Spin Dependence of the s-Wave Neutron Interaction with Li^7†

R. G. THOMAS, M. WALT, R. B. WALTON,* AND R. C. ALLEN
Los Alamos Scientific Laboratory, Los Alamos, New Mexico
(Received September 9, 1955)

The angular distributions of the neutrons scattered elastically by Li^7 have been measured at four energies in the vicinity of the p-wave resonance at 256 kev. Pronounced departures from symmetry are observed, the scattering being predominantly forward below resonance and backward above resonance. These departures are analyzed for information on the nature of the s-wave "background" interaction. By taking into account the known values of the coherent and incoherent scattering cross sections at zero energy, it is possible to conclude that the parallel-spin ($J=2^-$) s-wave interaction is the stronger. Several other examples are cited from the literature on light nuclei which also indicate a stronger parallel-spin s-wave interaction, the magnitudes of the splittings being of the order of 1 Mev.

I. INTRODUCTION

THE neutron scattering length provides a measure of the s-wave neutron-nucleus interaction at zero energy. A large negative value is indicative of a resonance at low, positive neutron energies whereas a value which is positive and larger than the interaction radius indicates that there is at least one bound state of the compound nucleus with the same spin and parity as the compound nucleus formed in the interation; an absolute value which is small compared with the radius indicates that the interaction at zero energy is effectively small.

Shull and Wollan[1] measured the slow-neutron coherent scattering lengths of a large number of elements. For Li^7 they obtained a value $\mathfrak{a}=-2.2\times10^{-13}$ cm; a negative sign had previously been reported by Fermi and Marshall.[2] Since the spin of Li^7 is $\frac{3}{2}$, compound states of spin J equal to 1 and 2 are involved in the s-wave interaction, and the scattering length is therefore a sum $\mathfrak{a}=\mathfrak{g}_1\mathfrak{a}_1+\mathfrak{g}_2\mathfrak{a}_2$, where $\mathfrak{a}_1$, $\mathfrak{a}_2$ are the scattering lengths and $\mathfrak{g}_1=\frac{3}{8}$, $\mathfrak{g}_2=\frac{5}{8}$ are the statistical factors associated with the respective states. Solutions can be obtained for the individual $\mathfrak{a}_1$ and $\mathfrak{a}_2$ with the additional knowledge of the zero-energy total neutron cross section, which is given by $4\pi(\mathfrak{g}_1\mathfrak{a}_1^2+\mathfrak{g}_2\mathfrak{a}_2^2)$. The total cross section of Li^7 was measured by Adair[3] for neutrons in the range 0.2 to 1.4 Mev; an extrapolation of his results to zero energy gives 1.1 barns. More recently measurements were made in the range 1 to 340 kev by Hibdon,[4] which indicate a value of 1.07 ± 0.04 barns for the zero-energy cross section. Because of the quadratic nature of the total cross-section expression, two sets of solutions are found to be consistent with these data[5]: (I) $\mathfrak{a}_1=-4.65\pm0.20$, $\mathfrak{a}_2=-0.75\pm0.25$; (II) $\mathfrak{a}_1=0.25\pm0.35$, $\mathfrak{a}_2=-3.67\pm0.08$, the units being 10^{-13} cm. Figure 1 displays the graphical method[1] for arriving at these solutions. There the permissible ranges of values of $-\mathfrak{a}_1(=k^{-1}\sin\delta_{10}$, where δ_{jl} is the phase shift for channel spin j, angular momentum l,[6] and k is the wave number) and of $-\mathfrak{a}_2(=k^{-1}\sin\delta_{20})$ are graphed, the region between the parallel straight lines being compatible with the coherent scattering datum and the region between the two ellipses being compatible with the total cross section (incoherent scattering) datum. The two permissible sets of solutions are shown as the common, shaded areas I and II. The distinctive feature of these two sets is that whereas in the case of I there is indication of an appreciable interaction in the antiparallel-spin state of $J=1$ and effectively none in the parallel-spin state of $J=2$, in the case of solution II just the converse is true. Thus, with solution I, 97.4% of the zero-energy scattering intensity arises from the antiparallel-spin interaction whereas with solution II, 99.5% arises from the parallel-spin interaction.

