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Inelastic Proton–Deuteron Scattering at 135 MeV

M. J. ESTEN, T. C. GRIFFITH, G. J. LUSH, A. J. METHERINGHAM
University College, London, England

1. INTRODUCTION

A general survey of inelastic *p–d* interactions at 135 MeV has been made using a counter-controlled high-pressure Wilson cloud chamber with protons from the synchrocyclotron at the Atomic Energy Authority, Harwell. Preliminary results reported earlier[1,2] have now had various selection criteria and corrections due to fiducial volume restrictions applied in detail. The 1048 photographs of *p–d* collisions accepted in the final analysis were taken in two runs for which experimental details were given by Cairns *et al.*[3] There was no magnetic field on the chamber but the deuterium filling pressure ensured that accurate energy (from range) measurements on 1- to 6-MeV protons was achieved whatever their angle of emission. On the basis of the Fermi motion of nucleons in the deuteron one would expect to stop 80% of the "spectator" protons from quasi *p–n* collisions and a complete kinematic analysis of such events yields the angle and energy of the associated neutron.

2. CHARGED-PARTICLE CROSS SECTIONS

As described by Cairns *et al.*[3] the total number of protons entering the cloud chamber are counted so that absolute cross sections can be deduced. The total cross sections for elastic and inelastic scattering obtained in the present work are in good agreement with other data.[4] Due to the geometry of the counter selection system, however the cross sections are for events in which no charged particles of energy >6 MeV are emitted at laboratory angles <10°. The correction for events within this 10° restriction is estimated to be 4 to 7 mb for inelastic collisions and 3 to 5 mb for elastic scattering. The cross sections without these corrections are:

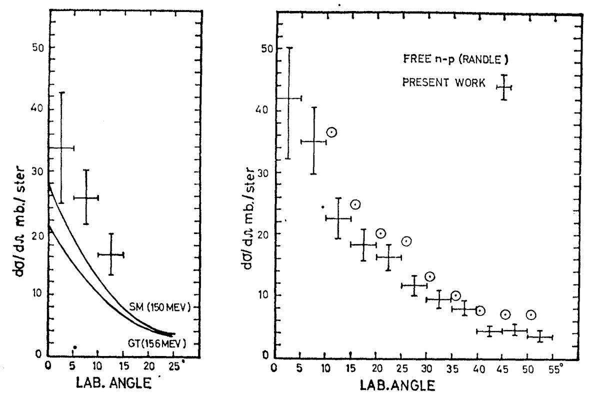
$$\sigma_{\text{elastic}}=13.6\pm1.0 \text{ mb}; \qquad \sigma_{\text{inelastic}}=56.4\pm1.9 \text{ mb}.$$

$$\sigma_{(\text{el+inel})}=70.0\pm2.2 \text{ mb}.$$

The results for the elastic scattering differential cross sections are in good agreement with the Harvard data.[5] The differential cross section of all protons with energy >6 MeV from elastic and inelastic collisions, except at the more forward angles, are also essentially in agreement with the Harvard data.[6]

3. HIGH-ENERGY NEUTRONS

The differential cross sections for neutrons of energy within 8 MeV of the maximum possible energy at each angle are given in Fig. 1(a). The unknown bias against measuring the energy of protons >6 MeV reflects as an unknown bias in the neutron cross sections at laboratory angles >13.6°. The results for the bias free region are compared with the impulse approximation calculations of Castillejo and Singh[7] using SM and GT potentials. It is clear that the present results are consistently higher than theory. The discrepancy is not due to the calculations being for the $d(n, p)2n$ reaction rather than the measured $d(p, n)2p$ reaction. Phillips[8] has shown that,



(a) (b)

FIG. 1. (a) Angular distribution for neutrons of energy down to 8 MeV below maximum possible energy. (b) Angular distribution of all neutrons >10 MeV.

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[1] M. J. Esten, T. C. Griffith, G. J. Lush, A. J. Metheringham, and C. P. Van Zyl, *Conference on Nuclear Forces and the Few-Nucleon Problem* (Pergamon Press, London, 1960), p. 227.

