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NEUTRON-HELIUM SCATTERING

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Abstract: Relative differential cross sections of neutrons elastically scattered from ^{4}He were measured at neutron energies of 0.55, 0.84, 1.16 and 1.33 MeV. The scattered neutrons were detected in a time-of-flight spectrometer for c.m. angles ranging from 25° to 161°. The relative differential cross sections are compared to curves generated from phase shifts published elsewhere.

E | NUCLEAR REACTIONS ^{4}He(n, n), $E = 0.55$, 0.84, 1.16 and 1.33 MeV; measured relative $\sigma(\theta_n)$. Compared to curves generated from phase shifts.

1. Introduction

The scattering of nucleons by helium is of interest from two perspectives. For the theorists this is a simple case of a nucleon-nucleus interaction. For the experimentalists the spin-orbit dependence of the interaction is a tool with which to analyze neutron polarization.

The present work employed a time-of-flight (TOF) spectrometer in which the neutrons scattered from helium were observed. The objective was to resolve discrepancies in the phase shifts below 1.4 MeV and to detect any systematic errors involved in the extensive previous work, almost all of which was based on the observation of α-recoil spectra.

The only previous TOF measurements observing the scattered neutrons was that of Young *et al.* [1]). They measured the n-He differential cross section at 1.79 MeV but were unable to decide unambiguously between the DGS phase shifts [the phase shifts of Dodder, Gammel and Seagrave [2, 3])] and those of Demanins *et al.* [4]) at that energy.

The phase shifts most often referred to are the so-called DGS phase shifts. Below 1.4 MeV the DGS phase shifts are those deduced from early proton-helium scattering. In 1952, Adair [6]) observed the n-^{4}He differential cross section at seven neutron energies between 0.40 and 1.40 MeV and showed that cross sections calculated from proton-helium phase shifts [5]) gave qualitative agreement with his data. Recently Satchler *et al.* [7]) fit both n-He and p-He differential cross section and polarization

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data using an optical-model potential. They found that the parameters providing the best fits are charge-dependent. In summary, below 1.4 MeV the DGS phase shifts deduced from proton-helium scattering and qualitatively verified by Adair, should come under careful scrutiny.

In 1967, Morgan and Walter [8]) measured the n-He differential cross section at 22 neutron energies between 0.20 and 7.0 MeV. The measurements were made by observing the energy distribution of the recoiling helium nuclei in a high-pressure gas scintillation detector. Utilizing all the data in searching for the best energy-independent parameters (e.g., the S-wave hard-sphere radius), Morgan and Walter deduced phase shifts as a function of energy throughout the entire energy range studied. Also they reviewed the disagreement between the published shifts, especially in the few MeV region. (One should also see the publications of Hodgson [9]) and Austin *et al.* [10]) for reviews of the work prior to 1962.)

The present measurements were begun before the completion of the work of Morgan and Walter [8]). Since discrepancies were already apparent for energies below 1.4 MeV, it was thought that any overlap in the results here with those of Morgan *et al.* would add confidence to the best set of shifts to use in this low-energy region. Furthermore, the detection of the scattered neutrons in a TOF spectrometer would provide a more accurate determination of the scattering at forward angles in contrast to the detection of helium recoils. There the helium recoil energy is so small for low neutron energies that one is concerned with systematic errors in the phase-shift analysis of helium recoil data.

2. Experimental procedure

A 5.5 MV Van de Graaff accelerator provided a pulsed proton beam of 10 ns duration at a repetition rate of 2 MHz. The bursts, subsequently compressed to about 2 ns duration by a Mobley bunching system [11]), impinged on a neutron-producing target with a $\pm 2°$ convergence. The average target current was several μA. The pulsed neutrons produced thus allowed sorting of the energy groups of scattered neutrons by time-of-flight techniques [12]).

A stainless steel spherical vessel† of 3.8 cm diam., 0.08 cm wall thickness was filled with 303 atmospheres of ^{4}He. The sphere was placed approximately 13 cm from the neutron-producing target on the 0° axis defined by the incident proton direction as shown in fig. 1. Scattered neutrons were detected at the end of a fixed flight path of 2.25 m with a plastic scintillator†† (12.7 cm diam. by 2.54 cm thick) coupled to a photomultiplier tube†††. A polyethylene wedge shielded the throat section of the collimator and detector from the direct flux from the target.

