evidence was found by Braams[45] for a $Ca^{43*}$ high-spin level at 1.678 Mev. Judging by the energies of the accepted $5/2^-$ and $3/2^-$ $Ca^{43*}$ $(1f_{7/2})^3$ levels, the $V^{51*}$ 20–28 core may be more rigid than the 20–20 $Ca^{43*}$ structure thus indicating that the high-spin $Ca^{43*}$ configuration levels should appear at lower energies than the comparable $V^{51*}$ levels. Other supporting evidence for a tighter core is the possible higher excitation energy in $V^{51*}$ for the $2p_{3/2}$ single-particle level plus even levels (representing breakup of the 20-proton shell core) that are low-lying in $Ca^{41*}$ and $Ca^{43*}$ vs apparently high-lying in $V^{51*}$. This conclusion is also suggested by the greater excitation energy of $Ca^{48*}$ vs $Ca^{40*}$ or the difference[8] in $Ca^{41*}$ and $Sc^{41*}$ excitation energies from those of $Ca^{49*}$ and $Sc^{49*}$.

If the tentatively assigned 15/2 level at 2.70 Mev exists, one wonders whether it corresponds to the $(p,p')$ 2.675- and 2.699-Mev doublet (angular momentum high for excitation). It would be useful to perform angular distribution measurements with stripping reactions on a $V^{50}$ target to help distinguish between single particle (seniority $s=1$) and mixed $V^{51*}$ states $(s>1)$. Definite assignments might be possible from such $(d,p)$ work to check the tentative proposals of the present work. Schwäger and Cox[24] developed a technique for preparing thin vanadium targets requiring a minimum amount of mother material which should help produce appropriate $V^{50}$ targets from a very limited amount of the enriched isotope. This would also permit $(p,p')$ investigations of $V^{50*}$ levels thus giving data on the coupling between $(1f_{7/2})^3$ proton configurations and a $(1f_{7/2})^{-1}$ neutron hole.

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# Elastic Scattering of Alpha Particles from Helium†

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The elastic scattering of alpha particles from helium has been investigated at laboratory energies of 6.43, 6.84, and 7.78 Mev. Complete angular distributions from 20° to 90° in the center-of-mass system were obtained. Analysis of the data suggests somewhat smaller values for the *D*-wave phase shift then previously reported.

## INTRODUCTION

THE elastic scattering of alpha particles from helium has been frequently studied in an attempt to better understand the structure of $Be^8$. The lower energy data have been quite completely reviewed in the work of Nilson, Jentschke, *et al.*[1] and more recently of Jones, Phillips, and Miller.[2] The energy region from 4 to 8 Mev (laboratory) is of particular interest in terms of extracting parameters relative to the quite broad first excited state in $Be^8$ at about 3 Mev. Utilizing the excitation curves at three judiciously chosen angles, specifically the zeros for the second and fourth order Legendre polynomials, Jones *et al.* have investigated this state in terms of a single-level dispersion theory. As is to be expected, the parameters obtained would appear to be a rather sensitive function of the *D*-wave phase shifts selected. Specifically, the use of somewhat smaller values than those chosen would tend to decrease the reduced width of the state and to increase the accompanying hard sphere radius. Such a lowering is indeed implied by an extrapolation of Nilson's data into this energy region. The data of Berk, Steigert, and Salinger[3] would likewise seem to support somewhat smaller values.

The various attempts to connect the experimental phase shifts with theoretical potentials are briefly reviewed by Butcher and McNamee.[4] Utilizing a force law combination observed to give good results in esti-

