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Neutron-Alpha Scattering in the 20-MeV Range

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Angular distributions of neutrons scattered by α particles were measured from 16- to 26-MeV neutron energy by observing the recoiling α particles in a high-pressure gas scintillator. Above 22 MeV, disintegration particles from the $He^4(n,d)T$ reaction were observed, also. Data were taken in 25-keV steps over the He^5 state at 16.7-MeV excitation energy (22.15-MeV neutron energy) and over the $He^4(n,np)T$, $He^4(n,n')He^{4*}$, and $He^4(n,2n)He^3$ thresholds. Total cross sections of helium were measured at 26 energies from 20- to 29-MeV neutron energy in a good geometry transmission experiment. Angular distributions at neutron energies <24 MeV were fitted with expansions of Legendre polynomials. Polynomials of order 0 through 4 provided a satisfactory fit. Below 22 MeV the angular distributions agree with calculations based on n-α phase shifts suggested by Perkins. Above 22 MeV the agreement is not as good. The total cross sections agree only qualitatively with these calculations. The total cross section and angular-distribution data are consistent with a $\frac{3}{2}^+$ assignment for the 16.7-MeV level. The measured yield curve for the $He^4(n,d)T$ reaction agrees with that computed from the cross section for the inverse reaction.

INTRODUCTION

THE results of recent measurements[1,2] of the asymmetry in the elastic scattering by helium of polarized neutrons at energies near 20 MeV have emphasized the lack of knowledge of the neutron-alpha phase shifts in this energy range. Two sets[3] of n-α phase shifts which are in use at these energies are a set[4] deduced from the results of a phase-shift analysis[5] of proton-alpha scattering (GTP phase shifts) and an extrapolation to 20 MeV of a set[6,7] which is consistent with n-α data for neutron energies below about 10 MeV (DGS phase shifts). The latter phase shifts are not compatible with the asymmetry measurements at 16.4 or 20.7 MeV. Although the GTP phase shifts appear to fit the asymmetry measurements at these two energies, they do not fit the measurements at 23.7 MeV.

The variation with energy of the n-α phase shifts must of course be consistent with the parameters of the resonance levels of the compound nucleus He^5. The states[8] of He^5 in the energy range of interest which may influence the phase shifts are shown in Table I. The state[9] at 19.0 MeV refers to the $T=\frac{3}{2}$ state of He^5 which may occur at this energy if H^5 exists.[10,11] However, if this analog state has a high degree of isotopic spin purity, it should have only a small effect on the n-α phase shifts. This state is shown in parentheses because it has not been observed experimentally.

Of these states the 16.7-MeV level is of special interest. The strongest evidence for this level is the resonance in the cross section for the $T(d,n)He^4$ reaction just above its threshold. Flowers[12] and, recently, Bransden[13] have pointed out that this resonance is not necessarily evidence for a level of He^5 since it may be possible to explain the resonance purely on the basis of barrier penetration effects. Conner *et al.*[14] have suggested that a study of n-α elastic scattering may indicate whether the level does in fact exist. Such a study by Bonner *et al.*[15] revealed an anomaly in the n-α scattering at 22.15 MeV which they associated with this level.

The determination of the phase shifts in this energy range may have to take into account the inelastic processes which occur. Indeed, there is evidence[16] in the

TABLE I. He^5 states and thresholds of inelastic processes for n-α scattering from 15 to 30 MeV.

Neutron energy of level or threshold (MeV)	Excitation energy of He^5 state (MeV)	Inelastic process
22.07		$He^4(n,d)T$
22.15	16.70	
24.87		$He^4(n,np)T$
25.0	(19.0)	
25.2		$He^4(n,n')He^{4*}$
25.81		$He^4(n,2n)He^3$
26	20	
29.95		$He^4(n,nd)D$

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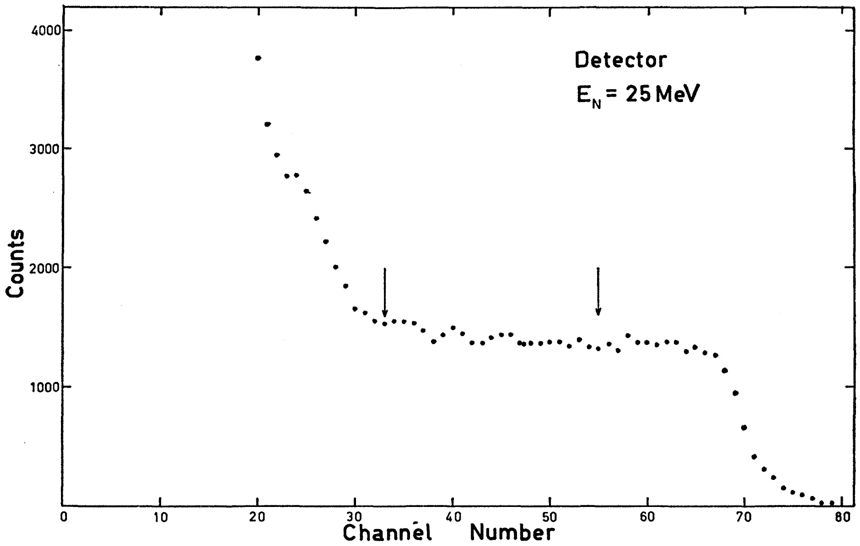

FIG. 1. Pulse-height distribution from the plastic scintillator used as the detector for 25-MeV neutrons. The arrows indicate the low bias and the high bias used at this energy.

analog p-α problem that imaginary phase shifts are necessary in order to fit recent polarization data[17,18] near 40 MeV.

The thresholds of inelastic processes which take place in the energy range of interest are listed in Table I. The threshold at 25.2 MeV assumes that He^4 has an excited state[19,20] at an excitation energy of 20.1 MeV. The GTP phase shifts do not take into account either the inelastic processes or the levels shown in this table.

At the present the amount of published n-α data for neutron energies between 15 and 30 MeV is small. The total cross-section measurements reported by the Los Alamos group[21] extend only up to 20 MeV. Angular distributions have been measured at Rice[15] and at Wisconsin[3] to about 23 MeV; however, no background corrections were made to the former distributions, and the background corrections applied to the latter distributions were large and uncertain. The recent asymmetry measurements have been mentioned above.

The purpose of the present experiment was to extend the total cross-section measurements for n-α scattering to higher energies and to provide improved angular distribution measurements for neutron energies near 20 MeV. Total cross sections and angular distributions were measured from 20 to 29 MeV and from 16 to 26 MeV, respectively. A brief report of the total cross-section measurements already has been published.[22]

TOTAL CROSS-SECTION MEASUREMENTS

Experimental

The total cross section was determined by measuring in good geometry the transmission through helium of the monoenergetic neutrons from the d-T reaction. The deuterons were accelerated by the ANU tandem and entered a tritium-filled gas target through a 1.2-μ-thick nickel foil. The tritium gas pressure was adjusted so that the total energy spread of the neutrons was about 40 keV for the measurements around the 16.70-MeV level and ranged between 60 and 130 keV elsewhere. This energy spread included contributions from the energy straggling of the incident deuterons in the nickel foil, the energy loss of the deuterons in the tritium, and the dependence of the neutron energy on the angle of emission of the neutrons.