One may hope to be able to determine which solution is the correct one by measuring the extent of the asymmetry in the angular distributions of the neutrons scattered elastically by the nearby p-wave resonance, the resonance parameters of which are now known with considerable certainty. The purpose of this note is to present the results of such a measurement and an analysis showing that solution II corresponding to the parallel-spin s-wave interaction is likely to be the correct one. Other evidence from the literature on light nuclei is cited which also indicates a stronger parallel-spin s-wave interaction. The present result on Li^7 may also be helpful for interpreting the interactions at higher energies where there is evidence of a broad resonance[7] and for considering the usefulness of Li^7 as an analyzer of neutron polarizations.

---

† Work performed under the auspices of the U. S. Atomic Energy Commission.

* Summer student from the University of Wisconsin, Madison, Wisconsin.

[1] C. G. Shull and E. O. Wollan, Phys. Rev. **81**, 527 (1951).

[2] E. Fermi and L. Marshall, Phys. Rev. **71**, 666 (1947).

[3] Robert K. Adair, Phys. Rev. **79**, 1018 (1950).

[4] We are grateful to Dr. Carl Hibdon for supplying us with his results prior to publication; some of them now appear in the third supplement to the *Neutron Cross Section Compilation*, Atomic Energy Commission Report AECU-2040 (Technical Information Division, Department of Commerce, Washington, D. C., 1954), Neutron Cross Section Advisory Group, April 1, 1954.

[5] See D. C. Peaslee, Phys. Rev. **85**, 555 (1952) and R. G. Thomas, Phys. Rev. **84**, 1061 (1951).

[6] Note that when $l=0$, the total spin J is the same as the channel spin j.

[7] Bockelman, Miller, Adair, and Barschall, Phys. Rev. **84**, 69 (1951); Freeman, Lane, and Rose, Phil. Mag. **46**, 17 (1955).

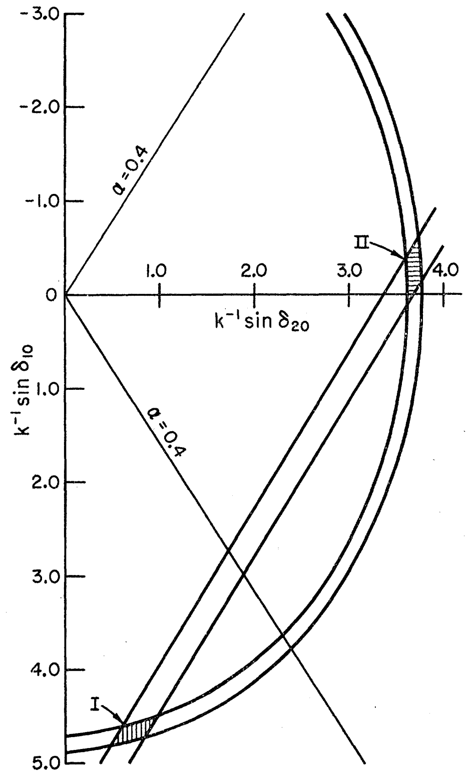

FIG. 1. The permissible ranges of $k^{-1}\sin\delta_{10}$ and of $k^{-1}\sin\delta_{20}$ for the s-wave interaction through the spin states 1 and 2, respectively, are graphed in units of 10^{-13} cm. At zero energy the quantities reduce to the negatives of the respective neutron scattering lengths. The region between the two ellipses is compatible with the total cross section data extrapolated to zero energy, while the region between the parallel straight lines is compatible with the thermal-neutron coherent scattering datum; the common areas I and II are thus compatible with both sets of zero-energy data. The region to the right of the two straight lines which are designated as $\alpha=0.4$ is compatible with the angular distribution data reported herein.

Concerning the Li^7+n,p-wave resonance, Adair[3] was the first to report it at about 270 kev with a width of 45 kev. Subsequently measurements with improved resolution were made by Stelson and Preston[8] who noted that a $J=3$, p-wave assignment is the only one consistent with the height and shape of their resonance curve. The width which they observed was 40 kev and the resonance position 256 kev. By applying the Wigner limit to this width, one may indeed verify that $l<2$, while, as noted by Adair, the absence of an interference minimum below the resonance implies that $l\neq 0$. Although the peak cross section observed by Stelson and Preston was about $1\frac{1}{2}$ barns below the predicted value for a $J=3$ resonance, the more recent measurements by Hibdon[4] with even better resolution are in excellent agreement with the prediction and indicate a somewhat smaller width of about 32 kev.

