such states for $C_6/2<T_5<C_6$. We desire to obtain the average width, Γ_4, of the overlapping states.

We let (5) be a proton and (3) be a neutron in this example. We take

$$\begin{aligned}&(3)\rightarrow \text{neutron},\\&(5)\rightarrow \text{proton},\\&m_4,m_6\gtrsim 10,\\&T_{30}=C_4=1.70,\\&T_{50}=(C_6-C_4)=4.00,\\&\Delta E=0.80,\\&\delta\epsilon=1.30,\\&\Delta\theta=15°,\\&T_{3L}\rightarrow T_{3U}=T_{5L}\rightarrow T_{5U}=2.20\rightarrow 3.50,\\&[\Gamma_4\lesssim 0.40],\\&\bar{f}_{sc}=\bar{g}_{sc}=\bar{g}_0=0.02\bar{f}_0'.\end{aligned} \tag{VI-17}$$

The relations (VI-4), (VI-5), and (VI-6) hold, where however all energies are multiplied by 10, distances are divided by $\sqrt{10}$, and dimensionless quantities remain the same, except for R which is the same and R/D_{53} which is multiplied by $\sqrt{10}$. The neutron-proton scattering cross section,[7] at T equal to 0.24 of our example, is 6.3. Let Γ_4' be equal to 0.40. We then have for $\mathcal{C}_{53m}{}^{sc}/\mathcal{C}_{53}{}^0$ from (V-26)

$$\mathcal{C}_{53m}{}^{sc}/\mathcal{C}_{53}{}^0=0.53(\Gamma_4/\Gamma_4')^2. \tag{VI-18}$$

The effect of proximity scattering can be quite large as illustrated in the examples of this section.

ACKNOWLEDGMENTS

I would like to thank Dr. H. Pierre Noyes, Dr. Michael Moravczik, and Dr. Stanley Schneider for a number of helpful suggestions, and for critically reading this manuscript. The work was performed under auspices of the U. S. Atomic Energy Commission.

PHYSICAL REVIEW VOLUME 125, NUMBER 1 JANUARY 1, 1962

Scattering of Neutrons by Alpha Particles*

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(Received July 17, 1961)

A precision n-α scattering experiment has been carried out in the energy interval 2–3 Mev. The angular distribution of neutrons elastically scattered by alpha particles has been measured at angles smaller than those considered in similar experiments. The phase-shift analysis of the data has led to the following results: (a) No D waves are detectable. (b) The phase shifts for the interaction in the $L=0$ and $L=1$, $J=\frac{3}{2}$ state agree very well with the values quoted in the literature. (c) The phase shift arising from the interaction in the $L=1$, $J=\frac{1}{2}$ state turns out to be much smaller than expected; it has been found $\delta_{\frac{1}{2}}{}^1=4°$ at 2.37 Mev and $\delta_{\frac{1}{2}}{}^1=8°$ at 2.87 Mev, instead of $\sim$20° in this energy interval. It is emphasized that such an unusual experimental result should be carefully considered in theoretical investigations concerning the spin-orbit potential, and in experimental researches using helium as a polarization analyzer.

LEVINTOV *et al.*[1] have claimed that the n-α interaction in the $P_{\frac{1}{2}}$ state is not well defined experimentally; the value of the $\delta_1{}^1$ phase shift,[2] evaluated from a left-right experiment at the incident neutron energy $E=2.45$ Mev is not consistent with the value obtained from phase shift analysis[3] of the angular distribution of neutrons elastically scattered by alpha particles. A somewhat similar result has been formerly obtained also by Seagrave[3] at $E=2.61$ Mev independently of polarization measurements; this situation has been later stressed by Pisent and Villi[4] in the framework of a phenomenological effective-range approach.

A precision n-α scattering experiment has been performed in order to investigate the energy dependence of $\delta_1{}^1$; the accurate knowledge of this dependence is

* This work has been carried out by the Istituto Nazionale di Fisica Nucleare, Sezione di Trieste, under contract Euratom-Cnen.

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[1] I. I. Levintov, A. V. Miller, and V. N. Shamshev, Nuclear Phys. 3, 221 (1957).