The neutrons were detected in a plastic scintillator 2.2 cm in diameter and 5 cm long which was placed at 0° with respect to the incident deuterons and at a distance of 122 cm from the gas target. The helium sample was contained at a pressure of about 180 atm in a 70-cm-long cell positioned half-way between the gas target and the detector. The number of helium nuclei in the cell was determined from weight measurements. The cell wall was made of stainless-steel tubing with an internal diameter of about 2.9 cm and a wall thickness of about 1.6 mm. The end caps of the cell also were composed of stainless steel and were hard soldered to the tubing. The thickness of the flat region of each end cap was machined to 1.588±0.005 mm. An identical cell which was evacuated was used for the "sample out" runs. The gas target, cell, and detector were aligned to an accuracy of about 0.2 mm with the aid of a theodolite.

The data at each energy were obtained in a series of about 20 runs which were taken in the sequence sample out, in, in, out, etc., in order to minimize effects caused

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by slow drifts in the neutron flux and in the electronic systems. The relative number of monoenergetic neutrons was monitored with a plastic scintillator at an angle of 60° with respect to the incident deuterons. For both the detector and the monitor a low-biased discriminator and a high-biased discriminator were used throughout each run. The high-bias data served as a check on the gain stability of the photomultiplier and amplifier systems. The monitor and the detector always were biased sufficiently high that a negligible number of breakup neutrons from the source reaction were detected.[23]

A pulse-height distribution obtained from the detector for 25-MeV neutrons is shown in Fig. 1. The arrows indicate the low bias and the high bias which were used at this energy. The total number of low-bias counts of about 60 000 shown in this figure was typical for a "sample out" run.

The number of background counts caused by neutrons and possibly gamma rays not from the source reaction was measured at each energy by taking a run with the gas target evacuated. This background always was found to be less than 0.5% of the number of counts with the sample out. The background caused by room-scattered neutrons was determined with the aid of a 38-cm-long brass shadow bar. This latter background was less than 1% at all energies.

Corrections were made to the observed transmission for the two backgrounds discussed above and for inscattering by the helium. The last-mentioned correction was about 0.1% of the transmission at each energy. Measurements of the composition of the gas sample with a mass spectrometer indicated a total quantity of impurities of less than 60 ppm.

TABLE II. The total cross section of helium for neutrons.

Energy (MeV)	Energy spread (keV)	Cross section (mb)	Statistical error (mb)
20.00±0.02	130	751	±8
21.00±0.02	120	721	8
21.85±0.02	110	730	8
22.00±0.01	40	713	15
22.05±0.01	40	745	15
22.10±0.01	40	821	15
22.13±0.01	40	863	15
22.15±0.01	40	885	15
22.18±0.01	40	840	15
22.20±0.01	40	804	15
22.23±0.01	40	758	17
22.25±0.01	40	804	14
22.28±0.01	40	743	17
22.30±0.01	40	756	16
22.35±0.01	40	750	16
22.60±0.02	100	711	12
23.00±0.02	90	685	8
24.00±0.02	80	652	8
24.50±0.02	70	659	6
24.75±0.02	70	636	6
25.00±0.02	70	633	5
25.51±0.02	70	616	8
26.00±0.02	70	612	7
27.00±0.02	60	598	8
28.00±0.02	60	591	8
29.00±0.02	60	577	12

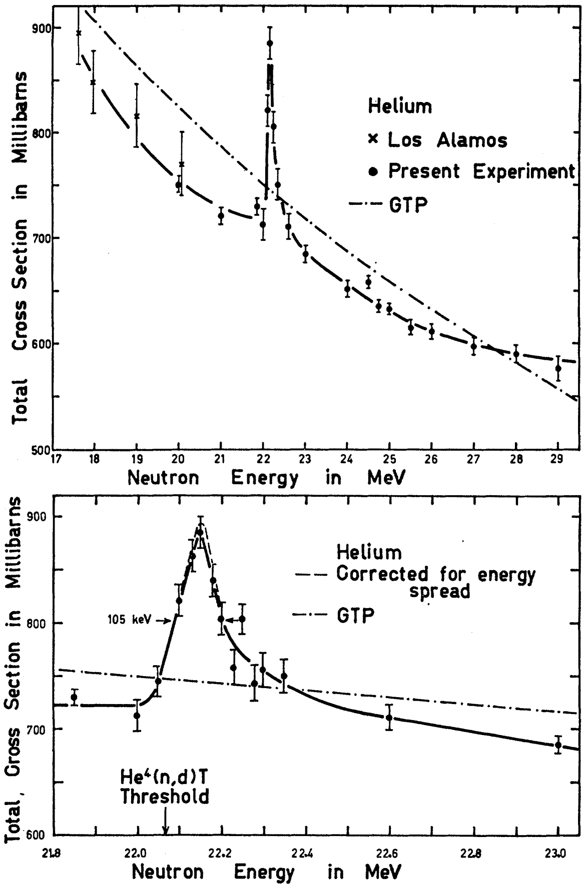

FIG. 2. The total cross section of helium for neutrons. The error bars of the present work indicate statistical errors only. The solid curve is a fit by eye to the data. The dashed curve over the resonance is the cross section obtained after a correction was applied for the neutron energy spread of about 40 keV. The dash-dot curve was computed from the GTP phase shifts (Ref. 4).

The possibility of gross errors in the present experiment was studied by measuring concurrently the total cross sections of helium and hydrogen for 20.00-MeV neutrons. A value for the *n-p* total cross section which is accurate to 0.5% has been reported by Day *et al.*[24] for 19.67-MeV neutrons. The concurrent measurements were carried out by taking data with a hydrogen-filled, a helium-filled, and an evacuated cell in the sequence hydrogen in, sample out, helium in, helium in, sample out, hydrogen in, etc. The *n-p* total cross section which was obtained was consistent with an extrapolation of that reported by Day *et al.* to within the statistical accuracy of about 1% of the present measurement.

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Results

The measured total cross sections are given in Table II and are shown in Fig. 2. Los Alamos data[21] are shown for comparison. The errors for the present work are statistical errors only. The uncertainty in the neutron energy is estimated to be about ±10 keV around the 22.15-MeV resonance and ±20 keV elsewhere. For the former data the thickness of the nickel foil was determined by measuring the shift in the threshold of the $C^{13}(p,n)$ reaction caused by inserting the foil in the proton beam. The solid curves are a fit by eye to the data. The dashed curve over the resonance was obtained by correcting the solid curve for the neutron energy spread. The energy spread was approximated by a rectangular function with a width of 40 keV. The dash-dot curves represent total cross sections computed from the GTP phase shifts. The energy and width of the resonance at 22.15 MeV indicate that it corresponds to the 16.70-MeV state of He^5.

