Polarization of Protons from Deuteron Stripping in Carbon

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The polarization of protons from the stripping of 4-Mev deuterons in carbon at 30° has been measured by scattering in helium. The value of $P=-58\%\pm13\%$ is larger than, but the sign is in agreement with, predictions based on a simple stripping-plus-potential scattering picture.

1. INTRODUCTION

A SUCCESSFUL theory of low-energy stripping reactions has been produced by Butler[1] and others.[2] The theory has made possible the assignment of a large number of nuclear energy level parameters by analysis of angular distributions of the outgoing nucleons from (d,p) and (d,n) reactions, and has shed new light on the structure of nuclei, particularly with respect to the shell model.

Refinements of Butler's theory[3–5] have taken into account the interaction of the outgoing particles with the stripping nuclei, and have predicted that these particles should be polarized. A measurement of this polarization would help to resolve ambiguities in the assignment of some level spin values, and would provide a further test of the model used in the stripping theory.

In the present experiment, the polarization of protons emerging at 30° from natural carbon bombarded by 4.05-Mev deuterons has been measured, using helium as an analyzer and nuclear emulsions as detectors. Only protons corresponding to the ground states of C^{13} and C^{14} had enough energy to be detected. The contribution from the latter is less than 1%,[6] and is neglected.

2. METHOD

Experiments on the scattering of protons by helium in the energy region 1–10 Mev[7] have shown that the collision is highly polarizing. A calculation of the polarization as a function of energy for center-of-mass scattering angles 110°–138° has been published by Brinkworth and Rose.[8]

If the asymmetry in the scattering of a beam of particles with polarization P_1 is defined as $e\equiv(L-R)/(L+R)$, where L and R are the scattered intensities at equal angles to the left and right in the plane perpendicular to P_1, then $P_1=e/P_2$, where P_2 is the polarization produced in the scattering of an unpolarized beam.

In the present experiment, the stripped protons were scattered in helium at equal angles to the left and right in the plane of the (d,p) reaction. P_2 was calculated for the angles and energies involved from the curves of Brinkworth and Rose. P_1, the polarization of the protons, was then just the corrected experimental asymmetry divided by P_2. The sign convention for the polarizations was that the positive direction is that of $\mathbf{k}\times\mathbf{k}'$, where $\mathbf{k}$ and $\mathbf{k}'$ are the propagation vectors of the incident and scattered waves, respectively.

3. EXPERIMENTAL PROCEDURE

The nuclear plate camera was designed by Brinkworth and Rose.[8] It allowed protons scattered in the helium gas filling of the chamber at angles greater than 120° in the center-of-mass system to enter nuclear emulsions placed to the right and left of the beam. No protons scattered only once by the metal parts could enter the plates.

The experimental arrangement is shown schematically in Fig. 1. Deuterons of 4.05 Mev from the Harwell Van de Graaff accelerator hit a gold target coated with 0.53 mg/cm² of carbon, placed at 15° to the deuteron beam. Protons emerging at 30° to the incident beam passed through a 15-mg/cm² aluminium window into the scattering camera, which was filled with purified helium to a total pressure of $2\frac{1}{2}$ atmospheres. The scattered protons were then recorded in 50 μ Ilford C2 plates.

A background exposure was also performed, by placing a nickel foil sufficiently thick to stop the protons immediately in front of the scattering volume of the camera. The integrated deuteron beam current was 68 microampere-hours for the main exposure, and 36 for the background.

A preliminary exposure revealed a heavy background of tracks from stray neutron recoils, as well as bad gamma fogging. A shield of four inches of lead and four inches of paraffin wax surrounding the vacuum tube between the carbon target and the chamber reduced both to a tolerable level.

The Q of the $C^{12}(d,p)C^{13}$ (ground state) reaction is +2.72 Mev. Emergent protons lost about half their energy in the helium collision, and also lost energy in

* Now on leave of absence at University of the Witwatersrand, Johannesburg, South Africa, where this work was completed.
[1] S. T. Butler, Proc. Roy. Soc. (London) **A208**, 559 (1951).
[2] See, for instance, W. Tobocman and M. H. Kalos, Phys. Rev. **97**, 132 (1955).
[3] H. C. Newns, Proc. Phys. Soc. (London) **A401**, 477 (1953).
[4] J. Horowitz and A. M. L. Messiah, J. phys. radium **14**, 731 (1953).
[5] W. B. Cheston, Phys. Rev. **96**, 1590 (1954),
[6] R. E. Benenson, Phys. Rev. **90**, 420 (1953).
[7] See, for instance, Kreger, Jentschke, and Kruger, Phys. Rev. **93**, 837 (1954).
[8] M. J. Brinkworth and B. Rose, Nuovo cimento **3**, 195 (1956).