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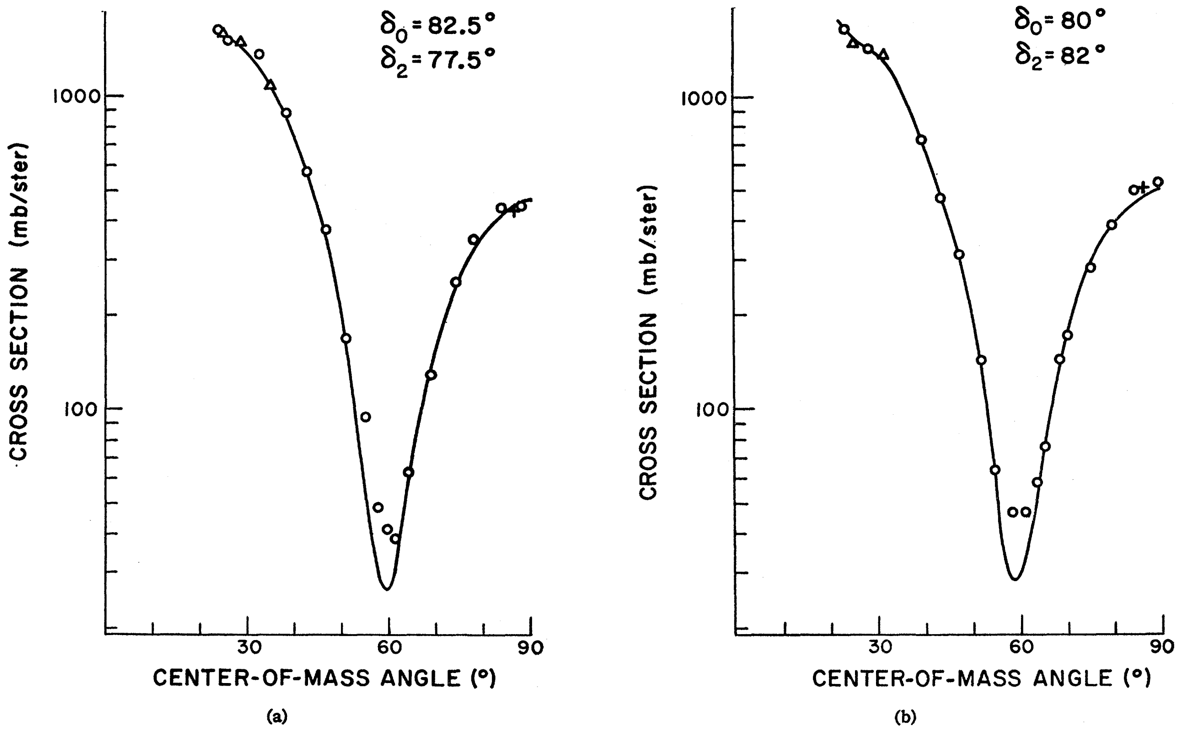
[1] R. Nilson, W. K. Jentschke, G. R. Briggs, R. O. Kerman, and J. N. Snyder, Phys. Rev. **109**, 850 (1958).

[2] C. M. Jones, G. C. Phillips, and P. D. Miller, Phys. Rev. **117**, 525 (1960).

[3] N. Berk, F. E. Steigert, and G. L. Salinger, Phys. Rev. **117**, 531 (1960).

[4] A. C. Butcher and J. M. McNamee, Proc. Phys. Soc. (London) **74**, 529 (1959).



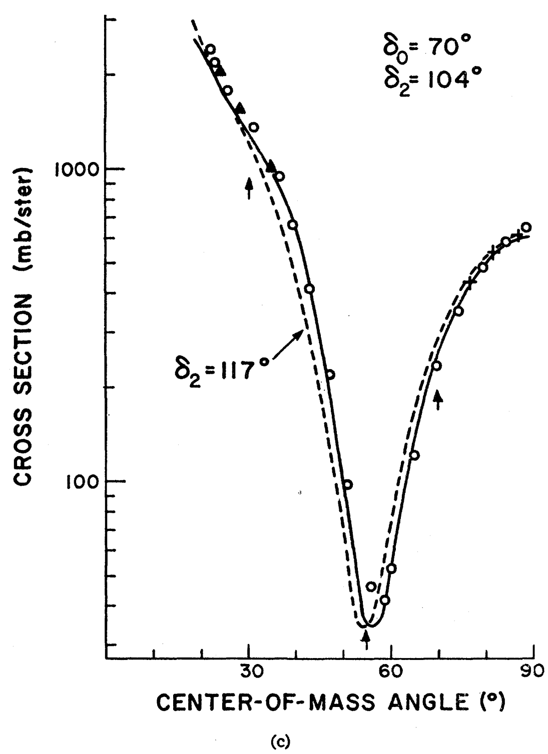




FIG. 1. The center-of-mass cross section as a function of center-of-mass angle at an incident laboratory energy of (a) 6.43 Mev, (b) 6.84 Mev, (c) 7.78. The triangles denote points from negative angles. The crosses denote points from laboratory angles greater than 45°. The solid curves are best fits to data and are obtained using the indicated phase shifts. The dashed curve is obtained using the larger value of $\delta_2$ indicated. The arrows correspond to observation angles used in reference 2.

mating the binding energy of $Be^8$ and $C^{12}$, they obtain quite reasonable fits to the experimental data over a wide range of energies. The marked exception is for the *D*-wave phase shift in the vicinity of the 3-Mev resonance. Using a more empirical approach, Wittern[5] has succeeded in reproducing rather well both the *S*- and *D*-wave phase shift data. His choice of parameters

[5] H. Wittern, Naturwissenschaften 46, 443 (1959).