[2] M. J. Esten, T. C. Griffith, G. J. Lush, and A. J. Metheringham, Proc. of Rutherford Jubilee International Conf., 1962, p. 163.

[3] D. J. Cairns, T. C. Griffith, G. J. Lush, A. J. Metheringham, and R. H. Thomas, Nucl. Instr. & Methods **10,** 272 (1961).

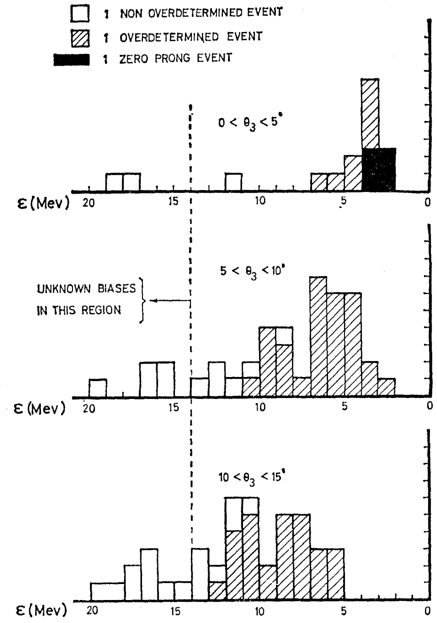
[4] R. Alphonse, A. Johansson, A. E. Taylor, and G. Tibell, Phil. Mag. **46,** 295 (1955).

[5] H. Postma and R. Wilson, Phys. Rev. **121,** 1229 (1961).

[6] J. N. Palmieri, A. M. Cormack, N. F. Ramsey, and R. Wilson Ann. Phys. (N. Y.) **5,** 299 (1958).

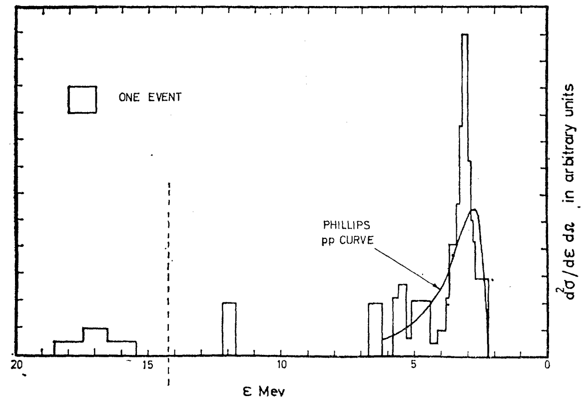
[7] L. Castillejo and L. S. Singh, in Ref. 1, p. 193.

[8] R. J. N. Phillips, Nucl. Phys. **53,** 650 (1964).



ENERGY SPECTRA OF FOWARD NEUTRONS

(a)



IDEOGRAM OF NEUTRON ENERGY SPECTRUM <5°

(b)

Fig. 2. (a) Histograms of neutron energy spectra. (b) Comparison of 0° to 5° neutron energy spectrum with theory.

although the different final-state interaction between two low-energy neutrons or two low-energy protons gives different shapes to the energy spectra of the fast nucleon in the two cases, the effect on the 0° cross section is negligible. The use of more recent nucleon–nucleon potentials is not likely to eliminate the discrepancy but a proper relativistic calculation might improve matters. If all the measured neutrons with energy >10 MeV are considered the cross sections are as shown in Fig. 1(b). All these cross sections are minimum values because neutrons from events where both protons have energy >6 MeV cannot necessarily be analyzed.