the entrance foil and gas of the camera. The protons were therefore expected to have ranges of 35–55 μ in the emulsions, corresponding to energies of 1.8–2.5 Mev. Elastically scattered 4-Mev deuterons would be stopped in the gas before entering the plates. Tracks with ranges of 30–59 μ were accepted, and showed a satisfactory peaking near 40 μ. The tracks were required to enter the surface of the emulsion, and to have a dip angle in the unshrunk emulsion of less than 14°. They were required to travel in a direction within $\pm 15°$ of the azimuthal angle of the scanned area with respect to the center of the beam, and in fact peaked sharply within these limits. Tracks whose ionization density was too low or definitely increased towards the surface of the emulsion, indicating that the particle was involved in a nuclear interaction or was traveling out of the emulsion, were discarded.

As a general check on the method, tracks entering the emulsion *towards* the scattering volume, but with otherwise similar criteria, were also recorded. Neither these tracks nor the background tracks showed any peaking in range or in azimuthal angle.

4. RESULTS

For tracks traveling away from the scattering volume, the results were as follows. Main exposure: 180 tracks in the right plate, 78 in the left; background: 12 right, 18 left. After correction for the ratio of the integrated exposures, this gives

$$R=157\pm15,\quad L=44\pm12,\quad \text{and}\quad e=-56\%\pm10\%.$$

The corresponding figures for tracks entering the emulsion towards the scattering volume were 28 and 19, with backgrounds 18 and 15, which are considered satisfactory. These tracks turned out to be almost entirely ones for which the direction of travel could not be determined from the ionization density; so that they were probably largely tracks of particles emerging from the surface of the emulsion. This was also true of most of the background tracks.

A correction to the experimental asymmetry arises from the nonuniform illumination of the helium scattering volume by the stripped protons. The proton cross section from deuteron bombardment of carbon falls off with increasing angle (i.e., towards the left plate) by about 3% per degree near 30°,[9] so that the proton flux falls by about 12% across the scattering volume. This affects the scattered intensity towards the plates, because the geometry is larger, and the helium scattering angle smaller (since the incident beam is slightly divergent), for scattering into the right plate from the *right* side of the beam than from the left.

The contribution of acceptable tracks to any point in the plates per unit cross-sectional area of the beam varies about inversely as the distance to that portion of the beam. The geometry effect is therefore estimated to make the observed asymmetry about 1% too high. The helium scattering cross section increases by about $1\frac{1}{2}\%$ per degree near 130°,[7] making the asymmetry too low by 0.1%, which is negligible.

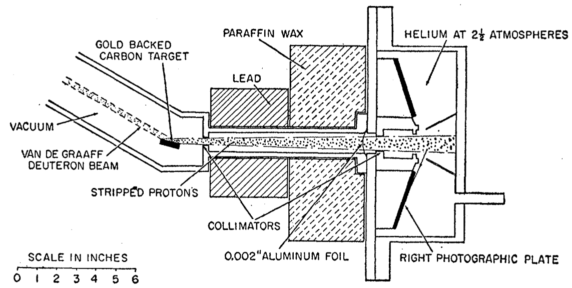

FIG. 1. Schematic diagram of the apparatus.

An experimental error could also stem from any misalignment of the axis of the scattering camera with respect to the collimated proton beam. This is estimated at less than a degree. Together with the variation in the proton-helium scattering cross section, this leads to an error of $\pm 1\frac{1}{2}\%$ in the asymmetry.

Because of the fairly heavy track background in the plates, there could have been some personal bias in plate-scanning efficiency. This was eliminated as far as possible by frequent interchange of plates being scanned, and by orienting the plates so that the apparent direction of the tracks was always the same.

The calculated average value of P_2, the helium polarization, was $+94\%\pm3\%$ for the energies and angles involved. The final corrected value of the proton polarization is then $P_1(30°)=-58\%\pm13\%$.

5. DISCUSSION

The value of the polarization is higher than that predicted by any stripping theory to date, but it is consistent with the high values found in some other nuclear reactions at low energies.[10] The sign is the same as, but the value larger than that obtained by Juveland and Jentschke[11] in a similar experiment with 11.9-Mev deuterons.