Since a comprehensive discussion of the sources of error which exist in an experiment of this nature already has been published,[24] the treatment here will be brief. In the present experiment each of the measured transmissions may be in error because of uncertainties in the background corrections and the inscattering correction. For the worst case these uncertainties cause errors in the measured cross sections of about 0.2% and 0.1%, respectively. The sources of error in the determination of the number per cm^2 of helium nuclei are the uncertainties in the weight of the helium, the volume of the cell, and the length of the cell. The sum of these last-mentioned uncertainties is about 0.3%. The arithmetic sum of all the above uncertainties suggests that the systematic error for each of the measured total cross sections is less than 0.6%.

ANGULAR DISTRIBUTION AND $He^4(n,d)T$ YIELD MEASUREMENTS

Experimental

The angular distributions were measured by observing the energy spectrum of the recoiling alpha particles in a high-pressure gas scintillator. The energy distribution of the recoiling alpha particles in the laboratory system is proportional to the angular distribution of the scattered neutrons in the center-of-mass system, provided that the neutron angular distribution is expressed as a function of the cosine of the c.m. scattering angle.[25]

Neutrons for these measurements were produced in the same manner as for the total cross-section measurements. The neutron flux was monitored by integrating the deuteron beam current. All data were taken with the scintillation counter at 0° with respect to the incident deuteron beam, except for data at 16.4 MeV for which the counter was at 73°. The distance from the center of the target to the center of the counter was 23 cm for the former and 30 cm for the latter data.

The scintillation counter used for these measurements is similar to the second of two described previously.[26] The gas scintillator consisted of a mixture of helium and xenon at a total pressure of about 140 atm. The helium served both as a target for the incident neutrons and as part of the detection system. The xenon was necessary to increase the light output of the gas and to decrease the range of charged particles in the gas. The pressures of xenon which were used ranged from 24 atm at 16.4 MeV to 38 atm at 26 MeV.

The scintillations were viewed through the glass window of the counter with an EMI 9536B photomultiplier. The voltage pulses from the photomultiplier were amplified by a Tennelec preamplifier and a Franklin amplifier and recorded by an RIDL pulse-height analyzer. The linearity of the amplifying and analyzing system was checked periodically with the aid of a Franklin precision pulse generator. The system always was found to be linear to about 1% for the range of pulse heights of interest.

The light output[27] of the gas scintillator as a function of alpha-particle energy was studied using the technique described in Ref. 26. The earlier work[26] was carried out with a mixture of 8-atm xenon and 42-atm helium. It indicated that the pulse height produced by an alpha particle was directly proportional to its energy up to about 6 MeV. In the present work the response of a mixture of about 30-atm xenon and 100-atm helium was studied for alpha-particle energies from 0.6 to 16 MeV. Contrary to the low-pressure results, the pulse height of the recoiling alpha particles was observed to be a linear function of energy only above about 2.5 MeV. Therefore, in the present experiment, only the portion of the distribution above the pulse height for 2.5-MeV alpha particles could be used. The effect of the nonlinear response on this portion of the pulse-height distribution was simply to change the channel which corresponded to a pulse height of zero. This adjustment to the channel scale of the pulse-height distribution was determined experimentally and was found to be about 4±0.5 channels for the conditions of the present experiment.

Several corrections must be applied to the pulse-height distributions. The source neutrons produce disintegrations and recoils in the xenon and in the walls of the counter. This counter background can be measured by taking a run with the counter filled only with xenon. However, the light output for the same particle energy is different for pure xenon from that for the xenon-helium mixture.[3] To compensate for this difference the gain of the electronic system must be adjusted.

The results of the Wisconsin work[3] at high neutron energies indicated that difficulties might arise in the present experiment in the measurement of this background. In particular, it was not clear how the magnitude of the above-mentioned gain adjustment should be

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determined. Therefore, in the present work, attempts were made to identify the background particles and to study their pulse heights as a function of gas composition. These auxiliary experiments were carried out at 22.6-MeV neutron energy. Although the energies of the particles which comprise this background can be very high, e.g., about 29 MeV for 22.6-MeV neutrons, only the range from about 3 to 15 MeV which is spanned by the helium recoils is of interest here.

In one auxiliary experiment the magnitude of the background was measured as a function of xenon pressure. This experiment indicated that the background was caused mostly by xenon disintegrations. In another experiment the contribution of the counter wall was reduced by covering the inside of the steel cell with 0.2 mm of lead and by decreasing by over a factor of 2 the amount of reflecting material and wavelength shifter inside the cell. No significant decrease in the number of background pulses was observed, which also suggested that most of these pulses corresponded to xenon disintegrations. Of the several kinds of charged disintegration particles which can be emitted from xenon with energies in the range of interest, only the singly-charged particles, i.e., protons, deuterons, and tritons, have a high probability for penetrating the Coulomb barrier of this nucleus. Therefore, it is believed that most of the counter background in this energy range can be attributed to these singly-charged disintegration particles.

The pulse heights for some of these background particles were studied as a function of gas composition by adding helium to 35 atm of xenon.[27] It is clear that only those background pulses above the pulses caused by the alpha-particle recoils could be investigated in this manner. For partial pressures of helium from 0 to about 100 atm, an appreciable number of counter background pulses could be observed as a "knee" just above the 14.5-MeV alpha-particle recoils. The pulse heights for this knee and for the 5.3-MeV alpha particles from a Po source were studied as a function of the amount of helium which was added. The pulses of the knee were observed to increase in magnitude by about 50% relative to the alpha-particle pulses for the total change of the helium partial pressure of about 100 atm. This increase was a measure of the gain adjustment required for the counter background measurement.

It should be pointed out that the gain adjustment determined in the above manner will be correct for most of the background particles only if the pulses of the observed knee also are due to singly-charged particles. Evidence was obtained that these particles are indeed singly-charged in experiments similar to the above experiment which were carried out with 0.51-MeV electrons, 5.3-MeV alpha particles, and 29-MeV alpha particles.[27]

Corrections also must be applied to the pulse-height distributions for the neutron background and for the wall effect. The neutron background is that caused by neutrons not from the source reaction which produce pulses in the scintillation counter. This background was measured by taking a run with the gas target evacuated. The wall effect refers to the distortion of the pulse-height distribution caused by alpha-particle recoils which collide with the wall and window of the scintillation counter. The correction for this effect is discussed in detail in Ref. 3.