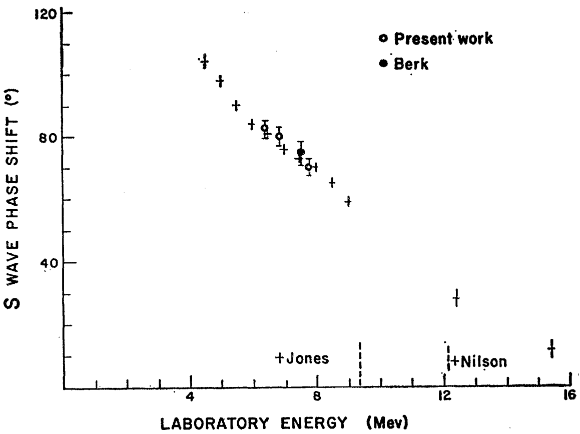



FIG. 2. The $S$-wave phase shift as a function of laboratory energy. Data from Jones, Nilson, and Berk are shown for comparison.

would suggest values for the latter only slightly larger than those used by Jones.

The present experiment is an attempt to verify the phase shifts in the region of 6 to 8 Mev (laboratory) by means of more complete angular distributions.

## EXPERIMENTAL PROCEDURE

The scattering chamber used in this experiment was of the double-pillbox type. The lower half was fixed with respect to the beam, while the upper half was free to rotate about an axis normal to the beam direction. The beam entrance slits and several fixed observation ports were located in a plane near the top of the stationary portion. The main observation port was near the base of the rotating portion. This was inclined at an angle of 11° 45′ to the plane defined by the fixed port system. The intersection of the axis of this port with the center of rotation and with the geometrical center of the system as defined by the lower apertures was determined optically to be invariant to less than 0.001 inch.

Since the entire chamber was to be filled with helium, the magnetically analyzed alpha particles from the cyclotron were admitted through a nickel gas retaining window. For the highest energy a nickel foil of 0.71 mg/cm$^2$ and a gas pressure of 5 cm of mercury were used. This reduced the beam energy from its analyzed value of 8.04 Mev to 7.78±0.04 Mev at the center of the gas target volume. Correspondingly heavier nickel windows were utilized to obtain the lower bombarding energies. The quoted incident beam energy was confirmed by range measurements in Ilford $E1$ nuclear emulsions. The beam particles could be directly calibrated in terms of natural alphas from ThC′ and ThC″ in the same emulsions. The widths of all peaks were as expected from straggling considerations alone.

In a typical run the fixed ports at 180° and 0° would house the beam collimation system and the Faraday cup, respectively. Two particle detectors and their respective collimators would be placed one in a fixed port, as at 15°, and the other in the inclined port in the movable lid. The use of the auxiliary detector at a fixed location served a twofold purpose. The second counter served as an additional beam monitor for defining relative yields. It further facilitated experimental verification of the alignment by providing a comparison between the fixed port yields and those at equivalent angle settings of the rotating head. The beam input and detector collimators used resulted in a mean angular spread of the order of a half degree. At no angle used was the direct beam able to see the first detector slits or the detector able to view the final beam aperture.

Commercial grade helium, quoted to have less than 0.01% impurity, was used as the target gas. A liquid nitrogen trap was used to further minimize any condensable contamination. As indicated below, no evidence of an impurity fraction was found. The absolute density was measured and maintained to 1% or better. The detectors used were $\frac{1}{2}$-mm thick thallium-activated CsI crystals mounted directly onto the face of DuMont 6292 photomultipliers. The particle pulses were passed through a white follower stage, amplified, and then analyzed. The final signal was split between a grey wedge-type multiple-channel analyzer for general monitoring and a single-channel analyzer for particle counting. All detected particles in the elastic group were accepted. No particle pulses were observed outside the elastic group. In particular, no higher energy particles, indicative of heavy contaminants such as nitrogen, were detected even during prolonged runs. Runs were terminated when the particle pulses were sufficiently reduced in magnitude so as to be subject to interference from the background noise.

Data were taken at either side of straight forward to check the alignment of the beam axis relative to the scattering chamber geometry. Such negative-angle points are indicated separately as triangles in Fig. 1. Additional data were also taken as far back as 100° to check on impurity scattering from targets heavier than helium. As was anticipated from the absence of double peaks at the forward angles, no large-angle scatterings were observed. In all cases the combined detector and monitor statistics for a given point were between 1% and 4%. All points were repeated to check reproducibility. The absolute beam integration was checked by means of a Carey Vibrating Reed Electrometer and was reproducible to within 2%. The contributions expected from slit edge scattering, higher order geometry corrections, and multiple scattering were estimated to be less than 1% for the experimental conditions here applicable. Accordingly no adjustments of the data were made on this account.