The energy spectra of neutrons emitted in the angular ranges 0° to 5°, 5° to 10°, and 10° to 15° are shown as histograms in Fig. 2(a). For the 16 events at 0° to 5° the energy difference ϵ between the incident proton and emitted neutron is very precisely determined. Both protons stop in the chamber here and ϵ is measured directly. Moreover the problem is overdetermined thus permitting a least squares fitting of the measurements on these events to determine ϵ more precisely. By considering the spectrum in ϵ, rather than in neutron energy, the smearing effect of the incident beam energy spread (that would be reflected directly in the neutron energy) is eliminated. Figure 2(b) shows an ideogram of the energy spectrum compared with the calculations for 0° neutrons by Phillips.[8] Bowen *et al.*[9] have also measured the neutron energy spectrum and observe a peak at the correct position but their experimental energy resolution was too large to allow firm conclusions about the width of the spectrum. Recent improvements of this technique at Harwell[10] has yielded energy resolution comparable to the present work, with statistics which allow detailed comparison with theory.[8]

4. "SPECTATOR" PROTONS

The present data on the angular and energy distribution of the low energy protons are a little difficult to interpret theoretically. The protons arise from two distinct processes; there are genuine "spectator" protons from quasi *p–n* collisions and also low-energy protons from large angle scattering of the incident proton off either nucleon in the deuteron, the other particle being the "spectator." These "pseudo-spectators" can be identified by noting that hardly any true "spectators" of energy >10 MeV are to be expected. Hence, when only one of the three particles has energy <10 MeV the "spectator" is specified with reasonable certainty. In Fig. 3(b) the angular distributions of the low-energy protons are given for the energy intervals 1 to 2 MeV and 2 to 6 MeV with no restriction on the energy of the other two particles. Figure 3(a) shows similar distributions for events where two of the particles have energy >10 MeV. There is hardly any change in the shape of these distributions when the energy cut-off is increased from 10 to 20 MeV. It is observed that when there is no energy restriction there is pronounced forward peaking due to the inclusion of "pseudo-spectators." This peaking forward of 90° is however still present when the energy cut-off of 10 or 20 MeV is imposed. The forward/backward ratios are 1.32±0.25 with the 10-MeV cut-off and 1.23±0.27 with 20-MeV cut-off for 1- to 2-MeV "spectators." For the 2- to 6-MeV "spec-

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[9] P. H. Bowen, G. C. Con, G. Huxtable, A. H. Langsford, J. P. Scanlon, and J. J. Thresher, Nucl. Phys. **30**, 475 (1962).

[10] A. Langsford (private communication).

tators" the corresponding ratios are 1.37±0.21 and 1.42±0.26. The impluse approximation calculations, effected using the free *n–p* cross sections, in contrast, show slight backward peaking. This disagreement is probably due to the neglect of final-state interactions and off-the-energy-shell effects in the theory. Such conclusions are corroborated by the fact that there is less forward peaking for the 1- to 2-MeV group where the process is more nearly on the energy shell and final state interactions are less important.

The results for the energy distribution of low-energy protons lead to similar conclusions. These results are best demonstrated using a Chew–Low[11] extrapolation procedure first used in this problem by Palmieri *et al.*[6] At the unphysical spectator kinetic energy of −1.113 MeV a pole in the matrix element representing the process of quasi *p–n* scattering with spectator proton, is expected. This process should, therefore, entirely dominate the scattering at that point and any other effects due to final state interactions should vanish. Moreover, the process can easily be shown to be on the energy shell at that point and hence the agreement between theory and experiment should be exact. This can be verified by plotting the ratio R of the experimental to theoretical cross sections, $(\sigma_{\text{exp}}/\sigma_{\text{theor}})$, as a function of spectator energy and extrapolating the graph to −1.113 MeV where the ratio should be unity. These graphs are shown in Fig. 3(c), the values of R at −1.113 MeV being 1.13±0.17 with a 20-MeV cut-off and 0.93±0.13 with the 10-MeV cut-off. A χ^2 and F test of these data indicates a quadratic extrapolation for the 20-MeV cut-off and a linear extrapolation for the 10-MeV cut-off.