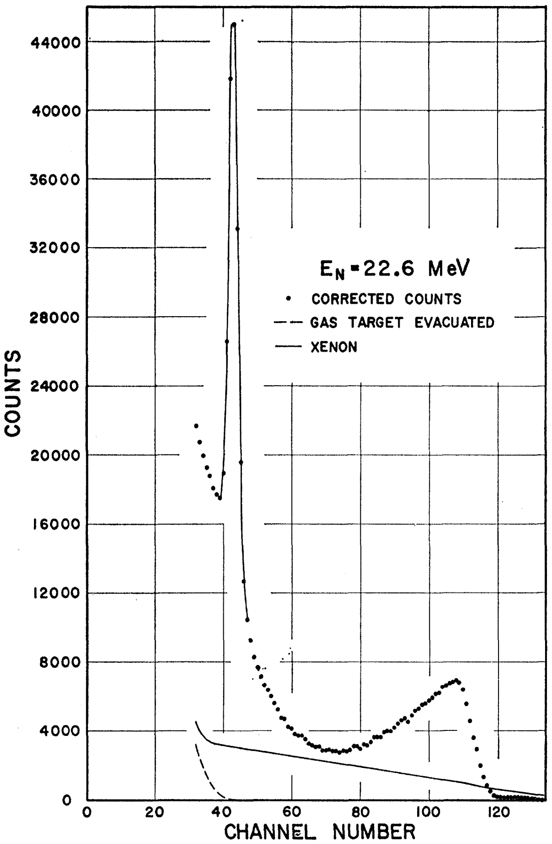

FIG. 3. Pulse-height distribution resulting from the interaction of 22.6-MeV neutrons with alpha particles. Corrections for the neutron background, the counter background, and the wall effect have been applied. The peak at channel 43 is caused by disintegration particles from the $He^4(n,d)T$ reaction. The remaining pulses are due to α-particle recoils produced by elastic scattering. Also shown are the neutron background (gas target evacuated) and the counter background (xenon only in the counter) at this energy.

Effects which were observed to be negligible in the present work were the background caused by room-scattered neutrons and the effect of neutrons scattered by the steel cell of the scintillation counter. An estimate of the neutrons scattered backward into the counter by the window indicated that this background also was not important.

The procedure generally used for taking data was as follows. First the scintillation counter, filled with the helium-xenon mixture, was bombarded with neutrons. Second, the effect of the neutron background was measured by taking a run with the gas target evacuated. Third, after the above data had been taken at several energies, the counter background was measured at the

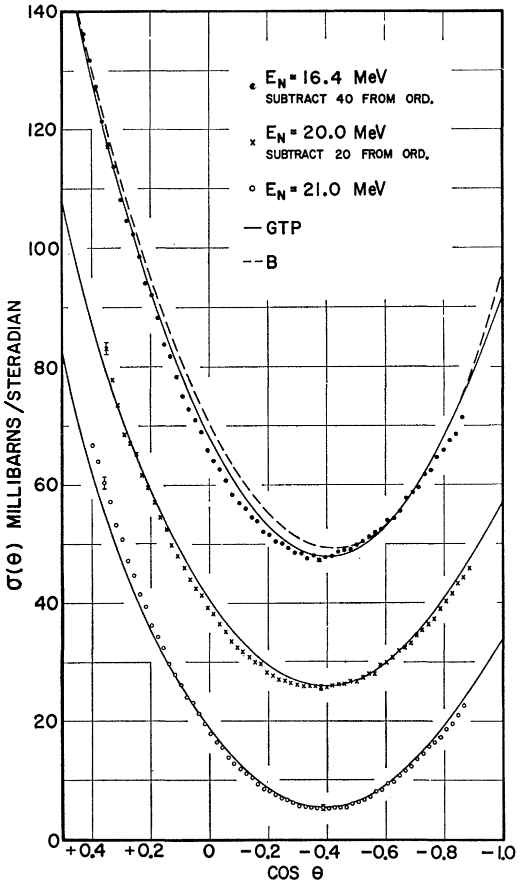

FIG. 4. Differential cross sections in the c.m. system for the scattering of 16.4-, 20.0-, and 21.0-MeV neutrons by alpha particles. Note the shift of the cross-section scale at 16.4 and 20.0 MeV. The error bars indicate possible systematic errors and are explained in the text. The solid curves were computed from the GTP phase shifts; the dashed curve from Brockman's p-α phase shifts (Refs. 4 and 29).

same energies by bombarding the counter with neutrons when it was filled only with xenon at the same pressure as in step one.

For the above procedure an error in the counter background measurement is introduced because the ranges in the gas of the particles which comprise this background are not the same for steps one and three. This error was about 10% or less for the pressures of xenon and helium which were used in the present experiment.

An error in the counter background measurement is introduced, also, if the xenon or tirtium pressures are not the same for steps one and three. Therefore, at several energies data also were taken in the sequence three-one-two, a procedure which eliminated these two possible sources of error. There was very good agreement between the two sets of data.

In Fig. 3 are shown the background corrections and the corrected pulse-height distribution for 22.6-MeV neutrons. The dashed curve and the solid curve represent the neutron background and the counter background, respectively. For the smallest recoil energies, where it is seen to be largest, the former background varied from 4% for 16.4-MeV neutrons to 13% for 26-MeV neutrons. The counter background is seen to be relatively the largest near the minimum in the corrected distribution, i.e., near channel 70 in this figure. Near the minimum this background ranged from 20% at 16.4 MeV to 65% at 26 MeV. The correction for the wall effect, which is not shown in the figure, was less than 5% for all the data of the present experiment.

The pulse-height distribution obtained after the two background corrections and the wall-effect correction were applied is shown by the closed circles. The peak in this distribution at channel 43 was caused by disintegration particles from the $He^4(n,d)T$ reaction. The tail above channel 108 is a result of the resolution of the scintillation counter. The techniques employed to attain the observed spread of about 5% in the pulse heights of the recoil alpha particles are described elsewhere.[27] In this pulse-height distribution and for all the others which were obtained, no data are shown for the lowest channels because large backgrounds in this region make the data unreliable.