The "nonresonant" background of the total cross section is constant at about 1 barn up to 0.6 Mev, at which energy it begins a monotonic rise to 2.5 barns at 4 Mev.[9] It was noted by Adair that this rise could be interpreted as a broad $J=2^-$, s-wave resonance in the vicinity of 1.1 Mev. However, in view of the continuation of the rise which was observed later, it is evident that p and higher partial waves must be contributing, and it is not now possible to conclude with certainty that there is such a resonance.

[8] P. H. Stelson and W. M. Preston, Phys. Rev. 84, 162 (1951).

II. THE ANGULAR DISTRIBUTION FORMULAS

For the purpose of analyzing the s-wave background, the $J=3$, p-wave resonance assignment is a fortunate one because the resonance can have only a $j=2$ channel spin component, and therefore interference with the background will occur only if there is a similar component in the background. Thus, neglecting for the moment a possible energy dependence of the relative contributions to the background from the two channel spins, solution I, which is essentially pure $j=1$, would give rise to a nearly symmetrical angular distribution whereas solution II, which is essentially pure $j=2$, would give rise to a large asymmetry. However, owing to a possible energy dependence of the relative contributions, the selection of the correct zero-energy solution is somewhat more involved than merely determining experimentally whether or not there is an asymmetry.

According to the general formulas of Blatt and Biedenharn,[10] the form of the differential scattering cross section per unit solid angle for these interactions is

$$k^2\sigma(\theta)=(k^2\sigma_o/4\pi)+(7/8)\sin^2\delta_{21} +(7/4)\sin\delta_{20}\sin\delta_{21}\cos(\delta_{21}-\delta_{20})P_1(\cos\theta) +(21/50)\sin^2\delta_{21}P_2(\cos\theta), \quad (1)$$

where δ_{jl} refers to the phase shift for the interaction through channel spin j, angular momentum l, and the total cross section of the isotropic background is

$$\sigma_o=(4\pi/k^2)(\tfrac{3}{8}\sin^2\delta_{10}+\tfrac{5}{8}\sin^2\delta_{20}). \quad (1a)$$

The contributions from the higher partial waves, as well as from the non resonant p-waves, can be neglected at the low energies of concern. It is convenient to introduce a quantity α for the $j=2$ fraction of the s-wave scattering intensity:

$$\alpha\sigma_o=(4\pi/k^2)(5/8)\sin^2\delta_{20}. \quad (1b)$$

For the phase angle δ_{20} in the interference term of (1), one may then substitute

$$\delta_{20}=\sin^{-1}(2\alpha\sigma_o k^2/5\pi). \quad (1c)$$

If the ratio $\sin\delta_{20}/\sin\delta_{10}$ were the same in the vicinity of the resonance as it is at zero energy, then solution I would correspond to a value of $\alpha=0.04$ and solution II to a value $\alpha=1$.

[9] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. 27, 90 (1955).

[10] J. M. Blatt and L. C. Biedenharn, Revs. Modern Phys. 24, 258 (1952).

The phase shifts may be expressed in terms of the R functions by means of the relation[11]

$$\delta_{jl} = \tan^{-1}(R_{jl}P_l/1-R_{jl}S_l)-\phi_l, \qquad (2)$$

where

$$R_{jl} = \sum_\lambda \gamma_{\lambda jl}^2/(E_\lambda - E), \qquad (2a)$$

and S_l, P_l, and ϕ_l are the shift, penetration, and hard-sphere-phase factors, respectively, for angular momentum l. In the case of s-waves, $P_0=\phi_0=ka\equiv\rho$, where a is the interaction radius, and $S_0=0$, so that

$$\delta_{j0} = \tan^{-1}(\rho R_{j0})-\rho. \qquad (2b)$$

The scattering length $\mathfrak{a}$ is defined in the limit $k=0$:

$$\mathfrak{a}_j \equiv -\lim k^{-1}\sin\delta_{j0} = a[1-R_{j0}(0)]. \qquad (3)$$

The p-wave phase shift may be approximated by the one-level formula

$$\delta_{21} = \tan^{-1}(\tfrac{1}{2}\Gamma_\lambda/E_\lambda+\Delta_\lambda-E), \qquad (4)$$

where

$$\tfrac{1}{2}\Gamma_\lambda = P_1\gamma_\lambda^2 = \rho^3(1+\rho^2)^{-1}\gamma_\lambda^2, \quad \Delta_\lambda = -S_1\gamma_\lambda^2 = (1+\rho^2)^{-1}\gamma_\lambda^2. \qquad (4a)$$

At the low energies of concern, ϕ_1 and the contributions from the distant levels are small and of opposite sign, so that they may safely be neglected. The values of the parameters of (4a) which fit Hibdon's data are $\gamma_\lambda^2 = 0.307$ Mev and $E_\lambda = -0.043$ Mev for an assumed interaction radius of $a = 4.0\times10^{-13}$ cm.