The data for the three energies used are displayed in Fig. 1 as center-of-mass cross sections versus center-of-mass angle. The triangles and crosses, respectively, indicate negative angles and observation beyond 45° in the laboratory. The smooth overlap of these three center of-mass quadrants would indicate reasonable geometrical alignment. Except near the minima, the relative

cross sections are estimated to be good to about 3%. Because of the extremely long runs required in the neighborhood of 60°, however, the possibilities of inclusion of random noise pulses could not be entirely ruled out. As a result the data here might conceivably be systematically high by somewhat more than 3%. The absolute cross section, on the other hand, is probably only reliable to of the order of 10%. The absolute angle measurements are considered accurate to better than 15 minutes.

## DATA ANALYSIS AND RESULTS

The center-of-mass cross sections illustrated were analyzed in terms of the usual polynomial expansion involving the nuclear phase shifts $\delta_l$.[6] Consistent with previous results in this energy region it was not found necessary to invoke terms of higher angular momentum than two. The best fits to the data as obtained by simultaneous adjustment of both $\delta_0$ and $\delta_2$ are shown by the solid lines in Fig. 1. The values of the parameters used are as indicated.

The dashed curve in Fig. 1(c) is the cross section to be expected if one uses a larger value of $\delta_2$. While the difference is not large it is systematic. The data appear to be displaced by about 2° (1° in the laboratory) from the dashed theoretical curve. However, assuming a systematic error and shifting the circles the necessary amount leftward would require concurrent rightward adjustment of the same magnitude of the associated triangles and crosses. Such a process would obviously render these negative and backward angles inconsistent with the remainder of the data. The disagreement shown would appear to be outside the probable experimental errors. It should be noted that the two theoretical curves predict nearly identical results at the three angles chosen for analysis in reference 2 [arrows Fig. 1(c)]. This is expected at 54° 44′, which is the zero of the second order Legendre polynomial, since the curves only differ in the choice of $\delta_2$. The near coincidence at 30° 33′ and 70° 7′ is, however, fortuitous.

The phase shifts necessary to best satisfy the present work are displayed in Figs. 2 and 3. The respective results of Jones, Berk, and Nilson in the region of interest are also shown. The $S$-wave phase shifts from all sources superimpose extremely well between six and eight Mev. Considering the sensitivity of the relative cross sections to the value of $\delta_0$, the agreement is not too surprising. This is to be contrasted with the correspondingly weak dependence on $\delta_2$. Whereas a 5° shift in $\delta_0$ would result in a major change in the over-all shape and cross section, particularly in the vicinity of the minimum and at forward angles, the primary effect of a 15° change in $\delta_2$ [e.g., Fig. 1(c)] can be described as a small angular displacement.

[6] J. A. Wheeler, Phys. Rev. 59, 16 (1941).

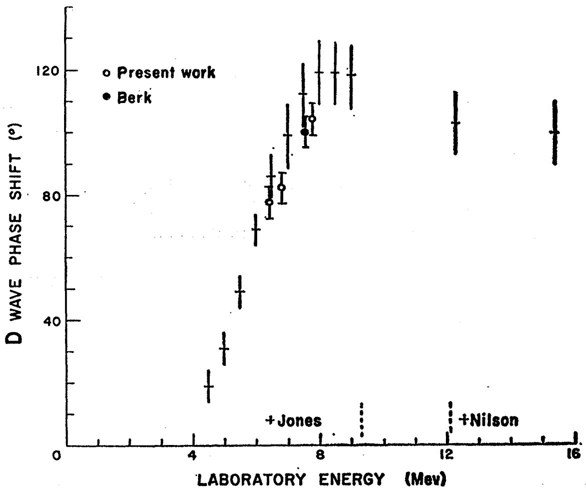



FIG. 3. The $D$-wave phase shift as a function of laboratory energy. Data from Jones, Nilson, and Berk are shown for comparison.

The values of $\delta_2$ which seem to best reproduce the present data lie consistently below those chosen by Jones for his subsequent analyses. This is in agreement with the results of Berk. This should not be interpreted as a disagreement between the data, however, since the experimental error bars clearly overlap. The major difference would appear to be that the more complete angular distribution is usually able to impose narrower limits on the choice of parameters than a three point fit. These phase shifts are nevertheless still somewhat higher than an extrapolation of Nilson's data might suggest.

No attempt has been made to compute in detail the parameters which would be required to fit the new data to the single-level dispersion theory. Qualitatively, however, it would appear that one manner in which these smaller values of $\delta_2$ might be explained is by the use of a larger hard-sphere radius and a narrower half-width for the resonance. In addition these also appear to improve the fit to the lower energy data. One such solution is in fact shown as curve $A$ in Fig. 7 of reference 2. However, the improvement is apparently only to be bought at the expense of the fit to the higher energy phase shifts. The effect of different radii in a model such as Wittern's has not been calculated as yet.

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