If the ground state of C^{13} is $(\frac{1}{2}, -)$,[12] the experimental sign of the polarization is opposite to that predicted by the simple Newns theory, which assumes the nucleus to be perfectly absorbent to the proton. Horowitz and Messiah predict the same sign as Newns, using a repulsive hard-sphere potential for the proton-nuclear interaction. However, assuming that the proton after stripping scatters in an attractive complex central plus spin-orbit well ("cloudy crystal ball") with parameters

[9] Holmgren, Blair, Simmons, Stratton, and Stuart, Phys. Rev. **95**, 1544 (1954).

[10] See, for instance, Adair, Darden, and Fields, Phys. Rev. **96**, 503 (1954).

[11] A. C. Juveland and W. Jentschke, Bull. Am. Phys. Soc. Ser. II, **1**, 193 (1956).

[12] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).

satisfying other low-energy scattering data, Cheston obtains for the polarization the experimental sign, though only about a third of the experimental magnitude. He suggests[13] that the inclusion of the spin-spin and tensor interactions would enhance the predicted polarization.

[13] W. B. Cheston (private communication).

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Cross Sections for Photoneutron Emission Induced by the Lithium Gamma Rays*

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Cross sections for emission of photoneutrons produced by $Li^7(p,\gamma)$ gamma rays in thirteen middle-weight and heavy nuclei have been measured. Neutrons were detected by BF_3 counters embedded in paraffin, and the gamma-ray intensity was measured with a NaI scintillation detector. Measurements made with two groups of neutron counters whose efficiencies depended differently on neutron energy indicated that the energy distributions of the emitted neutrons are evaporation-like in shape. The present cross section values are about 20% higher than previous measurements of McDaniel, Walker, and Stearns, but the difference is within the combined errors. The measurements provide an independent check on the accuracy of the cross-section curves obtained with bremsstrahlung beams; agreement is obtained with University of Pennsylvania betatron data but not with some other betatron results.

INTRODUCTION

A LARGE number of measurements of photonuclear reaction cross sections have been made in the last few years, especially in the region of the giant absorption resonance near 15 Mev, with a view to obtaining a better understanding of the photon absorption process.[1] Most of these measurements have been made with bremsstrahlung beams from electron accelerators. The magnitudes and shapes of cross-section curves obtained in this way are subject to several uncertainties. Because of the continuous nature of the photon spectrum, the observed excitation curves must be analyzed by a "photon difference" method[2] to obtain the cross section as a function of photon energy. This procedure exaggerates considerably any errors present in the original data. In addition, the results are rendered somewhat uncertain by a lack of exact knowledge of the bremsstrahlung spectrum shape, and by the x-ray intensity monitoring methods commonly used.

Measurements of photonuclear cross sections using monoenergetic gamma rays, while restricted to a few energies, avoid the above difficulties and provide an important check on the accuracy of the cross section data obtained with x-rays. This paper presents measurements of cross sections for photoneutron emission by the $Li^7(p,\gamma)$ gamma rays for thirteen middle-weight and heavy nuclei. Direct neutron detection is employed. These measurements represent an extension, with some improvements, of the work of McDaniel *et al.*[3] Those authors obtained cross-section values somewhat lower than the betatron data, and it was thus of interest to obtain independent values for these numbers.

One interest in accurate measurements is to make a comparison of experimental values for the integrated cross section for photon absorption by nuclei with the theoretical predictions of the sum rules.[4,5] In the case of heavy nuclei, the absorption of gamma rays results predominantly in the ejection of neutrons, and consequently these photoneutron cross sections are a good measure of the cross section for absorption.

EXPERIMENT

The lithium proton-capture gamma rays consist of a narrow line at 17.6 Mev and a broad line at 14.8 Mev. In the present experiment these gamma rays were produced by bombarding a thick lithium metal target with a magnetically analyzed beam of 480-kev protons from the Pennsylvania electrostatic generator. Under these conditions nearly all the gamma rays are associated

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[1] For reviews of this field see K. Strauch, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Stanford, 1953), Vol. 2, p. 105; J. S. Levinger, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Stanford, 1954), Vol. 4, p. 13.

[2] See, for example, L. Katz and A. G. W. Cameron, Can. J. Phys. **29**, 518 (1951).

[3] McDaniel, Walker, and Stearns, Phys. Rev. **80**, 807 (1950).

[4] J. S. Levinger and H. A. Bethe, Phys. Rev. **78**, 115 (1950).

[5] Gell-Mann, Goldberger, and Thirring, Phys. Rev. **95**, 1612 (1954).