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Alpha-Alpha Scattering from 12.88 to 21.62 Mev

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The differential scattering cross section of alpha particles on helium has been investigated as a function of energy in the range from 12.88 to 21.62 Mev. The data obtained indicate a very strong angular dependence. This further appears to be a fairly sensitive function of energy. At the lower excitations there is a rather singular interference between the Coulomb and nuclear interactions. Above 20 Mev, interferences among the various components of the nuclear phase shifts again give rise to marked singularities. These data have been analyzed with respect to the phase shifts arising from the angular momentum components of the interaction. This decomposition indicated resonances at 7.55 and 10.8 Mev with widths, Γ of 1.2 Mev in each case and state assignments of 0 and 4, respectively.

INTRODUCTION

A STUDY of the high-energy interaction of two alpha particles encompasses two basic aspects. There is the fundamental concept of the type of potential to be associated with the alpha particle itself. This gives rise to the nonresonant or potential scattering. The interaction will also be influenced by the virtual energy states of the barely unstable compound nucleus of Be^8. This will result in the superposition upon the potential scattering of a resonant behavior characteristic of the angular momenta involved.

Until about 1950 this problem had been investigated only over the range of energies available from naturally radioactive substances. This early work has been thoroughly discussed by Wheeler[1] and more recently by Haefner.[2] It is perhaps sufficient to say that these experiments were plagued by all the difficulties attendant upon the low intensities of the sources then available. Taking these experimental limitations into consideration, Wheeler treated the data analytically and gave an apparently reasonable interpretation to it. The reported analysis showed one rather undesirable aspect, however. The resonance structure is observed in the S wave in direct contradiction of the results of other data. On the theoretical side of the problem, an encouraging point has been Haefner's success in obtaining Wheeler's nonresonant phase angles using a rather simple model.

More recently, attempts to extend the data to higher energies have been made by Mather[3] and Graves[4] at 20 and 30 Mev, respectively. These will be discussed more fully below. The work of Heydenburg and Temmer[5] in the lower-energy region is not as yet definitive.

The present research was undertaken in an attempt to obtain better resolution and with the use of better techniques to extend the data to cover a greater range of energies. It was found, however, that the method of reducing the cyclotron beam energy by the use of absorbing foils was impracticable below about 12 Mev, owing to the loss in beam intensity. No information could be obtained, therefore, on the question of the angular momentum of the 3-Mev resonance. Data were taken, however, covering the region from 12.88 to 21.62 Mev. This made it possible to obtain information regarding the two known states at 7.5 and 10 Mev in Be^8.

EXPERIMENTAL PROCEDURE

Apparatus

The external ion beam of the Indiana University cyclotron was passed through a double-sector inhomogeneous-field focusing magnet and a 32° homogeneous-field analyzer magnet into the scattering chamber. The focal properties of this lens system were adjusted to give an image point at the center of the scattering chamber. The resolution of the system was measured by observation of the alpha particle, deuteron doublet with a constant magnetic field. This was calculated to be about 45 kev/mm for 22-Mev alpha particles. The field of the analyzer magnet was maintained at predetermined values by means of an electronic stabilizer circuit utilizing a Brown converter and a phase-sensitive detector. The magnitude and constancy of the field were determined by the use of a calibrated search coil.

The analyzed beam was defined by a $\frac{1}{8}$-in. diameter circular slit of tungsten backed by lead and entered the scattering chamber through a $\frac{1}{4}$-in. cylindrical tube to within $\frac{1}{4}$ in. of the actual scattering center. At the terminus of this tube final definition was given by a $\frac{1}{16}$-in. diameter brass slit. The scattering chamber was isolated from the main cyclotron vacuum system by a 0.2-mil aluminum foil window covering this last slit. Visual observation of the beam image on a Willemite screen, as well as on photographic plates, showed no evidence of beam spread as a result of slit scattering.