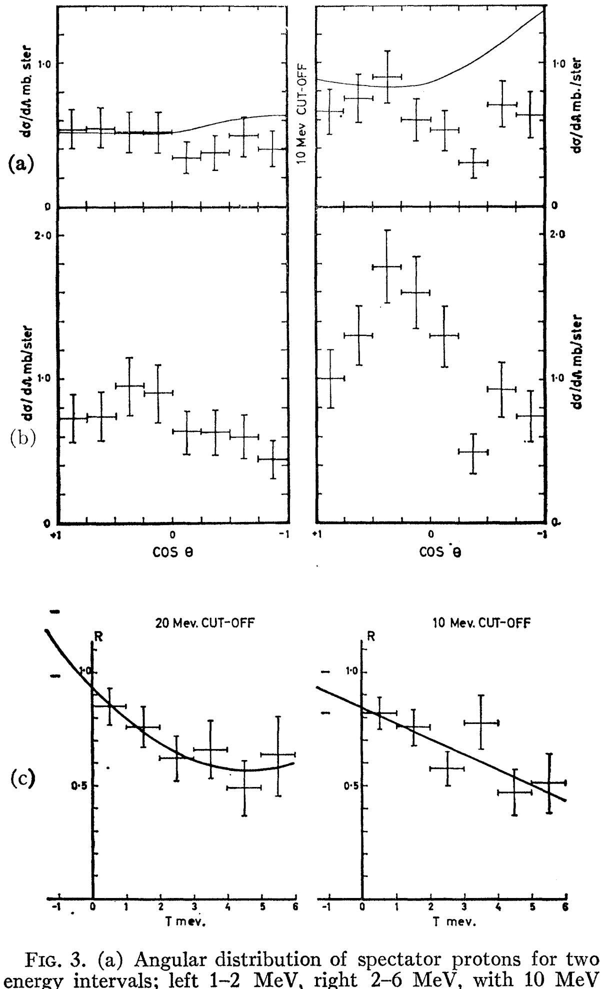

Fig. 3. (a) Angular distribution of spectator protons for two energy intervals; left 1–2 MeV, right 2–6 MeV, with 10 MeV cut-off. The curves represent impulse approximation calculations. (b) Angular distribution of low-energy protons; left: 1–2 MeV, right 2–6 MeV, without cut-off. (c) Extrapolation of R as function of spectator kinetic energy T.

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Discussion

McCarthy: I would like to make a comment on Dr. Griffith's paper, which is a belated answer to Dr. Eisberg's question on three-body forces. Let us look at the theories of these experiments which use two-body scattering data; that is, two-body data on the energy shell. Before we get the three-body forces, we still have to try and get away with using models for the two-body forces off the energy shell. For example, the theory of Amado, Yam, and Aaron has a potential which is a good model for the two-body forces off the energy shell. Maybe they will not be the right models. It is very clear that the impulse approximation is not bad, so there is not too much information off the energy shell. But in Dr. Griffith's work the impulse approximation (in the sense of using two-body amplitudes on the energy shell) scattering data are not good enough, so we have to have a better theory of some kind. I think you have to try to explain the data with acceptable two-body forces, and be sure this cannot be done before starting to worry about three-body forces.

Also, the best way to get off the energy shell is to get into a situation with a lot of distortion such as (p, $2p$) on a nucleus. Probably in the deuteron there is not enough distortion.

Griffith: I agree entirely with Dr. McCarthy's statement.

Pugh: I would like to ask Dr. McCarthy a question which may may be somewhat naive. In this particular case, what is the difference between a two-body force off the energy shell and a three-body force?

McCarthy: I don't know. A three-body is a force between two bodies that is different because you have got a third body there. For the two-body force off the energy shell you use elements of the free two-body T matrix which do not conserve energy or momentum. In a three-body reaction, it is a different T matrix, because the T matrix is affected by the other body.

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[11] G. F. Chew and F. E. Low, Phys. Rev. **113**, 1640 (1959).

ZUPANČIČ: Maybe I could give a classic example of a three-body force. Take three charged metallic spheres; just consider them as elementary particles; you have three-body forces between those three spheres, because the loose charges move. When any of the spheres is displaced the force between any two spheres depends on the position of the third sphere. That is what I think is meant by three-body forces in nuclear physics as well.

SLAUS: Thank you for this classical comment.

There was a suggestion from the audience, maybe someone could give us a sort of summary? Is anyone willing to give us a summary? (No response.)

Before closing, I would like to thank all the speakers and participants, and I know I express the opinion of all of us when I express our deep and sincere thanks to the members of the organizing committee.

This is the end of the conference.