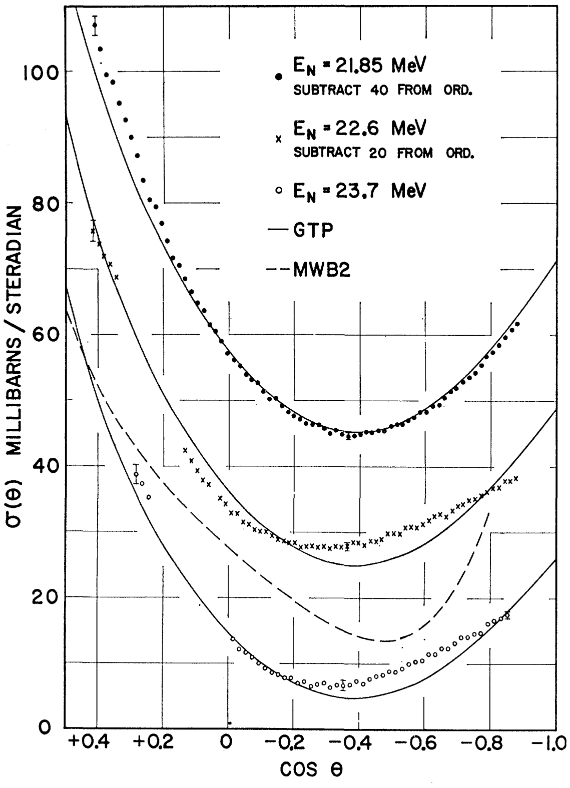

FIG. 5. Differential cross sections in the c.m. system for the scattering of 21.85-, 22.6-, and 23.7-MeV neutrons by alpha particles. Note the shift in the cross-section scale at 21.85 and 22.6 MeV. The error bars indicate possible systematic errors and are explained in the text. At 22.6 and 23.7 MeV no data were obtained near $\cos\theta = +0.2$ because of the presence of disintegration particles from the $He^4(n,d)T$ reaction. The solid curves were computed from the GTP phase shifts; the dashed curve from phase shifts suggested by May *et al.* (Refs. 4 and 2).

In the present experiment the pulse-height distributions of the recoil alpha particles which were obtained correspond only to relative angular distributions. For several of the measurements a cross-section scale was determined by normalizing the angular distribution, expressed in terms of a Legendre polynomial expansion,[28] to the total elastic-scattering cross section.

Results

Angular Distributions

Angular distributions which were obtained below and above the 22.15-MeV resonance are shown in Figs. 4 and 5. The differential elastic-scattering cross sections are plotted as functions of the cosine of the scattering angle in the c.m. system. The statistical uncertainties are greatest for the 16.4-MeV data where they range from 1% at the smallest angle to 3.5% at the minimum of the distribution. For the measurements at 22.6 and 23.7 MeV, no angular distribution data were obtained near $\cos\theta = +0.2$ because of the presence of disintegration particles from the $He^4(n,d)T$ reaction. The neutron energy spread was less than 170 keV for each of these measurements, except at 16.4 MeV where the spread was about 700 keV.

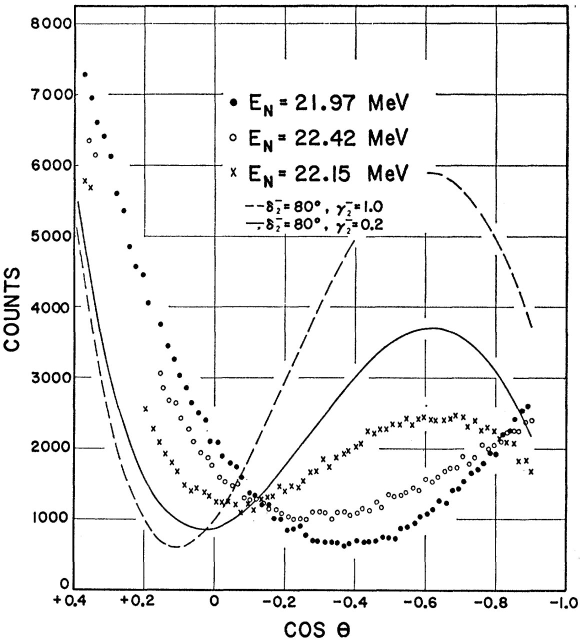

FIG. 6. Relative angular distributions for n-α elastic scattering measured just below, on, and just above the 22.15-MeV resonance. The neutron energy spread for these data was about 70 keV. The dashed curve at 22.15 MeV was computed from GTP phase shifts which were modified to take into account the 16.7-MeV level of He^5. For the solid curve, both the 16.7-MeV level and the $He^4(n,d)T$ reaction were taken into account. The symbols δ_2^- and γ_2^- refer to the $d_{3/2}$ phase shift and the $d_{3/2}$ inelastic parameter, respectively.

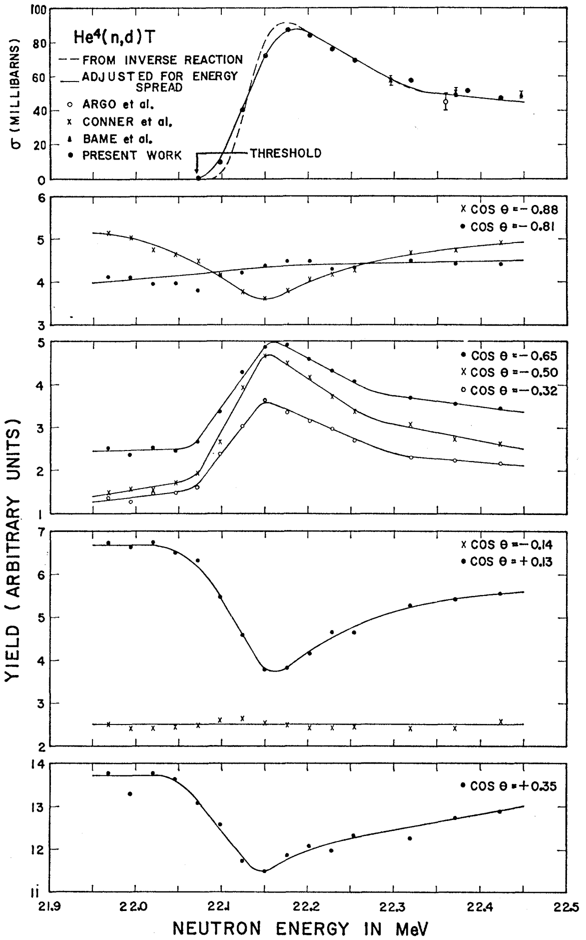

FIG. 7. At the top is shown the measured yield from the $He^4(n,d)T$ reaction over the 22.15-MeV resonance. The dashed curve was computed from the cross section for the inverse reaction. For the crosses, open circle, and closed triangle, the published cross sections for the inverse reaction were used (Refs. 14, 32, and 33). The solid curve was obtained by adjusting the dashed curve for the neutron energy spread of about 70 keV. The present data were normalized to the solid curve at its maximum. The remainder of the figure shows part of the n-α angular distribution data obtained over this resonance plotted as 8 excitation functions. Each data point is the sum of two channels of a pulse-height distribution. The smooth curves are fits by eye to the data. The yield and angular-distribution data shown at each energy were obtained at the same time.

The solid curves in these figures are differential elastic-scattering cross sections which were computed from the GTP phase shifts. The dashed curve at 16.4 MeV is the cross section computed from phase shifts for p-α scattering which were suggested by Brockman.[29] At 23.7 MeV, the dashed curve corresponds to phase shifts published by May *et al.*[2] which are consistent with total cross section[22] and asymmetry measurements.[2]

Relative angular distributions which were measured just below, on, and just above the 22.15-MeV resonance

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[28] M. E. Rose, Phys. Rev. **91**, 610 (1953) and L. G. Lawrence, Australian National University Report ANU-P/287 (unpublished).

