Importance of Large-Angle Data in Optical-Model Analysis of Helion Elastic Scattering*

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(Received 22 February 1972)

Optical-model analyses which include data far into the backward hemisphere for elastic scattering of complex projectiles at intermediate energies are found to produce optical potentials with many of the common ambiguities removed. This paper reports differential cross-section data with an extensive optical-model analysis for 59.8-MeV helions elastically scattered from ^{27}Al and ^{52}Cr. The data include scattering angles back to 166° for ^{27}Al and to 149° for ^{52}Cr. Optical-model fits to these data are satisfactory only with a surface-peaked absorption term and with a spin-orbit term included in the potential. The discrete or family ambiguity in the potential is removed, and continuous ambiguities are notably suppressed.

INTRODUCTION

The nuclear optical model has been very successful in describing the elastic scattering of not only nucleons by nuclei, but of composite particles for a wide range of nuclei. The first optical-model analyses of helion elastic scattering data were reported by Hodgson[1] in 1961. Since then many analyses have been reported.[2] These have usually been successful in that they produced potentials that predict angular distributions in agreement with the experimental data. Perhaps the analyses have been too successful in that there are a number of ambiguities in the optical-model potentials thus determined. Among these are discrete families of real well depth and an unclear choice between a surface-peaked or volume-absorption term.

One reason, we believe, for the ambiguities in optical-model potentials for nuclear scattering of strongly absorbed particles is lack of data in the far backward-angle region. This is especially true for helions where the large-angle elastic scattering cross sections are smaller than for deuterons or α particles. An example of a 50-MeV helion elastic scattering angular distribution[3] is shown in Fig. 1. Between 20 and 70°, $\sigma(\theta)$ decreases by 5 orders of magnitude. An extrapolation of this trend would indicate that large-angle cross sections are prohibitively difficult to measure. It is seen in Fig. 1, however, that between 70 and 120° $\sigma(\theta)$ decreases by only 1 order of magnitude rather than 5, as between 20 and 70°, and hence exceeds the extrapolation of forward-angle data by a large factor.

Large-angle data were shown in Ref. 3 to be more sensitive than the forward-angle data to the details of the helion-nucleus potential. This suggests that large-angle data may be useful for removing some of the ambiguities in the optical-model parameters. Recently, results were reported of optical-model analyses of 30- and 32-MeV data[4] and of 38-MeV data.[5] The data of Ref. 4 extended to 168°, and that of Ref. 5 to 155°. In both cases a number of target nuclei were studied. The fits with surface-peaked absorption wells are consistently better than those obtained for potentials with volume-absorption terms. In both studies the inclusion of a spin-orbit term in the potential significantly improved the optical-model

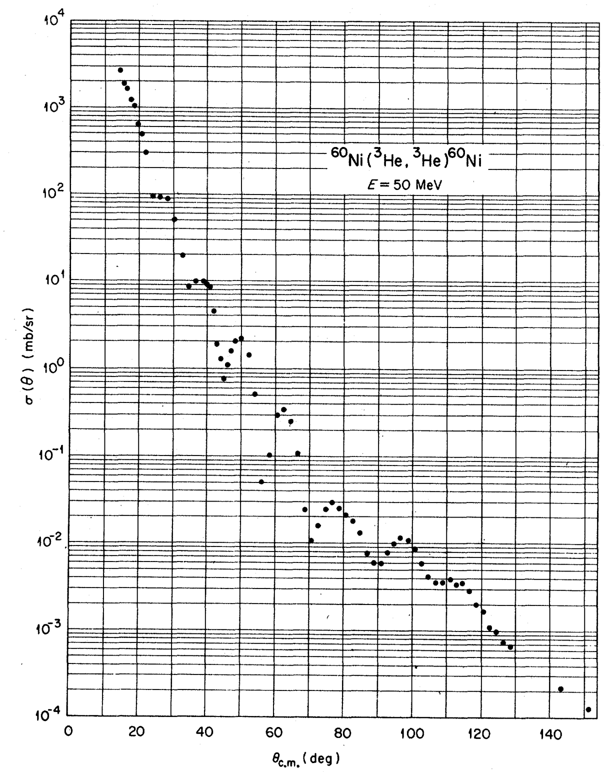

FIG. 1. Angular distribution for 49.7-MeV helion elastic scattering from ^{60}Ni.

fits to the data.

In neither of the studies reported in Refs. 4 and 5 did the analysis of data which extend into the backward hemisphere resolve the discrete ambiguities in the real well depth. One conclusion of the study of Ref. 4 is that analyses of higher-energy data are needed to determine the optical-model parameters more precisely.