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† Supported by the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.
[1] J. A. Wheeler, Phys. Rev. 59, 16 (1941).
[2] R. R. Haefner, Revs. Modern Phys. 23, 228 (1951).
[3] K. B. Mather, Phys. Rev. 82, 126 (1951).
[4] E. Graves, Phys. Rev. 84, 1250 (1951).
[5] Cowie, Heydenburg, Temmer, and Little, Phys. Rev. 86, 593 (1952); G. M. Temmer and N. P. Heydenburg, Phys. Rev. 90, 340 (1953).

The range in energies used was obtained by interposing aluminum absorbing foils at the cyclotron exit, approximately at the effective object point of the lens system. The energy was then defined by momentum analysis. Energies of 21.62, 20.95, 20.38, 19.62, 19.47, 18.82, 18.32, 16.55, 14.86, and 12.88±0.06 Mev were so obtained.

The actual scattering volume was defined by means of the slit system illustrated schematically in Fig. 1. A number of $\frac{1}{16}$-in. wide slits were machined in each of two brass cylinders concentric with the scattering center. These slits were aligned radially as shown at each of the angles 15°, 30°, 45°, etc., spaced every 15° up to 165° counterclockwise with respect to the incoming beam and $22\frac{1}{2}$°, $37\frac{1}{2}$°, $52\frac{1}{2}$°, $67\frac{1}{2}$°, $82\frac{1}{2}$°, 90°, and $97\frac{1}{2}$° clockwise. Kodak NTA emulsions of 50 and 60 micron thickness were used as detectors. These were centered vertically with regard to the beam axis and radially along the slit axes. They were further oriented so as to form an angle of 7° between the vertical plane of the emulsion and the plane of the slits. For the

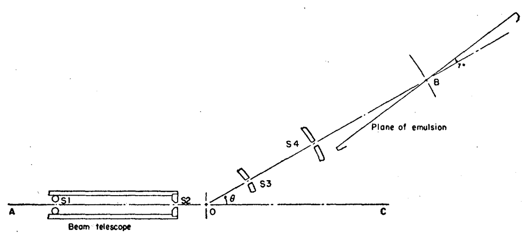

FIG. 1. Schematic drawing of slit system. $S1$ and $S2$ are circular beam apertures of tungsten and brass, respectively. $S3$ and $S4$ are rectangular brass slits oriented every 15° for θ 15° to 165° counterclockwise and $22\frac{1}{2}$° to $97\frac{1}{2}$° clockwise. AOC defines the incident beam direction. Point O is the scattering center and point B the center of the detecting plate.

scattering experiments the entire chamber was filled with helium gas to pressures of 5 to 8 centimeters of mercury as measured on a mercury manometer before and after each run. The chamber was evacuated and flushed with helium twice before each filling. Both high purity and commercial grade helium were used in different exposures.

The beam left the chamber through a second aluminum foil window and was monitored by means of a Faraday cage and an integrating circuit of the type developed at Wisconsin.[6] Secondary electron emission from the Faraday cup, and the aluminum window was eliminated by the use of a guard ring maintained at −300 volts. Beam currents from 0.01 to 0.3 microampere were used. Exposures were from one to fifteen minutes.

Control Experiments

Several control experiments were performed to check the apparatus used. A complete set of plates, including

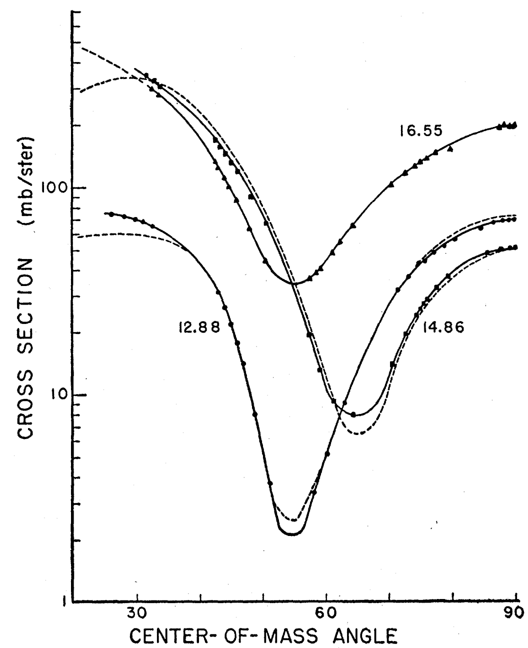

FIG. 2. Differential scattering cross section in millibarns per steradian for incident energies of 12.88, 14.86, and 16.55 Mev. Dashed curves indicate best fit using only S- and D-wave interaction.