† On loan from Los Alamos Scientific Laboratory; see also ref. [13]).
†† Nuclear Enterprises NE102 scintillator.
††† Amperex Electronic Corporation 58AVP.

In taking angular distributions of scattered neutrons, the target and sphere positions remained fixed while the detector, shielding, collimator and wedge were readjusted for angles taken counter-clockwise as shown in fig. 1. The angles were alternated between large and small values between 20° and 155° (lab) and recorded from an angle indicator on the pivot beneath the helium sphere.

Background runs consisted of replacing the filled sphere with an evacuated one supported above it. Both spheres were supported by thin tungsten wires and a filling tube mounted within an aluminium frame which was raised and lowered [13]). Upon

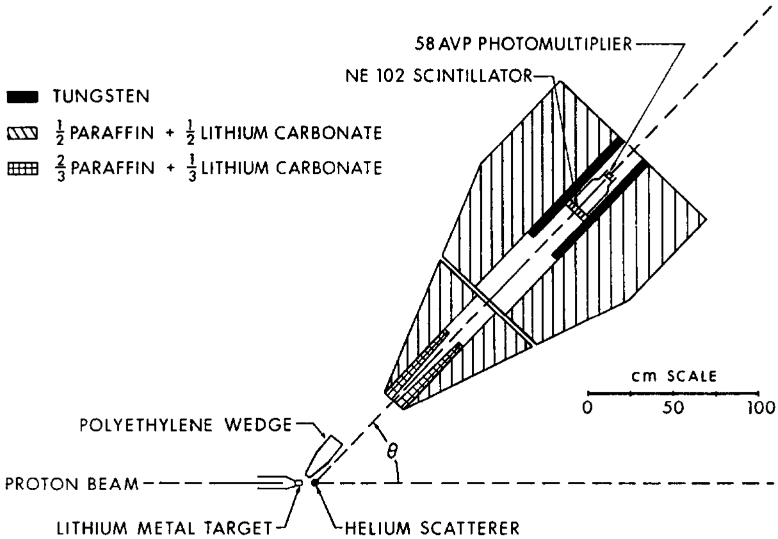

Fig. 1. Schematic of the laboratory arrangement.

raising or lowering the frame, the alignment was checked with two transits at approximately 4 m at 0° and 90°, respectively.

The length of a run was determined for simplicity by the total charge collected on the target. For most runs 900 to 1800 μC of charge was collected, requiring 15 to 20 min. As the data were taken the charge was adjusted to maintain 2 % precision in the statistical accuracy in the difference between the helium and background runs, referred to in the following as the "in" and "out" runs. In analyzing the data the yields were normalized to the total counts in a high-bias monitor mounted in a large, floor-mounted shield positioned below the scattering plane, at 85° from the 0° direction. This monitor consisted of a 5 cm diam. by 5 cm thick plastic scintillator coupled to a photomultiplier. A discriminator was set on the "slow" linear output of the monitor to pass only those pulses with amplitudes above that corresponding to the peak in the pulse-height distribution arising from the capture of the 60 keV γ-rays of ^{241}Am.

The neutrons scattered from the sphere were detected with conventional TOF electronics. The fast pulses from the anode of the 12.7 cm photomultiplier tube started a time-to-amplitude (TAC) converter which was stopped by delay pulses derived from an induction cylinder through which the beam bursts passed to the target. The TAC pulses were recorded in 256 channels of a 1024-channel analyzer, which was gated open by the requirement that the anode pulse (TAC start pulse) had fallen above the bias on the "slow" linear pulses derived from the 11th dynode. In this way

