in the differential cross section and polarizations which are seen at medium energies are smoothed out when the energy becomes high enough for the wavelengths to be of the order of many times the nuclear surface thickness. The same thing seems to have happened here where there is no sign of an $l = 1$ peak at some small angle in the pick-up differential cross section. Oscillations in the asymmetry which might have been associated with this peak in the same angular region are completely absent. The asymmetry is certainly very small at forward angles.

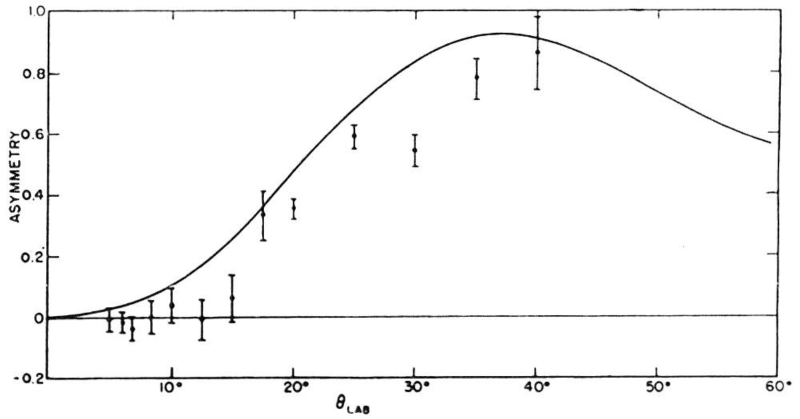

Figure 5
Asymmetry in the reaction $C^{12}(p, d)C^{11}$ by a 100% polarized beam. The theoretical curve is a fit by GREIDER.

The general situation in stripping polarization measurements is that they have established the central distortion theory as being qualitatively but only qualitatively valid for most reactions in the medium energy region. The agreement is sufficiently good however that polarization measurements could probably be used with a fair degree of certainty in this energy region to fix the predominating j of the captured nucleon.

On the other hand a comparison of polarization measurements with a full theoretical calculation, including spin dependent forces, could give information about the optical model potential which would suppliment that obtained more directly from scattering measurements.

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