Angular Distributions of Elastically and Inelastically Scattered Protons from Indium*

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Thin targets of natural indium were bombarded with 7.04-Mev protons, and the scattered particles were analyzed with a magnetic spectrograph. Inelastically scattered protons were observed corresponding to excited states in In^{115} at 1.078, 1.135, 1.292, and 1.982 Mev. Measurements were made on the variation of the absolute cross sections for elastic and inelastic scattering, and it is concluded that a direct interaction process is important in the excitation of these states.

I. INTRODUCTION

PREVIOUS investigations, at somewhat lower bombarding energies than used in the present experiment, have shown that inelastic scattering in nuclei neighboring indium, including the several isotopes of cadmium, proceed mainly by Coulomb excitation.[1,2] Initial cross-section measurements on the inelastic scattering of protons from indium[3] were inconsistent with this excitation mechanism. The angular distribution of the inelastically scattered protons was measured in an attempt to obtain more information about the process.

The angular distribution of the elastically scattered protons was separately measured for the purpose of normalizing the inelastic measurements. The 7.04-Mev bombarding energy is about three-fourths of the barrier height of indium, and the elastic distribution deviates substantially from Rutherford scattering.

II. APPARATUS

The apparatus used in these experiments has been described in some detail in previous publications.[4,5] The source of protons was the MIT–ONR electrostatic accelerator. The protons scattered from the target were analyzed by a broad-range magnetic spectrograph. The unscattered part of the beam passed through the thin target and was collected in a Faraday cup and measured with a current integrator.

The targets were prepared by the evaporation in vacuum of spectroscopically standardized natural indium onto thin films of Formvar supported on wire frames. A tantalum boat was used in the evaporation procedure. Natural indium consists of 95.8% In^{115} and 4.2% In^{113}.

III. PROCEDURE

Angular Distribution Measurements

Long bombardments, generally 1000 to 3000 microcoulombs at a rate of about two or three hundred per hour, were made at each of six angles of observation: 45, 60, 75, 90, 106, and $117\frac{1}{2}$ degrees. The spectrograph field was adjusted so that the protons elastically scattered from indium appeared at the upper ends of the photographic plates used for detection. Four inelastically scattered groups, together with those groups representing protons elastically scattered from the lighter elements present in the target (carbon, nitrogen, oxygen, and sulfur in the Formvar backing), were recorded at positions on the plates corresponding to lower proton energies. Typical data are shown in Fig. 1.

The groups associated with elastic scattering from indium were so dense as to be uncountable in these long exposures. Short exposures were made in separate zones of the photographic plate such that these groups could be counted. A current integrating circuit was used to measure the total current collected in the Faraday cup during the exposures. The circuit was only approximately calibrated for absolute current measurements and was used only to determine the relative lengths of the short to the long exposures. By varying the field of the spectrograph, two short exposures could be placed in each of the two other zones of the photographic plate without interfering with each other. These exposures were generally made before, after, and either once or twice at intervals in the period of the long exposure. The consistency of the results of the various short exposures was checked to detect any variations in target thickness or current measurements during the experiment.

The total number of proton tracks in the various inelastic and elastic groups were counted. From these data, the ratio $R(\theta)$ of the inelastic to the elastic scattering cross sections at the various angles was obtained. A correction factor was applied to account for the variation in the spectrograph solid angle with distance along the plate. This variation arises because