those at angles greater than 90° not accessible to alpha-alpha scattering, were exposed with the chamber evacuated to determine the background scattering of the incoming beam at the slits and the aluminum windows. A search was also made for contaminant groups of

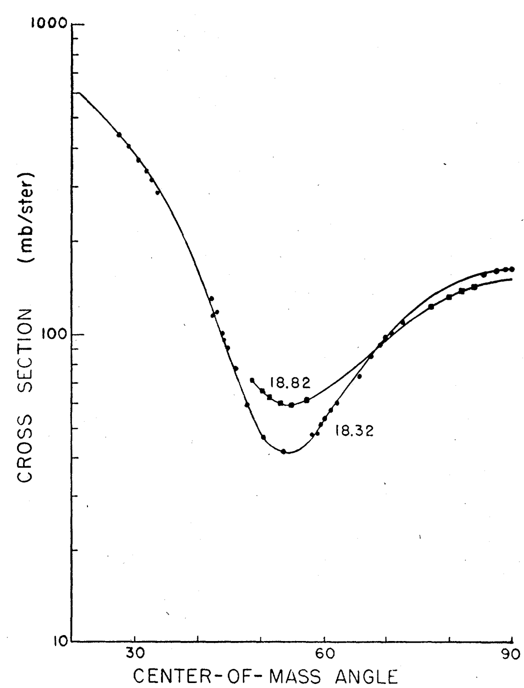

FIG. 3. Differential scattering cross section in millibarns per steradian for incident energies of 18.32 and 18.82 Mev.

[6] G. M. B. Bouricious and F. C. Shoemaker, Rev. Sci. Instr. 22, 183 (1951).

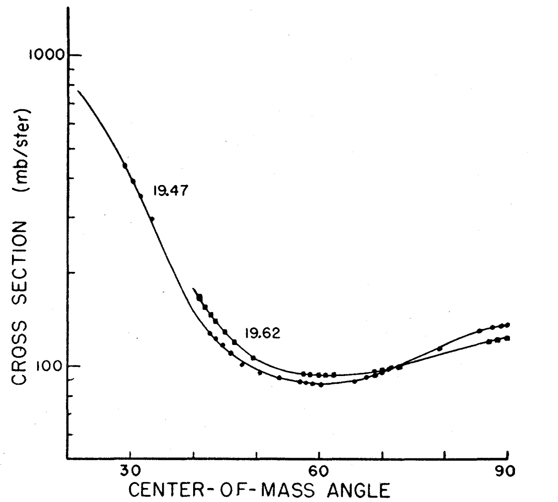

FIG. 4. Differential scattering cross section in millibarns per steradian for incident energies of 19.47 and 19.62 Mev.

elastically scattered particles from pump oil and other vapors which might be present in the scattering chamber. An exposure of one hour—about 500 microcoulombs of charge—was made, but no tracks other than thorium alphas and a few random protons were observed. None of these latter could possibly have come from the scattering volume seen by the plates. This suggested they were recoils from neutrons, possibly from the first beam slits. The low-energy spectrum of alpha particles normally observed on plates several months old has been successfully eliminated in this laboratory by the storage of the plates in cadmium containers.

Another set of plates was exposed to a source constructed of a $\frac{1}{16}$-in. diameter polished stainless steel cylinder uniformly coated with thorium-active deposit. This experiment simulated the cylinder of scattering centers across the chamber seen by the cylindrical beam. This gave a direct check on the alignment of the slit system, since the expected density of tracks at each angle was calculable. It also served as a check on the geometrically calculated corrections which were applied to the data from those portions of the plates situated a small distance from the slit axes. In all cases the calculations and direct measurements agreed to within 0.5 percent.

A third set of plates was exposed to a source of thorium active deposit with 0.2 atmosphere of helium gas in the chamber. Since the exposure could be quite accurately timed so as to correspond to a similar set using an evacuated chamber, this would provide a measure of the effects of straggling and the amount of secondary scattering to be expected at the two energies, 6.06 and 8.78 Mev. The relative density of tracks observed indicated that the secondary scattering was less than 0.5 percent.