[2] The phase shift for the n-α interaction in the state of orbital angular momentum L and total momentum $J=L\mp\frac{1}{2}$ will be indicated as $\delta_{2J}{}^L$ ($\delta_1{}^0\equiv\delta_0$).

[3] R. K. Adair, Phys. Rev. 86, 155 (1952); P. Huber and E. Baldinger, Helv. Phys. Acta 25, 435 (1952); J. D. Seagrave, Phys. Rev. 92, 1222 (1953); E. Clementel and C. Villi, Nuovo cimento 2, 1121 (1955); see also P. E. Hodgson, *Advances in Physics*, edited by N. F. Mott (Taylor and Francis, Ltd., London, 1958), Vol. 7, p. 1.

[4] G. Pisent and C. Villi, Nuovo cimento 11, 300 (1959); see also P. G. Burke, *Nuclear Forces and the Few-Nucleon Problem* (Pergamon Press, New York, 1960), Vol. II, p. 413.

highly desirable because helium can be safely used as a polarization analyzer provided its efficiency, which critically depends on δ_1^1, be well known.

The experiment has been carried out using the standard technique of measuring the pulses produced in a proportional counter by the recoils of alpha particles struck by the incident neutron beam.[5] Neutrons were obtained by a d-D reaction; the incident deuteron beam was raised to the energy of 150 kev by means of a radio-frequency Cockcroft-Walton accelerator.[6]

The main goal of the experiment was to detect neutrons scattered at small angles. Indeed, a possible explanation of the above mentioned discrepancy is that the cutoff angle θ_0 ($\simeq 60°$ in the c.m. system) is so large that the extrapolation to $\theta<\theta_0$ of the n-α differential cross section,

$$k^2\sigma(\theta)=\sum_{n=0}^{n=2L_m} A_n^{(L_m)}\cos^n\theta, \qquad (1)$$

L_m being the maximum orbital angular momentum, might be unreliable in spite of the fact that for $\theta \geqslant \theta_0$ the angular distribution coefficients $A_n^{(L_m)}$ fit the experimental points well. Inspection of the phase shift equations shows that δ_1^1 is a sensitive function of the real part of the forward scattering amplitude, which—in turn—strongly depends on the extrapolated value of the forward cross section $\sigma(0°)$. This circumstance has suggested measurements of the pulse spectrum at the output of the proportional counter in three successive steps, each one characterized by a suitable degree of amplification. The first spectrum (partial spectrum) extends approximately from $\theta_0^{(I)}\equiv\theta_0\simeq 60°$ in the c.m. system. The second spectrum (extended spectrum) starts from a lower limit $\theta_0^{(II)}\simeq 45°$; the angular interval between $\theta_0^{(II)}$ and $\theta_0^{(I)}$ has never been so far explored in n-α collisions. Finally, a third spectrum has been measured at angles smaller than $\theta_0^{(II)}\simeq 45°$; this spectrum, used only for testing the consistency of the partial and the extended one, has not been considered in the subsequent analysis of the data. All measurements have been performed by means of a 200-channel pulse analyzer.

The experiment has been restricted to the energy region where the "anomalous" values of δ_1^1 have been previously determined; for this reason, neutrons of energy $E=2.37$ Mev and $E=2.87$ Mev have been used. The observed neutron distribution at $E=2.37$ Mev is shown in Fig. 1, where the partial spectrum is represented by black points.

The measurement of the extended neutron spectrum has required a detailed examination of background disturbances. It has been experimentally ascertained that no unwanted counts due to backscattering have