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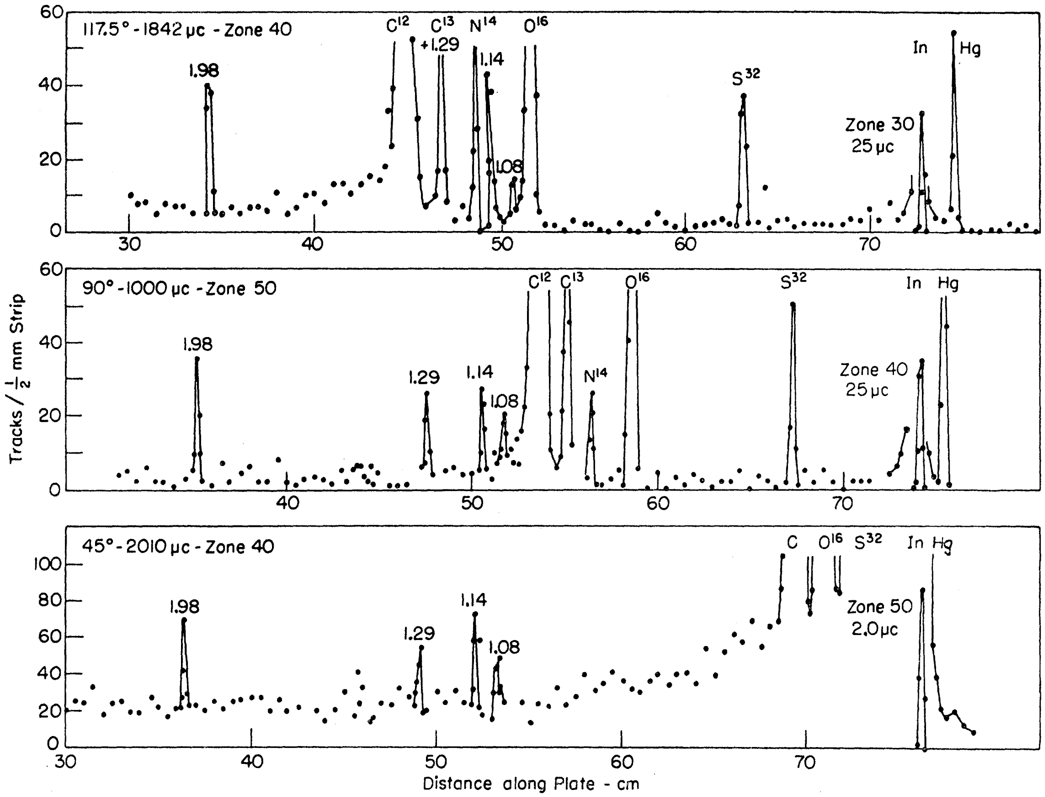

FIG. 1. Representative data for three of the angles observed in the angular distribution of inelastically scattered protons from In^{115}. The incident proton energy was 7.04 Mev. Peaks corresponding to elastically scattered protons are marked with the elements from which they are scattered. Peaks corresponding to inelastic scattering in In^{115} are marked with the energy of the corresponding level. In the position of the (uncountable) indium elastic peaks are shown the peaks obtained from one of the short exposures made to normalize the data. The exposures are given in microcoulombs (μcoul).

different positions on the plate correspond to different trajectory lengths in the magnetic field and, hence, different distances from the target. A geometrically derived correction factor was verified by measuring the variation in intensity of the elastically scattered group from a thin gold target as it was moved along the plate in 5-cm steps by varying the spectrograph field.

Since the inelastic scattering experiments were done with several different targets, it was necessary to relate the results of these measurements at the various angles by the measurement of the angular variation of the elastic cross section at this same energy. For this measurement, the target was inclined at 45 degrees to the beam. For the forward angles of observation from 30 to 90 degrees, the protons scattered through the target were examined. For the back angles from 90 to 130 degrees, the target was rotated by 90 degrees, and the protons scattered from the bombarded side were examined. The two runs were normalized to each other at 90 degrees. Exposures were made at the same angles as in the inelastic measurements. Two exposures were made at each position and each of the two runs was started and finished at 90 degrees. Thus, any changes in the target or the current measurements would have been detected. A total of eight exposures were made at 90 degrees, the normalizing angle. The exposures were adjusted so that approximately 3000 tracks were in each peak. This is about the maximum number that can conveniently be counted with peaks of the width used in these experiments. The number of protons observed in the two exposures at each angle agreed with each other within the expected statistical variation, and the totals were used in the calculations. The resultant curve of the angular distribution of the elastic scattering cross section was used with the inelastic measurements to obtain the relative angular distributions of the inelastic cross sections:

$$\frac{d\sigma_i(\theta)}{d\Omega} \approx R(\theta)\frac{d\sigma_e(\theta)}{d\Omega},$$

where $d\sigma_i(\theta)/d\Omega$ = relative differential inelastic cross section at the angle θ, $d\sigma_e(\theta)/d\Omega$ = relative differential elastic cross section at the angle θ, and $R(\theta)$ = experimentally determined ratio of the inelastic to the elastic scattering cross section at the angle θ.