III. EXPERIMENTAL PROCEDURES

As the experimental procedures used in the measurements were essentially the same as those previously described,[12] only a brief description need be given here. Neutrons were produced by bombarding a 15-kev thick Li target with protons from an electrostatic generator. A cylindrical sample of normal lithium, 3.8 cm in diameter and 5.1 cm long, was placed 30 cm from the neutron source, and the neutrons scattered by the sample were observed at various angles by a detector situated at an effective distance (d) of about 9 cm from the scatterer. The axis of the sample was perpendicular to the plane defined by the beam and the detector. The detector was shielded from the neutron source by paraffin wedges, the shapes of which were appropriate to the scattering angle. The counting rates of the detector were observed with the scattering sample in position (C), with the sample removed (B), and with the detector in the position normally occupied by the scatterer (D). Apart from the corrections which are discussed below, the differential scattering cross section is expressed in terms of these rates and the distance d according to

$$\sigma(\theta) = (C-B)d^2/DN, \qquad (5)$$

where N is the total number of nuclei in the sample.

The detector was of the hydrogen-filled recoil type having a 1.9-cm outer wall and 5.1-cm long, 1.3×10^{-3}-cm diameter center wire. It was operated at 10 atmospheres at 2700 volts. The discriminator bias was set just high enough to reject most amplifier noise. However, even at such a low setting, the sensitivity varied over the full energy range of the neutrons counted by as much as 40%, as determined by comparison with an energy-insensitive long counter.

Measurements were made at 15-degree intervals from 30 to 135 degrees in the laboratory system and with incident neutron energies of 229, 259, and 275 kev. These energies were uncertain by about $\pm2\frac{1}{2}$ kev, on account of the lack of precise knowledge of the target thickness and of the proton bombarding energy.

After completion of the measurements and of the analyses for these three energies, it was realized that an additional measurement at 210 kev with somewhat better resolution would be desirable. As the original equipment had been dismantled, another setup, which had then been designed and constructed for low-energy angular distribution studies, was employed. In this setup the scattering sample was a 1.9-cm diameter sphere of the pure Li^7 isotope placed 8.5 cm from the neutron source. A hydrogen-filled recoil counter was situated at an effective distance of 58 cm from the sample and was immersed in a barrel full of oil to provide shielding from the direct neutron beam, the entire assembly being free to rotate about the sample. The lithium target used as the source was 10-kev thick, and the neutron energy was considered as uncertain by $\pm2\frac{1}{2}$ kev. Measurements were made at laboratory angles of 30, 60, 90, and 120 degrees.

IV. REDUCTION OF THE DATA

In addition to a correction to (5) for detector sensitivity, several others had to be applied. In order to obtain sufficient counting rates it was necessary to use rather large samples, and a Monte Carlo procedure was used to correct for the resulting attenuation and multiple scattering. In this procedure the theoretical formulas of Sec. II $[\sigma_{\rm theor}(\theta)]$ were assumed to be the correct ones, and about 3×10^4 neutrons were traced through the sample for each of the three highest bombarding energies. The emerging angular distributions ($\sigma_{\rm MC}$) obtained by this Monte Carlo procedure were then compared with the assumed ones, and an approximate correction to the observed distribution ($\sigma_{\rm obs}$) was made in the manner

$$\sigma(\theta) = [\sigma_{\rm theor}(\theta)/\sigma_{\rm MC}(\theta)]\sigma_{\rm obs}(\theta). \qquad (6)$$

This procedure will in general not lead to the actual angular distribution unless the assumed one should happen to be the same as the actual one. Nevertheless,

[11] E. P. Wigner and L. Eisenbud, Phys. Rev. **72**, 29 (1947); the present notation is that of R. G. Thomas, Phys. Rev. **97**, 224 (1955).