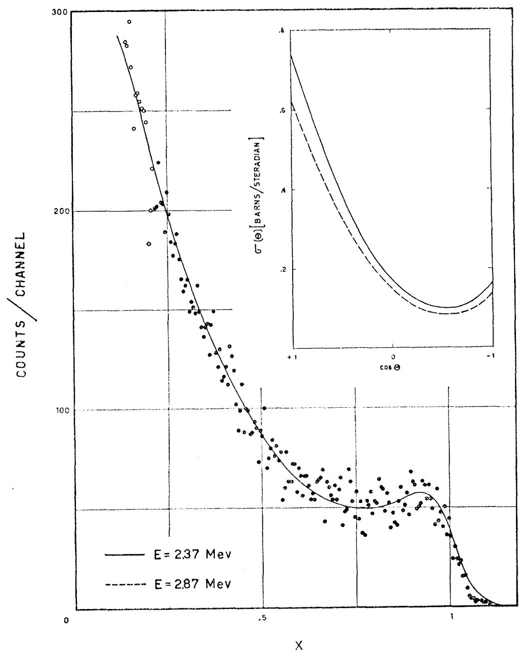

FIG. 1. Observed neutron distribution at $E=2.37$ Mev versus $x=E_\alpha/E_{\alpha m}$, E_α and $E_{\alpha m}$ being the energy and the maximum energy, respectively, of the recoiling alpha particle ($\cos\theta=1-2x$). Solid points refer to the partial spectrum and open points to the small angle contribution to the extended one. The n-α differential cross section $\sigma(\theta)$ at $E=2.37$ Mev and $E=2.87$ Mev, calculated using the angular distribution coefficients $A_n^{(L_m)}$, ($L_m=1$), listed in Table I, is shown in the inset.

influenced the measurement even at small angles, where amplification was maximum.[7] Effects arising from argon scattering were found to be restricted to angles smaller than $\theta_0^{(II)}$. The following corrections have been evaluated *exactly*: (a) finite size of the counter, (b) imperfect resolution of the counter and electronic chain, and (c) energy spread of neutrons. Correction (a), responsible for determining $\sigma(\theta)$ from the distorted shape of the observed spectrum, was less than 10%. Correction (b) turned out to be essential for the interpretation of the spectrum tail at large angles. The spectrum end ($x=1$) has been determined by means of a variational procedure. Values of x lower than about 0.8 were found to be practically unaffected by correction (b). Effects arising from the slowing down of deuterons in the target and the contamination of the beam due to D_2^+ ions turned out to be negligible. All calculations have been performed by means of the electronic computer IBM 650; the calculational program for the phase shift analysis has been developed following the method outlined in a series of preceding papers.[8] The results of the analysis of the extended

[5] E. Baldinger, P. Huber, and H. Staub, Helv. Phys. Acta **11**, 245 (1938); H. H. Barshall and M. H. Kanner, Phys. Rev. **58**, 590 (1940).
[6] F. Demanins and G. Poiani, Nuovo cimento **11**, 593 (1959).

[7] The distance between the counter and the target was $\simeq 10$ cm.
[8] E. Clementel and C. Villi, Nuovo cimento **2**, 845 (1955); E. Clementel and C. Villi, Suppl. Nuovo cimento **3**, 474 (1956); I. Gabrielli, G. Iernetti, E. Clementel and C. Villi, Suppl. Nuovo cimento **3**, 496 (1956); E. Clementel and C. Villi, Nuovo cimento **5**, 1343 (1957).

TABLE I. n-α angular distribution coefficients $A_n^{(1)}$ and phase shifts δ_{2J}^L (in degrees) evaluated in S and P wave approximation. The unphysical P phase shifts corresponding to the normal doublet of He^5 have been ignored. The normalization has been carried out using values of the integral cross section obtained by interpolation of the Los Alamos data.[a]

E (Mev)	$A_0^{(1)}$	$A_1^{(1)}$	$A_2^{(1)}$	δ_0	δ_1^1	δ_3^1
2.37	1.244±0.015	2.085±0.025	2.057±0.038	−41.2±0.7	4.5±1.2	120.4±1.1
2.87	1.327±0.013	2.134±0.023	2.024±0.031	−42.7±0.7	7.8±1.3	119.2±0.9

[a] J. H. Coon (private communication by J. D. Seagrave). The error on the phase shifts listed include the quoted experimental incertitude on the total cross section $\sigma_T(k)$. It has been proved that values of $\sigma_T(k)$ other than those used in the present calculation are incompatible with the general trend of the S-wave phase shift.

spectrum are listed in Table I. The phase shifts are compared in Fig. 2 with those derived by previous analyses.