Because large-angle helion elastic scattering cross sections are very small one must ask whether the optical-model formalism is applicable. In Ref. 5, data were obtained at 38 MeV for a number of medium-mass targets and for ^{58}Ni at 36.8, 37.4, 37.5, and 38.1 MeV. Smooth variations of the angular distributions with bombarding energy and target mass were observed and demonstrate that there are no significant contributions from compound elastic scattering or higher-order direct processes such as exchange reactions. These results suggest that it is justifiable to use the optical model to analyze large-angle helion elastic scattering at higher energy, although the cross sections are very small.

In the work reported here we measured 59.8-MeV helion elastic scattering angular distributions for ^{27}Al and ^{52}Cr. These data, which are part of a more extensive series of measurements in the energy region of 50–70 MeV, extend far into the backward hemisphere. We did an extensive optical-model analysis of the data in a search for systematic trends in the potential. The results indicate that the inclusion of large-angle data at sufficiently high energy removes the discrete ambiguity in the real well depth.

EXPERIMENTAL

The data were obtained by using a 59.8-MeV helion beam from the Oak Ridge isochronous cyclotron. Reaction particles were detected with ΔE-E counter telescopes that made particle identification possible and allowed separation of the pulses due to scattered helions from a strong background of α particles from (^{3}He, α) reactions. The data were stored in a two-dimensional ΔE-E array in the memory of a multichannel pulse-height analyzer. Each data array was processed by a digital computer to yield an energy spectrum of the scattered helions. The energy resolution was typically 300 keV full width at half maximum (FWHM) for transmission data.

The aluminum target was a piece of commercially available foil with a thickness of 1.08 mg/cm^2, as determined by weighing a large piece of the foil. The chromium target (99.9% ^{52}Cr) was determined to be 3.56 mg/cm^2 thick by measuring the energy loss of ^{210}Po α particles in passing through the target foil. After traversing the target the beam was stopped in a Faraday cup which served as a monitor. Another beam monitor consisted of a stationary particle detector mounted above the scattering plane at a scattering angle of 30°. This monitored the product of the beam intensity and target thickness.

To increase the rate of data accumulation two

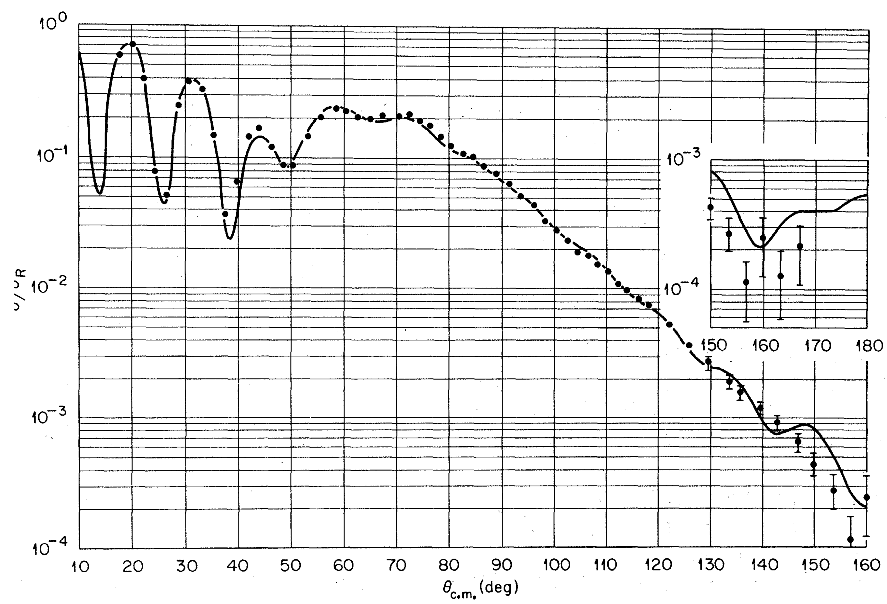

FIG. 2. Optical-model prediction compared with 59.8-MeV helion elastic scattering from ^{27}Al. The parameters for the optical-model prediction are listed in Table I.

detector telescopes were used. They were separated in scattering angle by 22°. Because of the large range of cross section (over 7 orders of magnitude) three different sets of collimators were used for the detectors. The solid angles ranged from 4.2×10^{-4} to 77.7×10^{-4} sr. The use of two detector telescopes and three sets of collimators resulted in considerable overlap of the data in several regions which served as a built-in check on the measurements.

OPTICAL-MODEL ANALYSES OF THE DATA

The 59.8-MeV ^{27}Al and ^{52}Cr data subtend the largest angular ranges in our present series of measurements and hence were selected for an extensive analysis in an attempt to learn something of the systematic trends of the optical-model parameters. The calculations used a local potential of the usual Woods-Saxon form to which was added the Coulomb potential from a uniformly charged sphere of radius $1.3A^{1/3}$ F. Almost all of the analyses were done with the code GENOA.[6] A few calculations for comparison were done with the code HUNTER.[7] An illustrative fit is compared with the ^{27}Al data in Fig. 2. The corresponding parameters of the potential are listed in Table I. The fit is reasonably good throughout the angular range of the data, both in magnitude of the cross sections and the structure of the angular distribution. The optical-model prediction also agrees with the data in the region of the angular distribution between ~70 and 130°, where the oscillations are very damped.