[29] K. W. Brockman, Jr., Phys. Rev. **110**, 163 (1958); W. T. H. van Oers (private communication).

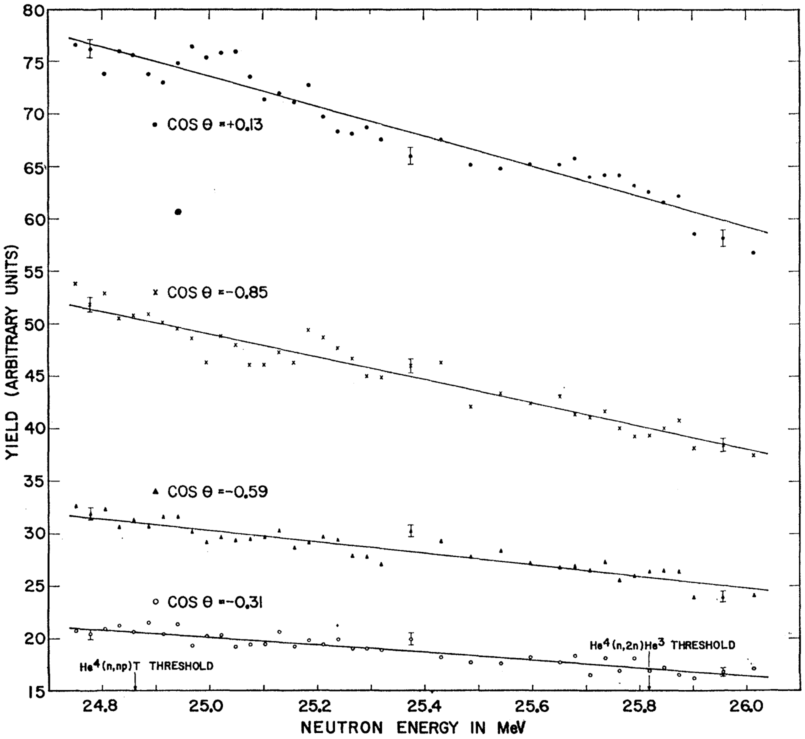

FIG. 8. Excitation functions for n-α elastic scattering measured over the $\mathrm{He}^4(n,np)$ and $\mathrm{He}^4(n,2n)$ thresholds and over the He^5 state (Ref. 9) at 19.0-MeV excitation energy (25.0-MeV neutron energy). If a He^4 state exists at 20.1-MeV excitation energy, the $\mathrm{He}^4(n,n')\mathrm{He}^{4*}$ threshold occurs at 25.2-MeV neutron energy (Refs. 19 and 20). Each data point is the sum of two channels of a pulse-height distribution. The error bars indicate statistical errors, only. The curves are straight lines drawn through the data points. The neutron energy spread was about 70 keV.

are shown in Fig. 6. These distributions have been corrected for backgrounds and for wall effect. The neutron energy spread for the data in this figure and in Fig. 7 was about 70 keV.

The dashed curve at 22.15 MeV shown in Fig. 6 is an angular distribution computed from GTP phase shifts which were modified to take into account the 16.7-MeV level. Since it is believed to have a spin and parity of $\frac{3}{2}^+$, this level should affect only the $d_{3/2}$ phase shift. The estimated value for this phase shift of 80° (instead of the GTP value of 12.5°) assumes that the resonance energy is just above 22.15 MeV. Using a value of 90° for this phase shift made the fit slightly poorer.

For the solid curve in this figure the GTP phase shifts were modified to take into account both the 16.7-MeV level and the $\mathrm{He}^4(n,d)\mathrm{T}$ reaction. This reaction can influence only the $d_{3/2}$ inelastic parameter[30] if it is assumed that at this energy the deuteron and triton which are emitted can have a relative orbital angular momentum only of zero and a total spin only of $\frac{3}{2}$. The value for this inelastic parameter of 0.2 (instead of 1.0) was computed from the $\mathrm{He}^4(n,d)\mathrm{T}$ cross section of 85 mb at this energy. The $\mathrm{He}^4(n,d)\mathrm{T}$ cross section was estimated from the measured cross section for the inverse reaction.[31]

Both the dashed and the solid curve are normalized to a cross-section scale (not shown) which was determined from the zero-order Legendre coefficient for the measured angular distribution at 22.15 MeV. The fit of the solid curve to the 22.15-MeV data can be improved by adjusting the resonance energy within its experimental uncertainty and by taking into account the neutron energy spread of about 70 keV. The large difference between the solid and dashed curves shows that the effect of the $d_{3/2}$ inelastic parameter is very large at this energy, as one might expect.

In Fig. 7 a part of the angular distribution data taken over the resonance is presented as 8 excitation functions. Each of the data points is the sum of two channels of a pulse-height distribution. Smooth curves have been drawn through these data points to guide the eye. These results appear to be consistent with those of Bonner *et al.*[15]

The data of the present experiment shown in Fig. 7 were corrected for backgrounds, wall effect, and a total variation in neutron flux with energy of about 2%. This variation was caused by the change in the cross section of the neutron-producing reaction and by the loss of tritium through the nickel foil.

Part of the data obtained over the 19.0-MeV level and the $\mathrm{He}^4(n,np)$, $\mathrm{He}^4(n,n')$, and $\mathrm{He}^4(n,2n)$ thresholds is shown in Fig. 8. The neutron energy spread for these data was about 70 keV. Each data point of these excitation functions also corresponds to the sum of two channels of a pulse-height distribution. These data were corrected for backgrounds, wall effect, and a total variation in neutron flux with energy of about 6%. The errors

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[30] See, for example, J. H. Foote, O. Chamberlain, E. H. Rogers, and H. M. Steiner, Phys. Rev. **122**, 959 (1961).

[31] J. E. Brolley, Jr., and J. L. Fowler, *Fast Neutron Physics* (Interscience Publishers, Inc., New York, 1960), part I, p. 73.

TABLE III. Values for A_λ/A_0 obtained by fitting the n-α angular distributions with Legendre polynomial expansions. Also given are values for A_0 which were computed as described in the text.