[12] M. Walt and H. H. Barschall, Phys. Rev. **93**, 1062 (1954).

the probable error of this correction is estimated as being in no case greater than 25% of the value of the correction. These values varied from 0 to 100%, depending on the energy of the emerging neutrons, the largest being for those neutrons of the resonance energy which were subject to severe attenuation. Figure 2 displays the nature of the correction at the resonance energy; at 229 kev the correction factor varied from 0.80 to 1.15, and at 210 kev it was even less important. The indicated errors of the reduced data, which are presented in Figs. 3, 4, and 5, include the estimated uncertainty of this correction. In the cases of the measurements at 275, 256, and 229 kev, a correction was also made for the small fraction of Li^6 in the sample using the measured values of the scattering distributions for Li^6.[13]

As there was uncertainty in the cases of the three highest-energy measurements in the value of the effective distance d to the detector and its possible dependence on neutron energy, the integrals of the computed differential cross sections were normalized to agree with the accurately known total cross sections. The effective distance indicated by this procedure agreed within 15% with the distance measured to the center of the active volume of the detector. However, with the setup employed at 210 kev, the effective distance was believed to be known accurately and the

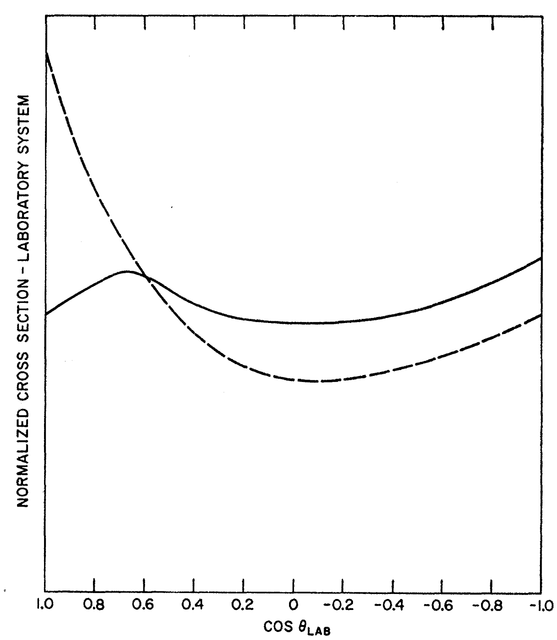

FIG. 2. The effect of multiple scattering. The dashed curve is the assumed differential cross section in the laboratory system at 259 kev. The solid curve was obtained by a Monte Carlo calculation and represents the cross section which would be measured experimentally if the assumed curve were the true one. The two curves are normalized to have equal areas.

[13] M. Walt (unpublished data).

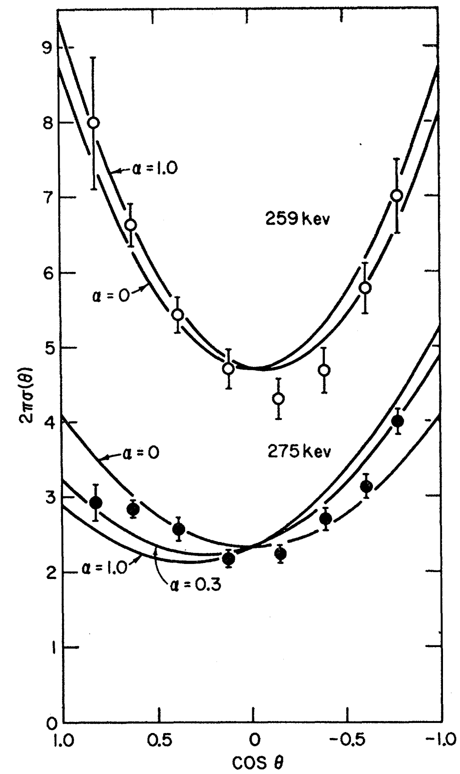

FIG. 3. The differential cross section $2\pi\sigma(\theta)$ in the c.m. system in barns plotted as a function of the scattering angle θ in the c.m. system. The open circles represent the data taken at the laboratory bombarding energy of 259 kev and the closed circles at 275 kev each set being corrected for multiple scattering and other effects. The two upper curves are the theoretical predictions at 259 kev for the values 1.0 and 0 of the interference parameter α, and the three lower ones are the predictions at 275 kev for the values 1.0, 0.3, and 0; the 15-kev beam energy spread has been taken into account.

points plotted on Fig. 5 are the absolute values as calculated directly from (5) with the appropriate corrections. As a check, the differential cross section of carbon was measured at 30 and 120 degrees. The values obtained indicated isotropy, as one would expect,[14] and agreed to within 5% with the values computed from the total cross section.[15] The area under a smooth curve passing through the four experimental points of the lithium data is 1.8 barns, which compares favorably with the total cross-section value of 1.9 barns.