It is seen that the behavior of δ_0 and δ_3^1 follows closely that determined from other experiments,

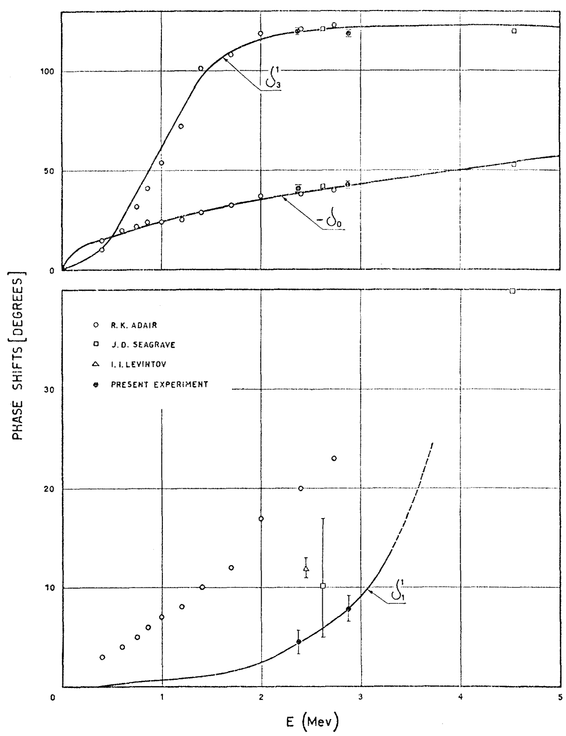

FIG. 2. Energy dependence of neutron-alpha S and P phase shifts. The solid line indicates the behavior of δ_{2J}^L determined from the phenomenological effective-range approach. The solid curves have been drawn using, in the notation of reference 4, the parameters (in fermis) $a_0=2.43$, $r_0=1.88$, $a_3^1=4.11$, and $r_3^1=2.78$. Further experiments are needed for a reliable determination of the effective range parameters of the $P_{\frac{1}{2}}$ state. The energy dependence of δ_1^1 has been evaluated assuming tentatively $a_1^1=1.23$ and $r_1^1=0.26$ (in fermis).

whereas the values obtained for δ_1^1 are surprisingly small. This unexpected result has been carefully checked. The experiment, repeated several times in such conditions that any misleading systematic error of instrumental nature would have been certainly revealed, has always led to the results listed in Table I. It is significant to note that the central value of δ_1^1 determined from the partial spectrum turns out to be *higher* than that determined from the extended one; for instance, at $E=2.37$ Mev one has $\delta_0=-41.3$, $\delta_1^1=8.9$, and $\delta_3^1=121.0$. No clear evidence of D-wave effects has been found at the scattering energies considered in the present experiment. A lengthy calculation has shown that both D phase shifts are smaller than 1°. Although this result should be taken with some reserve, it is nevertheless interesting to note that the perturbation brought about by small D phase shifts tends to *reduce* the value of δ_1^1 with respect to that determined from the extended spectrum analyzed in S- and P-wave approximation.

In conclusion, it has to be pointed out that the unconvincing $P_{\frac{1}{2}}$ discrepancy disclosed by Seagrave[3] and Levintov *et al.*,[1] has been confirmed and made even worse as a result of the present experiment,[9] and should be carefully considered in theoretical investigations concerning the spin-orbit potential and in experimental researches using helium as a polarization analyzer.[10]

ACKNOWLEDGMENTS

We are pleased to acknowledge a helpful criticism by Professor E. Baumgartner. We are also indebted to Professor J. D. Seagrave and Professor N. B. Cacciapuoti for a stimulating discussion.

[9] The results of this experiment extrapolated at $E=2.45$ Mev fit within 20% the polarization measured by Levintov *et al.*[1]

[10] A new analysis of Adair's data,[3] without resorting to the over-all fit criterion required by continuity considerations, has shown that the values of δ_1^1 are much smaller than those quoted in the literature, and agree well with those derived from the present experiment.