The starting values of the parameters, listed in Table I, were obtained from an earlier search on 29.6-MeV ^{27}Al-helion scattering data.[8] The most dramatic change between the starting and final values of the parameters in Table I is that of the real well depth. A number of earlier studies of helion elastic scattering at lower energies (e.g. Ref. 8) indicated discrete families of potentials at intervals of 40–50 MeV in the real well depth. The results summarized in Table I are thus surprising unless the discrete family ambiguity is removed for higher-energy data.

It was thus decided to fix V_S at 3.0 MeV and grid the real well depth at intervals of 10 MeV and minimize χ^2/N by varying the other parameters. Plots of χ^2/N vs V thus obtained are shown in Fig. 3. Gridding on V was done for the full angular range of the data and for forward-angle data only. For the latter the data beyond 71°, where there is a large exponentially decreasing region of very damped oscillations, was not included.

For the grid in which the full angular range of the data was used, only one deep minimum, at $V\sim120$ MeV, is observed in the plot of χ^2/N vs V in Fig. 3. For the grid in which only data forward of 71° were used, two deep minima are observed in the plot of χ^2/N vs V. These results suggest that at least some of the ambiguities are removed by the inclusion of large-angle data in the optical-model analysis.

TABLE I. Starting and final values of parameters in optical-model fitting of 59.8-MeV helion elastic scattering from ^{27}Al. The final values of the parameters were used to obtain the calculated angular distribution shown in Fig. 2.

Parameter	Starting value	Final value
V (MeV)	180	114
$r_R=r_S$ (F)	1.16	1.15
$a_R=a_S$ (F)	0.821	0.826
W_D (MeV)	18.5	18.8
r_I (F)	1.26	1.18
a_I (F)	0.770	0.820
V_S (MeV)	3.84	2.29

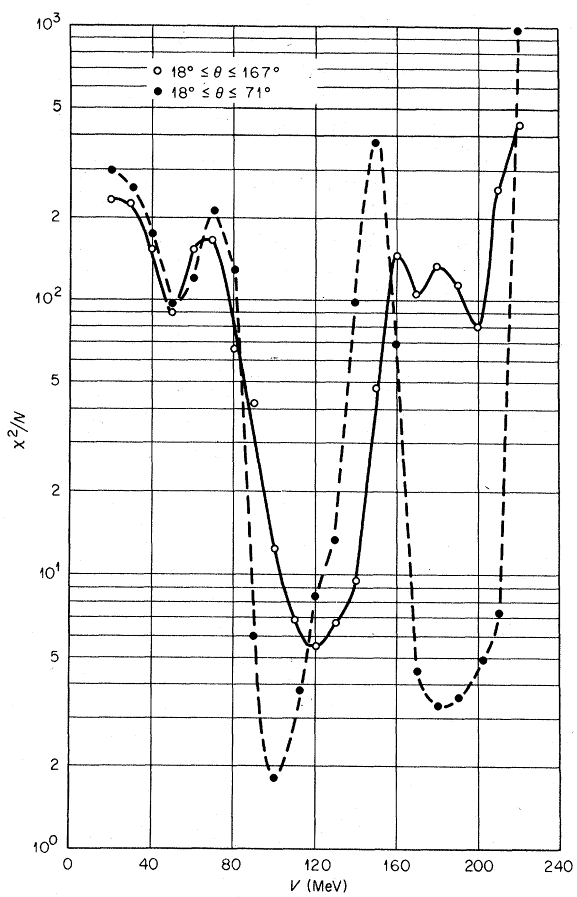

FIG. 3. χ^2/N vs V for 59.8-MeV helion elastic scattering data from ^{27}Al. Surface absorption was used in these searches and V_S was fixed at 3.0 MeV.

The discrete family ambiguity was not removed in Ref. 8 by the analysis of 29.6-MeV ^{27}Al-helion scattering data, although the data covered the angular range of $6.7 \leq \theta \leq 162.5°$. We thus decided to grid V and fit the 29.6-MeV ^{27}Al data to obtain a plot of χ^2/N vs V for the full range of the data. The resulting plot is shown in Fig. 4. We see, not a single deep minimum as in the case for our 59.8-MeV data, but two broad regions of almost constant χ^2/N. In these regions the "continuous ambiguity" is observed in which a change of the real-well-depth parameter is compensated by a corresponding change of the radius parameter for the real well. We note from Fig. 3 that when the full range of the 59.8-MeV data is used, not only is the discrete family ambiguity removed but also the continuous ambiguity is less evident.