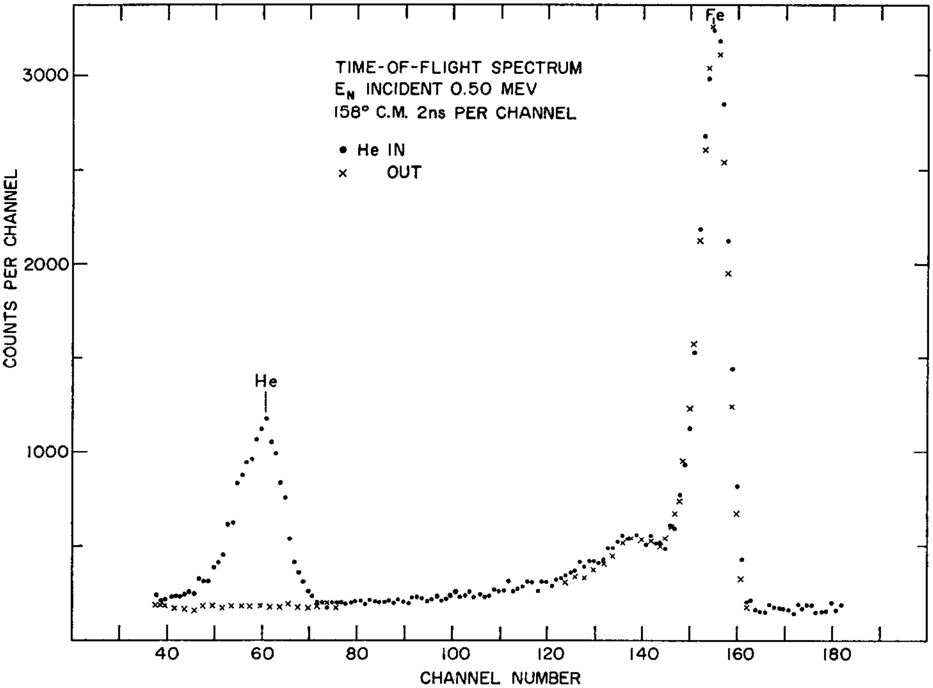

Fig. 2. Time-of-flight spectra for 0.55 MeV neutrons scattered at 150° (lab) from helium-filled and empty iron spheres.

the bias affecting the efficiency of the detector was reproducibly set at one-third of the pulse height at the peak in the pulse-height spectrum produced by the Am γ-ray.

Fig. 2 shows superposed in-out TOF spectra for 0.55 MeV neutrons scattered from the helium and iron sphere at 150° (lab). Due to the variation of the energy of the scattered neutrons with angle, at forward angles the helium group moves closer to the iron group so that the two merge at about 50° (lab).

The subtraction of the iron group (out-run) from the merged groups would have produced a net count attributed to several factors: the helium-scattered neutrons, the difference in mass of the in-out spheres and attenuation by helium of the neutrons scattered from the iron in the insphere. To subtract the correct fraction of the out-run and obtain the n-He counts, the sum of the last two effects was measured experimentally. The ratio R of the elastic iron group of the in to out runs was taken in the angular region where the groups were well separated. In the elastic scattering from iron, the variation of energy with angle was small. Consequently, the variation of the neutron attenuation by helium as a function of energy, and thus scattering angle, was not seen experimentally as a trend in R with angle. Taking R as a constant, values for the average and standard deviation were obtained and used in the region where the groups merged. A typical value for the ratio R was 0.96 ± 0.02. The standard deviation in R was the dominant error at the forward angles.

The attenuation by helium of the neutrons scattered from helium was dependent upon the scattering angle. To employ previous correction techniques [14]), it was assumed that multiple elastic scattering from helium could be considered as an inelastic process, because TOF sorting separated out those neutrons which lost additional energy through multiple scattering.

The relative efficiency of the neutron detector was obtained by measuring the angular distribution of neutrons scattered from a thin polyethylene radiator (0.26 cm diam.) and using TOF methods to sort out neutrons scattered from hydrogen and from carbon.

The efficiency curve was also calculated on the basis of a simple single-scattering model, which yielded a calculated efficiency maximum of 33 %. A marked excess of the experimental efficiency at low energy over that calculated is plausibly attributed to multiple interactions and eventual capture in the scintillator †. This interpretation is consistent with the fact that, for 250 keV neutrons incident on the scintillator, a long, high-energy tail was observed in the pulse-height distribution, which may be attributed to Compton recoils produced by capture γ-rays.

Two neutron-producing targets were employed. For neutrons of 0.545 and 0.840 MeV energy, Li metal was evaporated onto 0.38 mm thick Mo backings to a thickness of 16 and 26 (± 10 %) keV, respectively. The target thickness was determined by a comparison of the yield to that from a LiF target whose thickness had been measured by the rise-width method [15]). The mean neutron energy and energy spread were calculated using: (i) the energy calibration of the momentum-analyzing magnet, (ii) the Q-value of the Li(p, n) reaction, (iii) the target thickness and (iv) the kinematic energy spread arising from the geometry used.