These direct checks upon the apparatus demonstrate that the experimental data are limited by integration problems and by statistics rather than by any of the factors here considered. The first set of plates indicates that essentially all tracks observed originated in the target gas itself. No alpha-particle tracks scattered from either the apparatus or any apparatus contaminant were observed. The second set indicates that the alignment of the apparatus is certainly as good as the statistics available. The density of tracks as calculated from the geometry of the apparatus agreed with that observed to within 0.5 percent on the basis of about 10 000 tracks per plate. The third set of plates demonstrated quite clearly that the effect of secondary scattering either in the gas or from the slits was entirely negligible. No systematic difference in track densities was observed, the maximum effect being about 0.5 percent.

Scattering Experiment

The exposed plates were processed in the usual manner. Scanning was done on a Spencer binocular research microscope. The ranges of about 1000 tracks were measured on each plate preliminary to actual counting. In this manner a measure of the energy and a check on the impurities in the target were obtained. No contaminant tracks were observed on plates using high purity helium. A plot of the data obtained using the commercial grade helium indicated the impurities present were hydrocarbons. These gave rise to peaks well resolved from the helium and of less than 1 percent of the intensity. All tracks within the range limits thus prescribed by the helium peak were counted. Corrections were then applied to the track densities

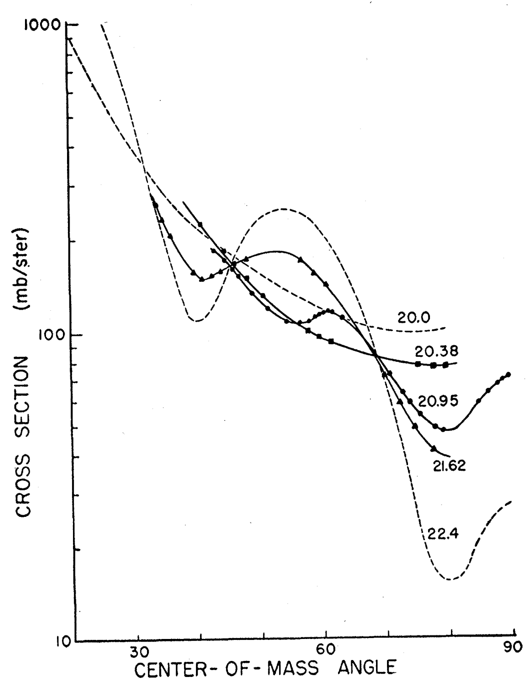

FIG. 5. Differential scattering cross section in millibarns per steradian for incident energies of 20.38, 20.95, and 21.62 Mev. Dashed curves are from Mather (reference 3), and Kerman, Nilson, and Jentschke (reference 8).

measured away from the center of the plate. The range measurements also gave an additional check on both the incident beam energy and on the angle of observation. In all cases the incident energies agreed to within 0.3 percent with the values obtained by magnetic analysis. On several plates additional range measurements were made to check the shift in angle occurring for the off center sections of the plate. The calculated energy shifts were within 2 percent of those measured.

After each exposure an additional plate was exposed at 45° to the incident beam at the same energy using a gold foil target. The elastic scattering from gold had been reported not to deviate from Coulomb scattering at 30 Mev for angles back to 50°.[4] This experiment was repeated here at 22 Mev and corroborated for the range of angles $22\frac{1}{2}°$ to 60°. These plates were then used to give an additional check on the absolute value of the cross section. In all cases where applicable the normalization to the gold cross section gave results which agreed to within 3 percent with the direct measurements using the integrator data.

The corrected data are given in Figs. 2–5. The absolute values are considered accurate to about 5 percent for the energies above 18 Mev and about 10 percent for those below. The relative values are considered to be better than 2 percent. This latter is primarily a function of the statistics, since the number of spurious tracks has been shown to be negligible, and the accuracy of the geometry was experimentally checked. The error in the absolute values is essentially that of the integration of the beam current, since the gas pressures were readable to better than 1 percent. Each curve represents a total of more than 30 000 tracks.