In another series of parameter searches, gridding was done on the real radius parameter, r_R. The plot of χ^2/N vs r_R thus obtained is shown in Fig. 5. For each increase of r_R there was a decrease in the value of V, but the plot shown in Fig. 5 shows a clear preference for a real radius parameter near 1.12 F.

It may be noted that the preferred values of V and r_R obtained from gridding are slightly different from the values listed in Table I. In the gridding searches the value of V_S shown in Table I is lower and was obtained as a variable parameter in that search. The purpose of the gridding searches was to study systematics of the potential rather than to achieve the best possible fit to the data.

For the gridding searches that yielded the plots shown in Figs. 3 and 4 the surface-absorption term in the potential was used as a variable parameter and the volume-absorption term was set equal to zero. A number of earlier studies at lower energy had not indicated a clear choice between the two. We explored this part of the potential by also gridding on the real well depth, with the full angular range of the data, for our 59.8-MeV data, and for forward-angle data only for ^{27}Al. The resulting plot of χ^2/N vs V for the full angular range of the data is compared in Fig. 6 with the plot obtained by gridding with a surface-absorption term. In Fig. 7 the plots obtained for the forward-angle data are compared. The plots obtained for the forward-angle data, Fig. 7, show no strong preference for either absorption term and are consistent with the results of earlier studies. The plots obtained for which large-angle data were included and which are shown in Fig. 6, however, show a distinct preference for a surface-absorption term in the potential.

The 59.8-MeV ^{52}Cr-helion elastic scattering data obtained in this work subtend the angular range $18° \leq \theta \leq 149°$. Figure 8 shows a plot of χ^2/N vs V obtained from a gridding search with surface absorption for which the full range of the data was used. Gridding searches were also done with a volume-

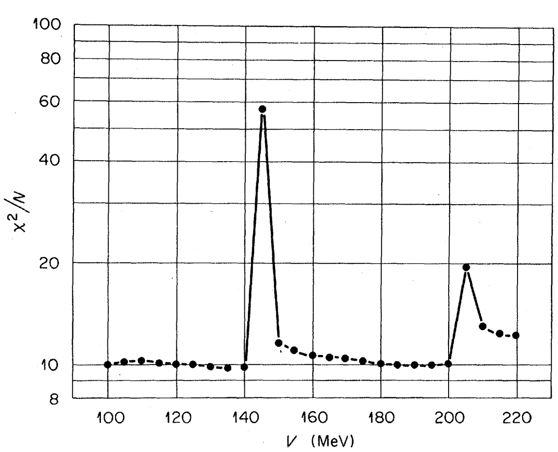

FIG. 4. χ^2/N vs V for 29.6-MeV helion elastic scattering from ^{27}Al.

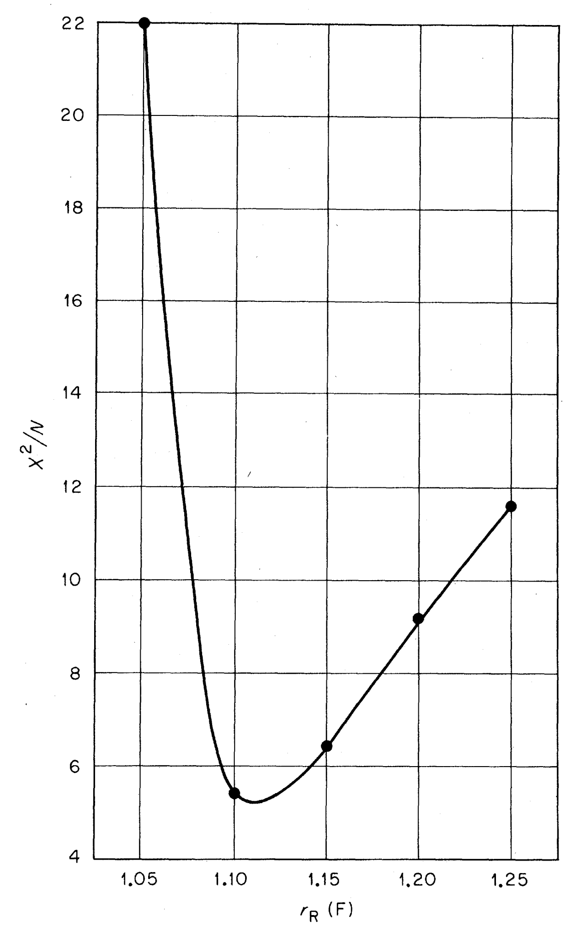

FIG. 5. χ^2/N vs r_R for 59.8-MeV helion elastic scattering from ^{27}Al.

absorption term rather than a surface-absorption term in the potential. For these the smallest value of χ^2/N was 26.3 at $V=120$ MeV, which is more than a factor of 10 larger than the smallest value of χ^2/N obtained with surface absorption. The evidence of a preference for surface absorption is thus somewhat stronger in the ^{52}Cr data than in the ^{27}Al data at 59.8 MeV.