For 1.16 and 1.33 MeV neutrons, the reaction ^{3}H(p, n)^{3}He was used, with tritium gas as the target. Target thicknesses were 30 and 54 (± 2 %) keV, respectively. The gas was contained in an all-tantalum cell 2 cm long designed for this purpose †. The mean neutron energy was obtained experimentally from two measurements of time and distance which determined the time-of-flight of the neutron group. With a change

† This is consistent with recent work on neutron detectors discussed in the NSF Progress report, University of Oregon, 1968, private communication.

†† Details of a new, all-tantalum gas-target cell are to be published. Electron beam welding and gold braising services were provided by Mariette-Martin Co., Baltimore, Maryland.

in radial distance of the detector of approximately 5 m, an accuracy of 2 % in the neutron energy was achieved. Furthermore, it was feasible to measure the energy spread directly from the TOF spectrum taken on the long flight path, where the predominant time spread arises from the energy spread in the primary neutron group. This measurement was consistent with the energy spread as determined from the gas pressure and the calculated proton-energy loss in the tritium.

3. Results

In the angular distribution data shown in fig. 3 the present data are given as the solid points with error bars. The least-square fit is given as the solid curve. For comparison with the results of Morgan and Walter [8]), the differential cross sections generated from their phase shifts are plotted as the dashed curve.

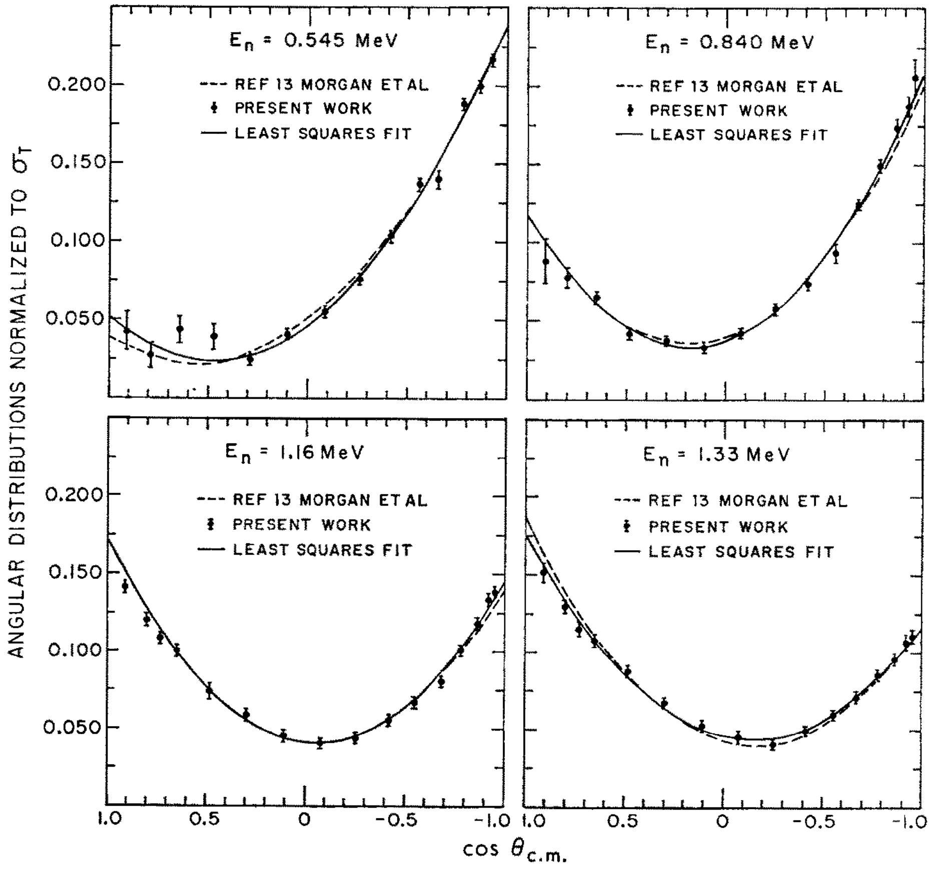

Fig. 3. Angular distributions of neutrons scattered from helium at neutron energies of 0.545, 0.840, 1.16 and 1.33 MeV. The ordinate is explained in the text.