E_N (MeV)	A_0 (mb/sr)	A_1/A_0	A_2/A_0	A_3/A_0	A_4/A_0
16.4	72.2±2.0	1.53±0.05	1.27±0.05	0.10±0.03	−0.03±0.02
20.0	60.1±0.6	1.64±0.08	1.46±0.09	0.31±0.05	0.08±0.03
20.0	60.1±0.6	1.58±0.07	1.38±0.08	0.21±0.04	0.04±0.02
21.0	58.0±0.6	1.63±0.05	1.41±0.05	0.26±0.03	0.05±0.02
21.85	56.9±0.6	1.66±0.04	1.44±0.04	0.30±0.03	0.06±0.01
21.85	56.9±0.6	1.60±0.11	1.36±0.11	0.20±0.06	0.03±0.03
21.97	56.9±1.1	1.64±0.10	1.40±0.10	0.28±0.06	0.04±0.03
21.99	56.9±1.1	1.62±0.14	1.36±0.15	0.23±0.09	0.01±0.04
22.02	57.3±1.1	1.66±0.13	1.40±0.14	0.30±0.09	0.02±0.04
22.05	58.1±1.2	1.70±0.08	1.47±0.09	0.39±0.05	0.06±0.02
22.07	59.3±1.2	1.67±0.08	1.43±0.08	0.38±0.05	0.03±0.02
22.10	61.1±1.2	1.76±0.18	1.63±0.19	0.69±0.12	0.13±0.06
22.13	62.8±1.3	1.80±0.10	1.74±0.11	0.90±0.07	0.14±0.03
22.15	64.0±1.3	1.89±0.07	1.90±0.07	1.11±0.05	0.21±0.02
22.18	62.4±1.2	1.88±0.11	1.89±0.12	1.07±0.08	0.19±0.04
22.20	60.5±1.2	1.87±0.07	1.86±0.07	1.02±0.05	0.19±0.02
22.23	58.9±1.2	1.81±0.06	1.76±0.06	0.89±0.04	0.15±0.02
22.25	58.1±1.2	1.83±0.13	1.79±0.14	0.89±0.09	0.18±0.04
22.32	56.2±1.1	1.73±0.10	1.63±0.11	0.67±0.07	0.09±0.03
22.37	55.3±1.1	1.76±0.06	1.66±0.07	0.69±0.04	0.13±0.02
22.42	54.7±1.1	1.75±0.11	1.65±0.12	0.66±0.07	0.14±0.03
22.6	53.3±0.8	1.68±0.06	1.53±0.07	0.52±0.04	0.07±0.02
23.7	50.1±0.7	1.63±0.13	1.42±0.14	0.37±0.08	−0.01±0.04

shown are statistical errors only. The curves are straight lines drawn through the data points.

Systematic errors may be present in each of the angular distributions because of a number of uncertainties. The largest errors are caused by uncertainties in the neutron background correction and the counter background correction. The difficulties involved in determining the latter correction have been discussed in the previous section. For each of the angular distributions shown in Figs. 4 and 5 an error bar is given at a small angle and at the minimum of the distribution to indicate the magnitude of the error caused by these background uncertainties. At the largest angle this error is about equal to or less than the size of the data point except at 23.7 MeV. The size of each of these error bars corresponds to an estimated uncertainty of only ±10% in the background corrections. Although it is possible that this uncertainty may be as large as 20%, a value much larger than 20% seems unlikely. The smallest correction to the data, the wall-effect correction, is believed to cause an error of less than 1% in the angular distributions.

The excitation functions include all the above errors and, in addition, errors caused by small changes in gain and in the neutron flux.

An estimate of the error in normalization of those angular distributions with cross-section scales can be obtained from the value of the residual error[28] of the zero-order Legendre coefficients. This error was about 4% or less for each of the angular distributions shown in Figs. 4 and 5. If the uncertainty in the total elastic-scattering cross section is taken into account, a total error in normalization of about 5% may be assigned.

The cosθ scale may be in error because extrapolations are necessary to determine the pulse heights which correspond to the extremes of +1.0 and −1.0. The uncertainties at these extremes are believed to be about 0.5% and 1%, respectively.

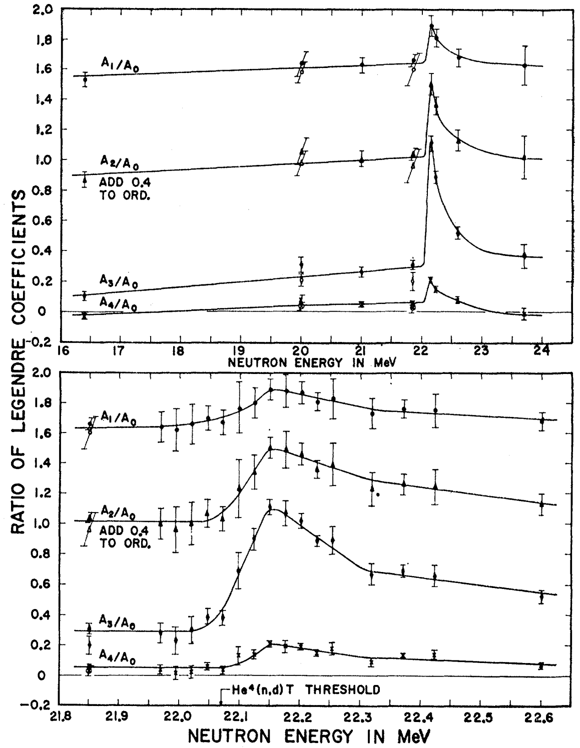

FIG. 9. Ratios of Legendre coefficients obtained by fitting the data of Figs. 4, 5, and 7 with expansions of Legendre polynomials (Ref. 28). Note the shifted ordinate scale for the ratio A_2/A_0. At 20 and 21.85 MeV, the data (not shown) represented by the open symbols was taken using a xenon pressure of 38 atm, as compared with 31 atm for the closed symbol data at these two energies. The error bars include the residual error of A_λ and of A_0 (Ref. 28).

Effects which may distort the angular distributions and for which no corrections have been applied are multiple scattering in the gas and a nonlinearity of the system. The former effect is estimated to be less than 2% for the present experiment. For each of the distributions the response of the gas scintillator and electronics system is believed to be linear to 2% over the recoil energy range which is given.

Only the angular distributions at neutron energies less than 24 MeV were fitted with expansions of Legendre polynomials.[28] All the distributions which were analyzed were fitted satisfactorily by expansions containing polynomials of order zero through four. The ratio of each of the Legendre coefficients to the zero-order coefficient is shown in Fig. 9 and listed in Table III. In Fig. 9 the coefficients represented by the solid symbols were obtained from the data displayed in Figs. 4, 5, and 7. Coefficients for two sets of data are shown at 20.0 and at 21.85 MeV. The open symbols at these energies correspond to data taken with the same xenon pressure as at 23.7 MeV.

The error which is given for each of the ratios includes the residual error of the coefficient A_λ and of A_0. The smooth curves in Fig. 9 are fits by eye to the data points. In the vicinity of the 22.15-MeV resonance no correction for the neutron energy spread has been applied to the ratios. However, the magnitude of this correction is believed to be much less than the size of the error bars.

Also listed in Table III are values for the coefficient A_0 which were determined from the measured total cross sections and computed $He^4(n,d)T$ cross sections. In the vicinity of the 22.15-MeV resonance, total cross sections were used which were corrected for the experimental energy spread. The errors shown are rms uncertainties and are approximate, only. For each of these errors the total cross section and the reaction cross-section uncertainties were assumed to be the statistical error and 5%, respectively. Additional errors may be present, particularly over the resonance, because of uncertainties in the energy scales of the two cross sections.