The graph in Fig. 8 shows the deepest minimum at $V \sim 130$ MeV and another minimum at $V \sim 180$ MeV. On the basis of the smallest χ^2/N the gridding results show a preference for the $V \sim 130$-MeV potential, but the removal of the discrete family ambiguity is not as emphatic as in the case of the 59.8-MeV ^{27}Al data. While the ^{52}Cr data extend far into the backward hemisphere, the range of the data is ~18° less than that of the ^{27}Al data. In Fig. 9 we compare the ^{52}Cr data with angular distributions predicted by the optical model for the $V=130$-MeV and for the $V=180$-MeV potentials. (The parameters are listed in Table II.) Except at the minimum near 55° the principal differences in the two calculated angular distributions occur for $\theta > 130°$. From the trend of the data beyond 130° it appears that if the range of the data were extended to 165°, the minimum χ^2/N near $V=180$ MeV would be somewhat larger than the value shown in Fig. 9 and there would be a more pronounced removal of the discrete family ambiguity.

A number of earlier studies (e.g. Ref. 8 and Table 4 in Ref. 2) have indicated the need for inclusion of a spin-orbit term in the potential, especial-

TABLE II. Optical-model parameters for 59.8-MeV helion scattering from ^{52}Cr. The two sets of parameters correspond to the minima in the plot of χ^2/N vs V shown in Fig. 8. V_S was fixed at 3.0 MeV.

Parameter	$V=130$ MeV	$V=180$ MeV
$r_R=r_S$ (F)	1.07	1.11
$a_R=a_S$ (F)	0.833	0.728
W_D (MeV)	20.3	25.6
r_I (F)	1.23	1.07
a_I (F)	0.818	0.924

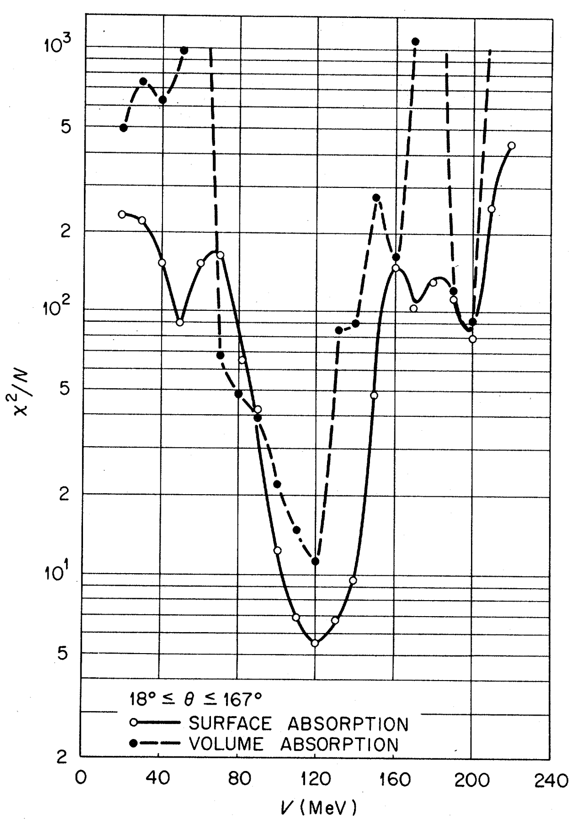

FIG. 6. χ^2/N vs V for 59.8-MeV helion elastic scattering from ^{27}Al for potentials with either volume or surface absorption.