ANALYSIS

The data represented by the solid curves in Figs. 2–5 were analyzed in accordance with the Legendre polynomial expansion suggested by Taylor[7] and used successfully by Wheeler and Haefner. Several minor changes were made for simplicity. The expression used is essentially that for a modified Coulomb field with point charges and identical particles. If we write the center-of-mass cross section as

$$\sigma(\theta)=R^2(2e^2/mv^2),$$

then

$$R=Ae^{-i\alpha}+Be^{-i\beta}+\Sigma A_L e^{i\gamma}(1-e^{2i\delta_L}),$$

where the summation is over even values of L because of the symmetry. The various coefficients are defined by

$$A=\csc^2\tfrac{1}{2}\theta \quad \alpha=n\ln(\sin^2\tfrac{1}{2}\theta),$$

$$B=\sec^2\tfrac{1}{2}\theta \quad \beta=n\ln(\cos^2\tfrac{1}{2}\theta),$$

$$A_L=2(2L+1)P_L(\cos\theta)/n,$$

$$\gamma_L=2[\arctan n+\arctan(n/2)+\cdots+\arctan(n/L)]-\pi/2,$$

$$n=4e^2/\hbar v,$$

[7] H. M. Taylor, Proc. Roy. Soc. (London) A136, 605 (1932).

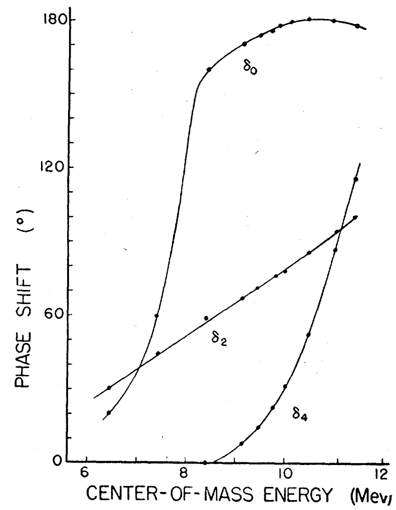

FIG. 6. The nuclear phase shift δ_L in degrees as a function of the center-of-mass energy in Mev. Data above 10.5 Mev are tentative.

where θ is the center-of-mass angle and δ_L is the nuclear phase shift of angular momentum L. It should be noted that in the summation γ_L is $-\pi/2$ for the S wave.

The complexity of these equations precludes any attempt at a simple analytical solution. Instead, a solution was sought by means of geometrical constructions. For simplicity the angles 15.3°, 27.3°, and 35.0° were chosen, the coefficients A_4, A_2, and A_4 vanishing, respectively, at these angles. Briefly, the procedure consists of adding the terms vectorially for one assumed phase angle, say δ_2, and determining what simultaneous values of δ_0 will give the observed cross section. This is repeated over the complete range of compatible variables, obtaining a locus of values which would satisfy the 15.3° cross section, for example. Similar loci may be found for the other two angles. Using the 15.3° and 35.0° data, simultaneous solutions for δ_0 and δ_2 are obtained from the intersection of the loci. The 27.3° data then determine acceptable values of δ_4. Up to eight such triads of solutions are possible. These are then individually checked to determine which of them gives the best fit to the rest of the experimental curve. Usually no unique solution is found for the limited range of angles available. A modification of this procedure is actually employed because of the experimental limitations. Solutions were sought using the observed cross section plus and minus the estimated experimental error. This resulted in areas of intersection rather than points as obtained in principle. The agreement between the solutions chosen and the experimental data is shown in Fig. 2. In cases where alternative solutions were available, a choice was based upon physical simplicity. For example, the solution requiring the smaller number of interacting orders was preferred. More important, however, was the restriction that the energy dependence of the respective orders be continuous and not arbi-

TABLE I. Comparison of levels and widths of excited states in Be^8.

$Li^7(d,n)$ Level energy Mev	Level width Mev	$\alpha+\alpha$ Level energy Mev	Level width Mev	State
7.5	1.7	7.55±0.08	1.2±0.4	$J=0$
10	~1.5	10.8 ±0.4	1.2±0.4	$=4$

trarily irregular. The best set of values so obtained is given in Fig. 6.