$He^4(n,d)T$ *Yield*

The observed yield from the $He^4(n,d)T$ reaction is shown at the top of Fig. 7. The errors are believed to be less than the size of the data points. The dashed curve represents the $He^4(n,d)T$ cross section computed from the cross section for the inverse reaction by using the principle of reciprocity. This curve corresponds to a smooth curve drawn through a plot[31] of published measurements for the inverse reaction. For the open circle,[32] crosses,[14] and closed triangle,[33] the individual published cross sections were used for the computation. The solid curve in this plot was obtained by adjusting the dashed curve for the neutron energy spread. For this adjustment the energy spread was approximated by a rectangular function with a width of 70 keV. The relative cross-section data of the present experiment was assigned a cross-section scale by normalizing the data to the solid curve near its peak.

DISCUSSION

The measurements of the present experiment agree only qualitatively with angular distributions obtained at 17.8 and 20.9 MeV by Austin *et al.*,[3] which appeared to favor the DGS phase shifts. However, their results were inconclusive at these energies because of the large and uncertain correction for the counter background.

Calculations based on the GTP phase shifts agree very well with the angular distributions measured below the 22.15-MeV resonance, in particular for $\cos\theta \leq +0.2$. Above the resonance the agreement is not as good. These results are consistent with those of the asymmetry measurements[1,2] and are not unexpected since the GTP phase shifts take into account neither the 16.7-MeV level of He^5 nor the $He^4(n,d)T$ reaction. Furthermore, since the GTP phase shifts have been derived from the p-α phase shifts of Gammel and Thaler,[5] the results of the present measurements and the asymmetry measurements imply that the Gammel-Thaler phase shifts do not describe p-α scattering above the analog level of Li^5 at 16.8-MeV excitation energy (23.4-MeV proton energy). It is known that these p-α phase shifts are in error above 29-MeV proton energy from the recent p-α polarization experiments.[17,18]

Systematic differences between the curves calculated from the GTP phase shifts and the total cross section and angular distribution data indicate that even below the 22.15-MeV resonance an adjustment of the GTP phase shifts may be required. An adjustment just above the resonance is particularly desirable because of recent n-p polarization measurements at 23.1 MeV[34] and 23.7 MeV.[35] In both of the n-p experiments helium was used to analyze the polarized neutrons.

The smooth variation with energy of the Legendre coefficient ratios suggests that the present data may be worthy of a phase-shift analysis. Qualitative information can be obtained from the coefficients by inspection. For example, the nonzero value for A_3 at 16.4 MeV is evidence that at this energy a partial wave (or waves) higher than p wave is important in the n-α interaction.[36] Also, the nonzero value for A_4 at about 20 MeV indicates that at this energy a phase shift (or phase shifts) for which $J>\frac{3}{2}$ must be included in the analysis.[37] This information is in accord with the results of analyses of p-α scattering for the comparable energy range.[5,29]

Values for the n-α phase shifts can be obtained directly from the Legendre coefficients by means of the method described recently by Pisent.[38] However, his method is applicable to single-channel reactions only and therefore cannot be used above the 22.07-MeV threshold for the present data. A phase-shift analysis using a search program[39] which can take into account inelastic processes is in progress at this laboratory.

At 16.4 MeV, the angular distribution calculated from Brockman's phase shifts[29] appears to fit the data reasonably well. Since these are p-α phase shifts a perfect fit is not expected. At 23.7 MeV, it is seen that the phase shifts suggested by May *et al.*[2] are not compatible with the angular distributions of the present experiment.

Evidence for the 16.70-MeV level was obtained in both the total cross section and the angular distribution measurements. Furthermore, the change in the total cross section caused by this level is consistent with the parameters $J=\frac{3}{2}$ and $\Gamma_n \approx \Gamma_d$ which have been obtained from studies of the $T(d,n)He^4$ reaction.[8] The solid curve shown in Fig. 6 suggests that the measured angular distribution at 22.15 MeV also agrees with a $\frac{3}{2}^+$ assignment for this level. Therefore it must be concluded that

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the interpretation of the resonance in the T(d,n) reaction as a barrier penetration effect is not correct.

It is seen from Fig. 9 that the effect of the 16.7-MeV level on the n-α scattering may be appreciable even at neutron energies about an MeV above the resonance. Since this level has a spin and parity of $\frac{3}{2}^+$, it can affect only the $d_{3/2}$ phase shift for n-α scattering. Its contribution to this phase shift at energies above the He$^4(n,d)$T threshold can be determined from the partial widths of this level by means of the graphical method described by Moss.[39] For the partial widths[8] consistent with a radius of 7 F, the contribution was estimated to be about 5° even as high as 23.7 MeV.

No evidence was obtained for the 19.0-MeV level in either the total cross section or the angular distribution measurements. If the 19.0-MeV state exists and has a width of about 100 keV or greater, then the data in Figs. 2 and 8 indicate that this level causes changes of less than a few percent in the measured total cross sections and of less than about 4% in the measured angular distributions. However, if the width of this state is much less than 100 keV, its effect on the present measurements would be small because of the relatively large neutron energy spreads which were used.

Neither the total cross section nor the angular distribution measurements gave evidence for the broad 20-MeV level. However, the latter measurements are inconclusive because they do not extend to high enough energies. If this level is instead at 22-MeV excitation energy as Rosen[40] has suggested, then the total cross-section measurements also are inconclusive for the same reason.

Of the thresholds listed in Table I the He$^4(n,n')$ and He$^4(n,2n)$ thresholds are noteworthy since under certain conditions a threshold in a given channel may cause an observable anomaly, i.e., a cusp[41] or a rounded step,[42] in the cross section of another channel. The conditions which must be satisfied are: (1) there are only two outgoing particles in the threshold channel,[43,44] (2) the outgoing particles have no Coulomb interaction between them,[42] and (3) the outgoing particles have zero relative orbital angular momentum.[42] Furthermore, a study of the cross section in the vicinity of the anomaly can give information about spins and relative parities.[45]

Baz[45] has pointed out that if other inelastic processes are present, these other processes decrease the size of the anomaly in any one channel. Also, if one of the outgoing particles in the threshold channel is not a sharp state, i.e., if it has a short lifetime, then the anomaly will be smeared out and may not be observable.[45]

The He$^4(n,n')$ threshold fulfils the three abovementioned conditions, and the He$^4(n,2n)$ threshold will, also, provided that the two outgoing neutrons are emitted as one particle, i.e., that the di-neutron exists.[46] The excitation functions shown in Fig. 8 indicate that if the 20.1-MeV excited state of He^4 exists, and if the di-neutron exists, then they cause threshold anomalies in the He$^4(n,n)$ cross section of less than about 4% for the conditions of the present experiment.

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