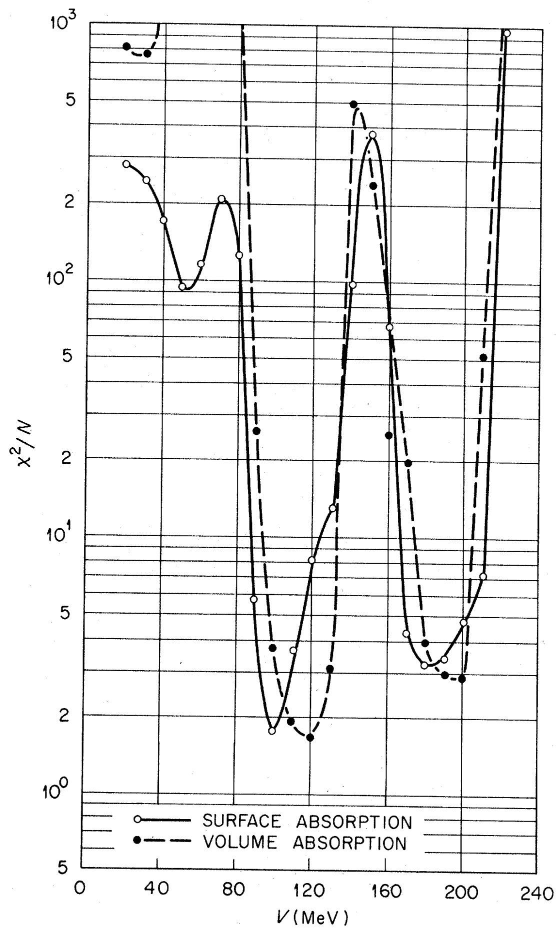

FIG. 7. χ^2/N vs V for forward-angle 59.8-MeV helion elastic scattering from ^{27}Al.

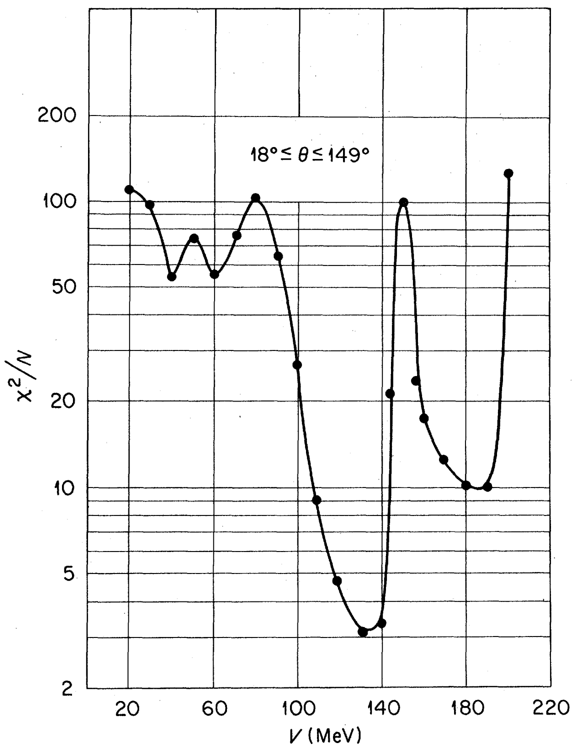

FIG. 8. χ^2/N vs V for 59.8-MeV helion elastic scattering from ^{52}Cr. Surface absorption was used in these searches and the value of V_S was fixed at 3.0 MeV.

ly when the data extend to large angles. The depth of the spin-orbit potential, however, has not been very well determined. In the present studies we explored this question by gridding V_S and obtaining plots of χ^2/N vs V_S. Figure 10 shows plots thus obtained for the 59.8-MeV data for ^{27}Al. For the plot obtained by using the full angular range of the data the minimum occurs for V_S slightly larger than 2 MeV and is consistent with the value of V_S (= 2.3 MeV) obtained from a seven-parameter search and listed in Table I. For the gridding on V_S in which only the data forward of 71° were used, there is very little variation in χ^2/N for V_S less than 4 MeV.

In Fig. 11 the 59.8-MeV ^{27}Al data are compared with the optical-model predictions for the parameter set listed in Table I (for which the value χ^2/N is a minimum) and for the parameter set obtained for $V_S = 0$ in the gridding of V_S with forward-angle data. The starting values of the parameters, other than V_S, used for the gridding of V_S are the final values listed in Table I. For the gridding with forward-angle data there were some adjustments of the parameters that resulted in slightly improved fits to the forward-angle data. The large-angle portions of the two curves shown in Fig. 11 are very different; only the one with $V_S = 2.3$ MeV agrees with the large-angle data. These results show, we believe, the importance of large-angle