With reference to the data it should be noted that in the reconstructed curves shown in Fig. 2, no fourth-order phase shift has been used. None appears to be necessary for the 16.55-Mev data. For the 12.88- and 14.86-Mev data small admixtures of negative fourth-order phase shift will improve the fit, but it is believed the correspondence shown is within the experimental accuracy. The higher-energy data may likewise be fitted to within the errors quoted. In Fig. 5 the data presented by Mather,[3] and a typical curve obtained by Kerman, Nilson, and Jentschke,[8] are shown for comparison.[9] The data obtained at Illinois agree very closely both in general shape and magnitude with that presented here. Mather's results are also in rough agreement, although a slight lowering of the right-hand portion of the curve would improve the agreement. There is no agreement with the results of Braden, Carter, and Ford.[10] This is undoubtedly because of their poor statistics.

DISCUSSION

The steep rise in the S-wave phase shift indicated in Fig. 6 can be accounted for by the assumption of a resonance level at 7.65±0.08-Mev excitation energy and a width Γ, of 1.2±0.4 Mev. The large error assigned the width measurement arises from the few points available to give the resonant shape. The values are obtained from fitting an $\arctan\frac{1}{2}\Gamma(E_0-E)^{-1}$ curve to the data at three energies.

The sharp rise in the G wave may similarly be accounted for. Fitting only the forward slope of this resonance, one obtains a level at 10.9±0.4-Mev excitation and a width Γ, of 1.2±0.4 Mev. These values do not take into account the Illinois data previously mentioned and will undoubtedly need revision when this analysis is complete.

The D wave shows no evidence of any resonance behavior in the energy region covered. In fact, irrespective of the choice made among the individually acceptable solutions, the value of δ_2 does not change by more than about 10°. The values indicated all fall within 2° of a straight line.

These facts are in good agreement with present knowledge concerning the Be^8 compound nucleus. Only two 2-alpha-particle states of sufficient width to be observed in this experiment are observed in the energy region covered. These would be an S state at 7.55 Mev and a G state at about 10.8 Mev, assuming the ground state to be unstable to 2-alpha particle breakup by 96 kev. These values compare favorably with the broad levels observed in the $Li^7(d,n)$ experiments.[11] A comparison is given in Table I.

The assignment also agrees with the available data on the beta decay of Li^8 [12] and on the $C^{12}(\gamma,\alpha)$ reaction[13] predicting a unique configuration for the 3-Mev state. If one temporarily disregards Wheeler's analysis, the weight of the experimental evidence favors the assumption of $J=2$ for this level.[14] The proposed assignments would still leave this D state unique as required.

A possible explanation for the inconsistency of Wheeler's assignment of $J=0$ to this first excitation level may be seen from Fig. 2. The minima are becoming narrower and more pronounced with decreasing energy. The observed energy dependence of δ_2 further suggests that this tendency may be extrapolated. Thus, it may well be that the relatively poor resolution of the early experiments would cause such an effect to have been missed. This would suggest that the original data rather than Wheeler's analysis are at fault. This point is further strengthened by the fact that the present experiments require only two orders of interaction—S and D wave—for an incident energy of 17 Mev, while the most reasonable analysis of the early data required admixtures of G wave at 6 Mev.

[8] Kerman, Nilson, and Jentschke (to be published).

[9] The authors wish to express their appreciation to Professor Jentschke and his group at the University of Illinois for making their data available prior to publication and also for many very helpful discussions on the problems involved in the analysis and interpretation of the data.

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[11] K. T. Richards, Phys. Rev. **59**, 796 (1941); L. L. Green and W. M. Gibson, Proc. Phys. Soc. (London) **62**, 407 (1949).

[12] W. F. Hornyak and T. Lauritsen, Phys. Rev. **77**, 160 (1950); C. W. Li and W. Whaling, Phys. Rev. **81**, 661 (1951).

[13] V. L. Tegledi and W. Zunti, Helv. Phys. Acta **23**, 745 (1950).

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