V. INTERPRETATION OF THE DATA

It is evident from Fig. 3 that nothing can be learned from the 275- and 259-kev data about the value of the interference parameter α, the data being reasonably consistent with the predictions for any value between

[14] Willard, Bair, and Kington, Phys. Rev. **98**, 669 (1955); see also R. G. Thomas, Phys. Rev. **88**, 1109 (1952).

[15] Kiehn, Goodman, and Hansen, Phys. Rev. **91**, 66 (1953); D. W. Miller, Phys. Rev. **78**, 806 (1950); Fields, Russell, Sachs, and Wattenberg, Phys. Rev. **71**, 508 (1947).

0 and 1.0.[16] The distribution at resonance is not expected to show much asymmetry, and the above-resonance distribution is subject to rather large uncertainties in the forward scattering because some of the neutrons are degraded in energy into the region of the resonance maximum where they are severely attenuated and scattered. The 229- and 210-kev distributions, however, show an appreciable asymmetry and should be reliable for interpretation because the multiple scattering corrections there are relatively small. The 229-kev distribution shown in Fig. 4(a) is evidently consistent with $\alpha=1.0$ corresponding to the parallel-spin solution II if one considers the uncertainty of the neutron beam energy. Values of α equal to or less than 0.4 do not appear to be consistent with the data as presented in Fig. 4(b). Similar statements concerning α follow from the data of 210 kev which is shown in Fig. 5. If the relative contributions to the background intensity from the two channel spins could be regarded as energy-independent, this conclusion would rule out solution I, as is evident from Fig. 1 where straight lines with slopes corresponding to $\alpha=0.4$ have been included to represent the interference lower limits.

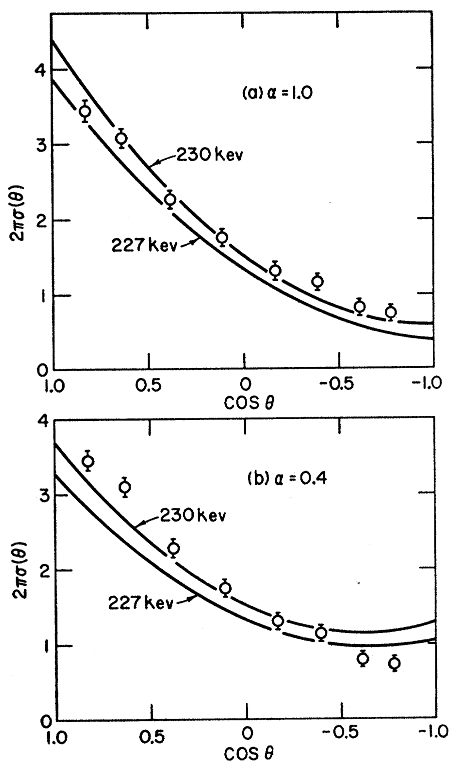

FIG. 4. The differential cross section $2\pi\sigma(\theta)$ in the c.m. system in barns plotted as a function of the scattering angle θ in the c.m. system for the data taken at 229 kev. (a) The upper curve is the theoretical prediction for 230 kev and the lower for 227 kev, the interference parameter α being set equal to 1.0 in each case. (b) The theoretical predictions for the same energies as in (a) but with $\alpha=0.4$. The 15-kev beam energy spread has been taken into account for both sets of curves.