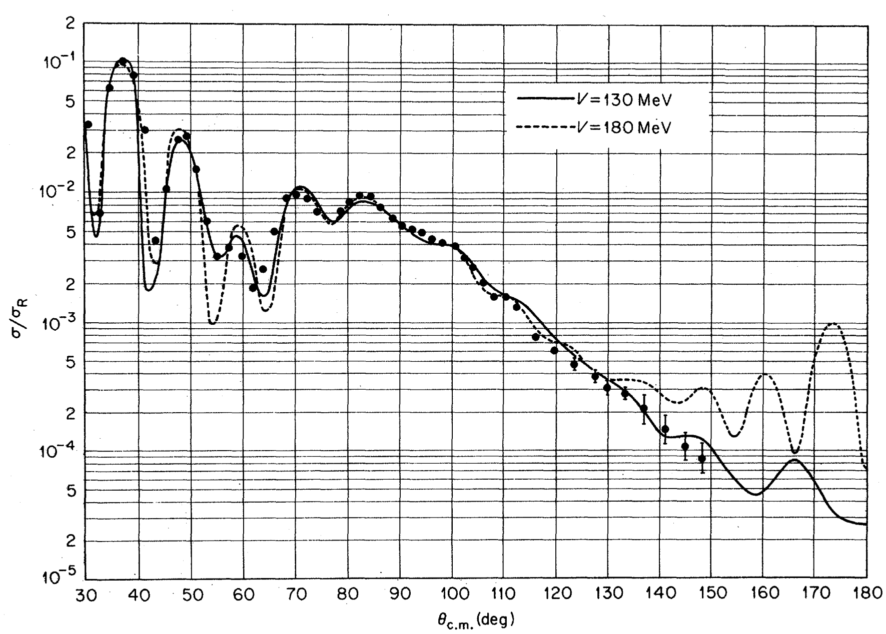

FIG. 9. Optical-model predictions compared with 59.8-MeV helion elastic scattering from ^{52}Cr.

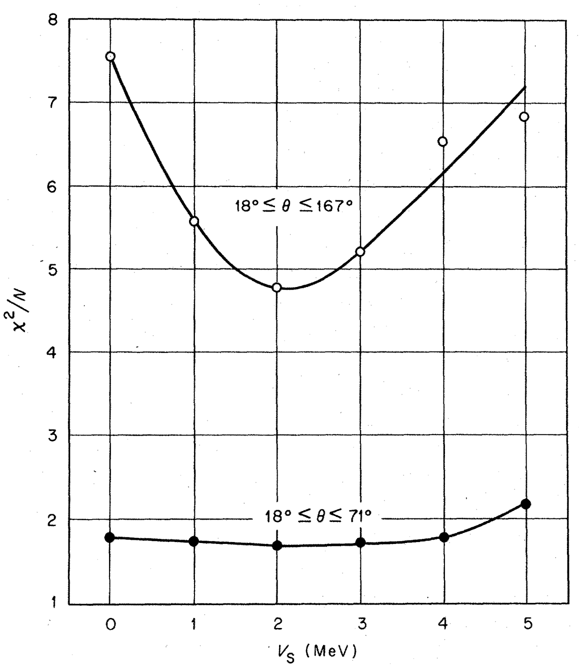

FIG. 10. χ^2/N vs V_S for 59.8-MeV helion elastic scattering from ^{27}Al.

data for demonstrating the need for a spin-orbit term in the optical-model potential and for determining the depth.

A plot of χ^2/N vs V_S obtained by gridding V_S for the ^{52}Cr data is shown in Fig. 12. For these calculations the full range of the data, $18° \leq \theta \leq 149°$, was used. The minimum in the plot occurs for $V_S \sim 2.5$ MeV. A more extensive study of V_S values obtained by gridding with data from a number of other targets will be discussed in a later paper.

A number of studies of elastic scattering of strongly absorbed particles[9-14] have given evidence for suitable potentials with a real well depth below 40 MeV. Some of the studies indicate a preference for the shallow well. Examples are the work of Bingham, Halbert, and Bassel[9] for forward-angle 65-MeV α scattering and the recent work of Watson *et al.*[13] on α scattering over a wide angular range at energies from 0.6 to 1.2 times the classical Coulomb barrier height. The usefulness of the techniques described in Ref. 13 was found to be limited to cases where absorption is small or ineffective.

The plots of χ^2/N vs V (Figs. 3, 6, 7, and 8) for our 59.8-MeV data show no evidence of a deep minimum below 40 MeV. For the full-angular range of the ^{27}Al data searches were made for fixed values of V at 2-MeV intervals between 14 and 40 MeV. For no value of V in this region was a value obtained for $\chi^2/N < 100$. In every case reasonably good agreement was obtained between the data and the optical-model prediction for $\theta \lesssim 50°$. For larger angles no reasonable agreement was obtained for potentials with a shallow real well.