A careful alignment of the spectrograph had previously been performed to insure that the beam spot was on the axis of rotation of the magnet[5] so that the solid angle subtended by the spectrograph did not vary with the angle of observation. As a further check on this important factor, as well as on the general experimental techniques, the angular distribution was essentially repeated at 5.0 Mev with a thin gold target. Exposures were taken only at the extremes of the distribution: two at 45 degrees; four at 90 degrees, the normalizing angle for the target shift; and two at 130 degrees. The results were compared with Rutherford scattering which should be completely dominant in this region, and within the experimental errors were in agreement with its predictions.

IV. ABSOLUTE MEASUREMENTS

The cross-section measurements were made absolute by experimentally determining the ratio of the elastic scattering cross section at the various angles to the cross section for Rutherford scattering. At sufficiently low energies and small scattering angles, the deviations of the elastic cross section from Rutherford scattering become negligible, and the absolute cross section can be calculated.

The angular variation of the elastic scattering cross section at 7.04 Mev was found to approach the predictions of Rutherford scattering at the forward angles, as can be seen in Fig. 2. Protons scattered to these angles have made collisions characterized by large impact parameters and thus are least affected by the short-range nuclear force. At these forward angles, it was assumed that the magnitude of the cross section, as well as its angular variation, was given by the Rutherford scattering formula.

The variation with energy of the 90-degree elastic scattering cross section was measured from 7.0 Mev down to 5.0 Mev, where the characteristic $1/E^2$ dependence of Rutherford scattering was observed. The relative cross section (times E^2) is shown in Fig. 2. Because of the presence of some unexplained data outside the expected statistical deviations, the experiment was repeated with the aid of a scintillation counter inserted in the spectrograph in place of the plateholder. Points were taken at 25-kev intervals in order to determine whether or not there were any sharp resonances in the elastic scattering cross section. No such resonances were found, and the counter data were in agreement with the solid curve shown in the figure. This figure shows the data from the photographic plate measurements only. No satisfactory explanation for the variations in the region of 6.5 Mev was found. The elastic cross section at 7.04 Mev is 11% below the Rutherford scattering cross section as determined by the asymptotic portion of the curve. This is to be compared with 9% from the corresponding point of the angular distribution. This is considered to be within the experimental errors.

Each of these two procedures effectively measures

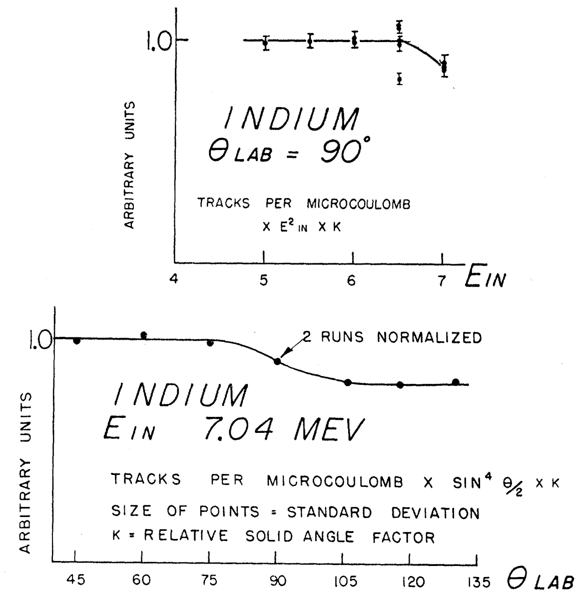

FIG. 2. Elastic cross-section measurements on In^{115}. The upper curve shows the variation of the 90-degree elastic cross section with energy. The Rutherford scattering energy dependence of $1/E_{in}^2$ has been removed. The lower curve shows the variation of the 7.04-Mev elastic cross section with angle. The Rutherford scattering angular dependence of $1/\sin^4(\theta/2)$ has been removed. The size of the points represents the standard deviation of the data. K is a factor correcting for the change in the solid angle subtended by the spectrograph with the distance along the plate at which the peak is recorded.