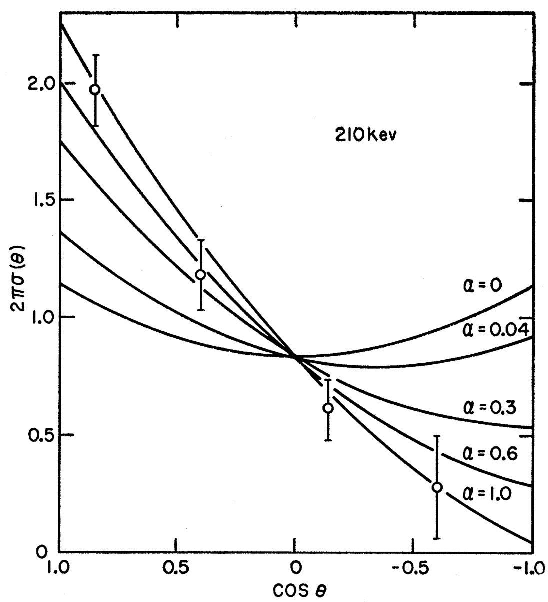

FIG. 5. The differential cross section $2\pi\sigma(\theta)$ in the c.m. system in barns plotted as a function of the scattering angle θ in the c.m. system for the data taken at 210 kev. The smooth curves are the theoretical predictions for the values 0, 0.04, 0.3, 0.6, and 1.0 of the interference parameter α.

In the consideration of the possibility of a large energy dependence of α, it is first noted that the fact that the background cross section is about the same near resonance as it is at zero energy implies that the representative point of the $(k^{-1}\sin\delta_{10}, k^{-1}\sin\delta_{20})$ plane for the resonance energy still lies between, or at least close to, the two ellipses. If solution I were the correct one, then $k^{-1}\sin\delta_{20}$ would have to increase by more than 1.5×10^{-13} cm as the energy increases from zero to the resonance. The following argument shows that such a large increase is not reasonable and therefore that solution II is very likely the correct one.

The energy derivative of $k^{-1}\sin\delta$ may be deduced from (2b); in the zero-energy limit it is given by

$$d(\rho^{-1}\sin\delta)/d\rho^2=\dot{\mathbf{R}}-\tfrac{1}{3}-\tfrac{1}{2}(R-1)(R^2+1), \qquad (7)$$

where $\rho^2=2Ma^2E/\hbar^2$, $\dot{\mathbf{R}}=d\mathbf{R}/d\rho^2$, and R is the value of $\mathbf{R}$ at zero energy. From (2a) one obtains

$$\dot{\mathbf{R}}=(\hbar^2/2Ma^2)\sum_\lambda\gamma_\lambda^2/(E_\lambda-E)^2. \qquad (8)$$

Since Li^8 has no bound, odd-parity levels, the distance $D_1=E_1-E$ to the first 2^- level is positive and so is its R value at zero energy. It is therefore possible to state that

$$\dot{\mathbf{R}}<(\hbar^2/2Ma^2)(R/D_1). \qquad (9a)$$

There is also the inequality

$$\dot{\mathbf{R}}>0, \qquad (9b)$$

[16] The tendency towards backward scattering above the resonance has also been observed by H. B. Willard, as reported in reference 9; see also Willard, Bair, and Kington, Phys. Rev. 94, 786(A) (1954).

which is the so-called causality condition,[17] so that the variation of $k^{-1}\sin\delta$ is restricted in both directions according to

$$0<\tfrac{1}{3}+\tfrac{1}{2}(R-1)(R^2+1)+d(\rho^{-1}\sin\delta)/d\rho^2 <(\hbar^2/2Ma^2)(R/D_1). \quad (10)$$

From the value of $\mathfrak{a}_2$ for solution I, one obtains a value of 1.2 for R_{20}; the behavior of the total cross section indicates that $D_1>0.9$ Mev. By substituting this information into (10), one finds from the upper limit that $d(k^{-1}\sin\delta_{20})/dE<5.3\times10^{-13}$ cm/Mev, whereas the correctness of solution I implies that $d(k^{-1}\sin\delta_{20})/dE>6.0\times10^{-13}$ cm/Mev, thus excluding solution I.

By applying (10) to the interaction data for the $J=1^-$ state of solution II, it is possible to conclude that in the vicinity of the resonance $-0.8<k^{-1}\sin\delta_{10}<1.1\times10^{-13}$ cm, and, because the representative point must lie between the two ellipses of Fig. 1, it can also be stated that $3.5<k^{-1}\sin\delta_{20}<3.8\times10^{-13}$ cm. These conclusions indicate that near the resonance energy the value of α presumably lies between 1.0 and 0.94.