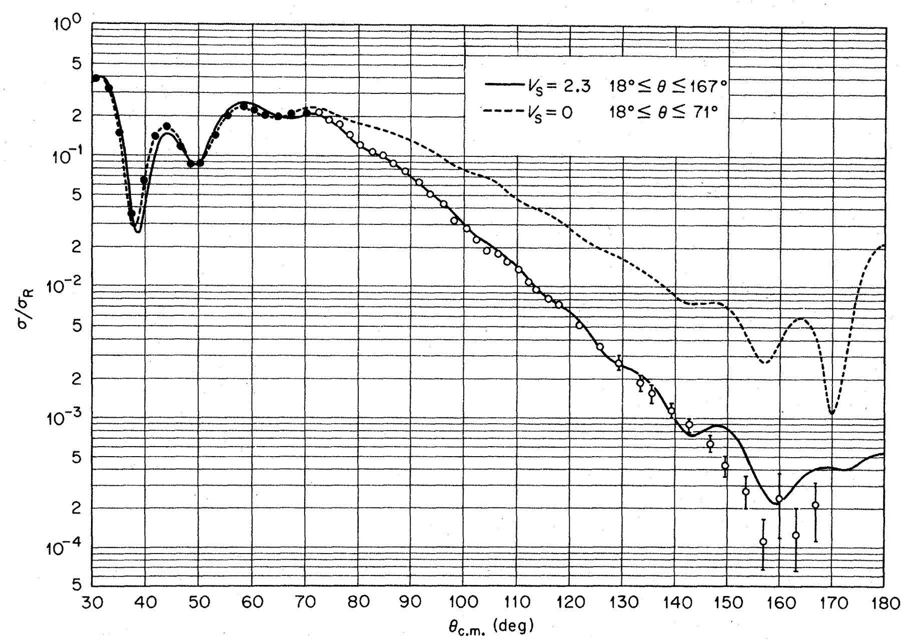

FIG. 11. Optical-model predictions compared with the 59.8-MeV helion elastic scattering from ^{27}Al. The curve labeled $V_S = 2.3$ is the same as that shown in Fig. 2.

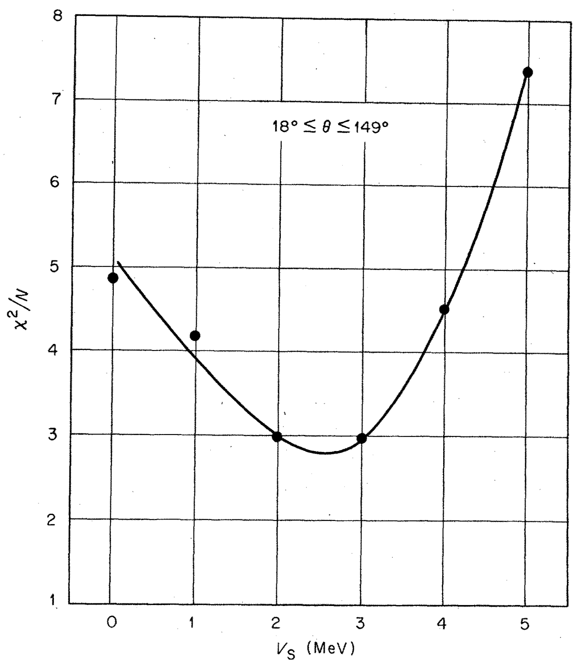

FIG. 12. χ^2/N vs V_S for 59.8-MeV helion scattering from ^{52}Cr.

DISCUSSION

The analyses described above demonstrate the importance of large-angle data of sufficiently high energy for a consistent set of parameters to describe the potential for helion-nucleus elastic scattering. The inclusion of large-angle 59.8-MeV data in the analysis results in a clear choice for a surface-peaked-absorption term, while the 29.6-MeV data for aluminum leaves ambiguous the choice of the absorption term. It appears that the higher-energy particles penetrate the nuclear surface enough to be more sensitive to the details of the potential. Similarly the particles scattered through large angles interact more strongly with the nuclear potential and hence reflect more of the details of the potential.

For the two targets studied the strength of the spin-orbit term is slightly larger than 2 MeV, which is reasonably consistent with the value indicated by the recent work of Urone *et al.*[5] In Ref. 3 evidence was presented for the existence of a target-spin dependence of helion elastic scattering. In the optical-model analysis of the data this dependence resulted in a larger value of V_S for ^{59}Co $(I=\frac{7}{2})$ than for ^{60}Ni $(I=0)$. The spin of the ^{27}Al nucleus is $\frac{5}{2}$ and, hence, there may be a target-spin dependence of the elastic scattering from that nucleus. This question will be explored in more detail in a later paper.

The discrete family ambiguity appears to be removed by the inclusion of large-angle data of sufficiently high energy. It is clearly removed for the 59.8-MeV data for ^{27}Al but not for 29.6-MeV data from the same nucleus. The results of gridding on V for the 59.8-MeV ^{52}Cr data show a preference for a value of V near 130 MeV similar to the preferred value for ^{27}Al. A comparison of Figs. 4 and 8 suggests that "sufficiently high energy" for removing the discrete family ambiguity may increase with target mass. The evidence from these studies indicate that the real well depth for helion-nucleus scattering is ~120–130 MeV.

The most encouraging result of this work is the demonstration that the analysis of large-angle data removes the ambiguities of the helion-nucleus potential. A good knowledge of the helion-nucleus interaction should make helions more useful as sensitive probes of the nuclear surface.

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*Research sponsored by the U. S. Atomic Energy Commission under contract with Union Carbide Corporation.

† Oak Ridge Associated Universities summer research participant from Washington University, St. Louis, Missouri, 1969 and 1970.

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