the product of target thickness and the spectrograph solid angle for the conditions of the elastic exposures.

As a check on the results of the previous procedures, a direct determination of the absolute elastic cross section was made at 7.04 Mev and 90 degrees, using a weighted target and absolute current measurements. For this a layer of indium was evaporated onto an aluminum foil through a circular aperture of known radius in a brass shield. The foil, together with a control foil which had been shielded during the evaporation process, was weighed both before and after the evaporation. The weight of the control foil remained constant. The radius of the circular area of indium on the foil was checked in a microscope equipped with a traveling stage whose movement was measured by a dial gauge. It agreed with the measurements on the brass shield.

The foil was mounted on a rigid target rod projecting through the roof of the target chamber with a 7-in. diameter protractor mounted on its top, and the angle of the foil to the beam line was carefully set.

The current integrating circuit previously described was replaced by a system designed to make absolute current measurements, in which a charged condenser was discharged by the beam current. A Lindemann electrometer examined with a low-power microscope was used as a null instrument to determine when the condenser was completely discharged. The exposure length was set by the voltage to which the condenser was initially charged. This voltage was measured with a precision voltmeter.

The solid angle subtended by the spectrograph was calculated from the slit system dimensions assuming simple trajectories. This assumption is justified by the coincidence of the experimental and geometrically calculated relative solid-angle curves of the spectrograph (see section on angular distributions). If the fringing field had any large effect on the trajectories, it would presumably affect the relative as well as the absolute solid angle. The total number of tracks in the indium elastic peak were counted, and the absolute cross section was computed from the following expression:

$$\sigma=\frac{C}{\omega\rho N}\left(\frac{\cos\theta}{t}\right),$$

where C is the total number of tracks in the peak, ρ is the number of indium atoms per cubic centimeter in the target, θ is the angle between the beam direction and a normal to the target, $(t/\cos\theta)$ is the effective target thickness, ω is the solid angle of acceptance of the spectrograph in steradians, and N is the number of protons in the incident beam throughout the exposure.

The average of the results of three different exposures at 7.04 Mev and 90 degrees gave a cross section 12% below the value expected from Rutherford scattering. This is in surprisingly good agreement with the other measurements. Considering the weighing uncertainties, nonuniformity of the target, current integration errors, and the uncertainty in target angle, a probable error of about 10% is estimated for this measurement.

The first two procedures for the determination of the absolute cross section are expected to be more precise, since the above factors do not enter. The important uncertainties in these measurements are felt to be the uncertainty in the relative solid angle determination which was used as a correction, errors in the shorter exposure which were due to the finite time necessary to turn off the beam (the current integrator read to the next lower tenth of a microcoulomb), and the statistical deviations in the peaks. This statistical uncertainty is shown plotted in Fig. 2.

V. RESULTS

Four groups of protons were observed whose energies varied with angle of observation and incident energy in the manner to be expected for inelastic scattering from indium. On the basis of intensity, it is assumed that the groups arose from In^{115} (abundance 95.8%). The energies of the corresponding excited states are 1.078, 1.135, 1.292, and 1.982 Mev. The estimated precision of these measurements is ± 10 kev.

Many levels have previously been observed in indium in various processes, such as β decay of Cd^{115},[6] inelastic neutron,[7] alpha,[8] and photon[9] scattering, and Coulomb excitation.[10] The correspondence in energy values among the results of the various experiments is not good, and it is difficult to determine which of the levels reported are actually the same.