VI. CONCLUSIONS: THE SPIN DEPENDENCE OF THE *s*-WAVE NEUTRON INTERACTION WITH Li^7 AND OTHER LIGHT NUCLEI

The present result indicates that the parallel-spin interaction is the stronger in the case of the *s*-wave, $T=1$ Li^7+n interaction. Equivalent square well potentials consistent with the interaction parameters indicate that the splitting is of the magnitude of $1\frac{1}{2}$ Mev. Several other examples from the literature on light nuclei may be cited which also indicate that the parallel-spin interaction is the stronger of the *s*-wave, $T=1$ nucleon-nucleus interactions and that the splittings are of a similar magnitude. $C^{13}+n$ and $C^{13}+p$: In C^{14} the 0^- state is 0.80 Mev above the 1^- state; the state in the mirror nucleus N^{14} corresponding to the 0^- of C^{14} is about 0.64 Mev above the state in N^{14} corresponding to the 1^- state of C^{14}.[18] $B^{11}+p$: The most probable assignments indicate that there is a $J=2^-$, $T=1$ level at 16.57 Mev excitation in C^{12} and a $J=1^-$, $T=1$ level 0.65 Mev above it.[9] Be^9+n: The fact that the scattering lengths for both *s*-wave interactions are about the same, positive, and greater than the nuclear radius implies that there are bound, $T=1$, $J=1^-$ and 2^- levels, the binding energies of which are $\lesssim 1.7$ Mev.[19] Levels in Be^{10} at 5.96, 6.18, and 6.26 Mev[20] have binding energies satisfying this condition. In the formation of these levels by means of the (d,p) reaction, the intensities of the first and third of these are observed to be much greater than that of the second. One would expect to be able to form readily the predicted 1^- and 2^- levels by stripping reactions with $l_n=0$, and according to the stripping theory their intensities should be proportional to $2J+1$. Indeed, the small-angle yield of protons associated with the 5.96-Mev level is about twice that associated with the 6.26-Mev level when 14-Mev deuterons are used.[21] Although both proton distributions are observed to be peaked forward, neither gives a quantitative fit to the theoretical stripping theory for $l_n=0$, and the distribution associated with the 5.96-Mev level actually appears more like $l_n=1$.[22] However, both levels are weakly bound, and it is known that in the case of $l_n=0$ capture, the stripping theory gives poor and sometimes incorrect assignments when the binding is weak or negative.[23] It is perhaps reasonable to conclude then that there may also be evidence in Be^{10} for a stronger parallel-spin interaction.

The spin-spin interaction has been discussed theoretically by de-Shalit.[24] The present observation may have some bearing on the empirical rule of Nordheim.[25]

The writers are grateful to R. L. Bivins, E. D. Cashwell, and C. J. Everett for formulating and coding the Monte Carlo calculation, to Max Goldstein for supervising some of the numerical work, and to Roger Perkins for assistance in taking data.

[17] Eugene P. Wigner, Phys. Rev. **98**, 145 (1955) and Am. J. Phys. **23**, 371 (1955).

Note added in proof.—Similar angular distribution measurements have been reported recently by Willard, Bair, Kington, and Cohn [*Elastic Scattering of Neutrons by* Li^6 *and* Li^7 (to be published)] who find that a "statistical" mixture ($\alpha=\frac{5}{8}$) gives the best fit to the below-resonance data, the predicted cross sections for $\alpha=1$ being inconsistent with the data. While our experimental results are not inconsistent with theirs, we have been unable to arrive at a satisfactory interpretation of their data using the above inequalities together with the thermal data.

[18] Mackin, Mims, and Mills, Phys. Rev. **98**, 43 (1955); R. G. Thomas and T. Lauritsen, Phys. Rev. **88**, 969 (1952).

[19] See F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 344 (1952).

[20] J. J. Jung and C. K. Bockelman, Phys. Rev. **96**, 1353 (1954).

[21] K. B. Rhodes and J. N. McGruer, Phys. Rev. **92**, 1328 (1953).

[22] J. N. McGruer (private communication).

[23] R. Huby, Progr. Nuc. Phys. **3**, 204 (1953).

Note added in proof.—On the basis of the observation of a 5.96-Mev gamma radiation from the Be^9+H^2 interaction and of no 6.26-Mev gamma radiation, it is suggested [Bent, Bonner, McCrary, Ranken, and Sippel, Phys. Rev. **99**, 710 (1955)] that the former level is spin 1 while the latter is 0 or $\geqslant 2$, contrary to our suggestion.

[24] A. de-Shalit, Phys. Rev. **91**, 1479 (1953); see also C. Schwartz, Phys. Rev. **94**, 95 (1954).

[25] L. W. Nordheim, Phys. Rev. **78**, 294 (1950) and Revs. Modern Phys. **23**, 322 (1951).