In the data representations of fig. 3 the ordinate scale is chosen so that the angular distribution yields unity when integrated over angle (both polar and azimuthal). This procedure is convenient for comparisons of relative angular distributions, since it separates out the uncertainties associated with the values adopted for the total cross section, which is usually obtained by an independent measurement.

The data obtained with the TOF spectrometer, corrected for detector efficiency and multiple scattering, are fitted directly with an expansion of the form

$$K^2 \frac{d\sigma(\theta)}{d\Omega} = \sum_{i=0}^{2} B_i(\cos\theta)^i,$$

where

$$K^2\sigma_T = 4\pi[B_0+\tfrac{1}{3}B_2].$$

At the energies investigated, D-waves have been shown previously to be negligible. Hence there are four parameters; there expansion coefficients or phase shifts and the

TABLE 1

Expansion coefficients in the cosine series expansion for the differential cross sections

Neutron energy (lab) (MeV)	Total cross section (b)	Coefficients in the cosine series expansion		
		B_0	B_1	B_2
0.545	1.75	0.137±0.003	−0.276±0.008	0.290±0.013
0.840	4.60	0.444±0.012	−0.534±0.020	1.507±0.042
1.16	7.67	1.111±0.017	0.352±0.036	3.206±0.059
1.33	6.81	1.284±0.017	0.831±0.026	2.810±0.047

TABLE 2

Available phase shifts at the energies at which the relative angular distributions were obtained

Neutron energy (lab) (MeV)	Ref.	Total cross section (b)	$S_{\frac{1}{2}}$	$P_{\frac{1}{2}}$ Phase shifts (deg.)	$P_{\frac{3}{2}}$
0.545±0.005	[8]	1.75	−18.1	2.0	15.1
	[7]		−18.4	2.0	13.7
	[17]		−18	3	20
0.840±0.008	[8]	4.60	−22.4	4.2	40.1
	[7]		−22.8	4.0	37.7
	[17]		−22.5	5.0	42.0
1.16 ±0.012	[8]	7.67	−26.4	6.3	80.5
	[7]		−26.8	6.6	77.0
	[17]		−27	7	78
1.33 ±0.013	[8]	6.81	−28.3	13.5	99.3
	[7]		−28.7	8.2	93.1
	[17]		−29	9	94

normalization of the relative angular distributions. This normalization is achieved by requiring that the integral over angle yield the total cross section values, for which the results published by Vaughn *et al.* [16]) have been adopted.

The values and errors for the coefficients B_l are given in table 1. The coefficients used in fig. 3 are obtained by dividing by the total cross section times the square of K, the neutron wave number in the c.m. system.

Using the phase shifts of ref. [8]) in table 2 the coefficients B_l are generated by means of the following relations

$$B_0 = \tfrac{1}{2}[2-\cos 2\delta^0-\cos 2(\delta^+-\delta^-)],$$
$$B_1 = \tfrac{1}{2}[3+2\cos 2(\delta^0-\delta^+)+\cos 2(\delta^0-\delta^-)-3\cos 2\delta^0-2\cos 2\delta^+-\cos 2\delta^-],$$
$$B_2 = \tfrac{1}{2}[6+3\cos 2(\delta^+-\delta^-)-6\cos 2\delta^+-3\cos 2\delta^-],$$

where δ^0, δ^+ and δ^- are the phase shifts for the $S_{\frac{1}{2}}$, $P_{\frac{3}{2}}$ and $P_{\frac{1}{2}}$ partial waves.

4. Discussion

The present results obtained by TOF spectrometry corroborate the work by Morgan and Walter within the experimental errors, but disagree with the data of Adair and the DGS phase shifts. As indicated earlier, the DGS values at these energies are from p-^{4}He data. Furthermore, fits to the Adair data at 0.865 MeV at this laboratory indicate that the data are not fit well by three phase shifts. In view of recent studies [18]) which indicate that the systematic effects in recoil detectors must be well understood, it is conjectured that the data of Adair were affected by instrumental difficulties.

Recently, Satchler *et al.* [7]) published phase shifts obtained from optical-model fits to the large body of n-^{4}He data. Our results are consistent with those and thereby reinforce the reliability of their phase-shift analysis.

The differential cross sections obtained at the two lower energies have been included in an extensive fitting of n-^{4}He data published by Arndt and Roper [19]).

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