The 1.292-Mev level observed here has been observed in the β decay of Cd^{115} and identified as an $11/2^+$ state.[6] The 1.078-Mev level could correspond to the 1.04 ± 0.02-Mev level reported by Waldman and Miller from a (γ,γ') process.[9] The 1.135-Mev level may correspond to the 1.15-Mev gamma ray of unspecified origin seen by Scherrer, Allison, and Faust[11] after neutron bombardment of indium. Day *et al.*[7] report a 1.11-Mev gamma ray from inelastic neutron scattering that could correspond to either of the levels seen here at 1.078 or 1.135 Mev.

The variations of the absolute cross sections for inelastic scattering, $d\sigma_i(\theta)/d\Omega$, are shown in Fig. 3. The values were calculated from the expression

$$\frac{d\sigma_i(\theta)}{d\Omega}=\frac{R(\theta)S(\theta)}{I}\frac{d\sigma_R(\theta)}{d\Omega},$$

where I is the isotopic abundance, $S(\theta)$ is the experimentally determined ratio of the elastic scattering to the Rutherford scattering cross section at the angle θ, and $d\sigma_R(\theta)/d\Omega$ is the calculated Rutherford scattering cross section.

As can be seen in Fig. 1, the cross sections for inelastic scattering were so low that at some angles various of

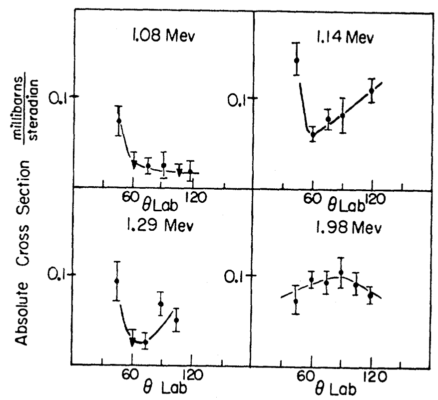

FIG. 3. Experimental angular variations of cross sections for inelastic proton scattering in In^{115}. The incident proton energy was 7.04 Mev. The bars through the points represent standard deviations. For the angles indicated by the arrows, only upper limits are indicated. The curves are drawn for the best fit to the data.

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the groups were close to the lower limit of detectability of the equipment, and targets thin enough to give a sharp peak distinguishable from the background resulted in yields almost too low to be observed. Because of the increasing background with decreasing angle, no usable data were obtained for angles less than 45 degrees. Over the angular range covered, three peaks were obscured by the background, and upper limits for the corresponding cross sections were calculated. These points are indicated by arrows in Fig. 3. For the other points, the standard deviations are plotted. The curves are drawn for the best fit to the data.

The major errors involved in the inelastic scattering measurements were due to the statistical uncertainties and the error involved in estimating the background to be subtracted from the peaks. An idea of the magnitude of this error can be obtained from Table I, where the percentage change in cross section for a 25% error in the background estimate has been computed for some typical exposures.

VI. CONCLUSIONS

Inelastic scattering is expected to proceed via one or more of three mechanisms; Coulomb excitation, compound nuclear formation, and direct interaction. The only Coulomb excitation processes of sufficient probability to be considered here are electric dipole and quadrupole transitions. An estimate of the electric dipole transition probability can be made for single-particle transitions in a spherical well.[12] Neglecting spin factors and other factors of the order of unity, one obtains $B(E1)/e^2=0.8\times10^{-26}$ cm^2. Collective effects would be expected to decrease this value.

An example of the expected angular distributions calculated with the semiclassical Coulomb excitation theory of Alder and Winther,[13] using this transition probability, is shown in Fig. 4. Only the 1.078-Mev level could be fitted with a dipole distribution, and this would involve using the upper limit of the transition probability. In practice, the relatively few electric dipole transitions that have been observed have had transition probabilities from 10^{-3} to 10^{-7} of this limit.[14]

A similar single-particle estimate can be made for the electric quadrupole transition probability, yielding

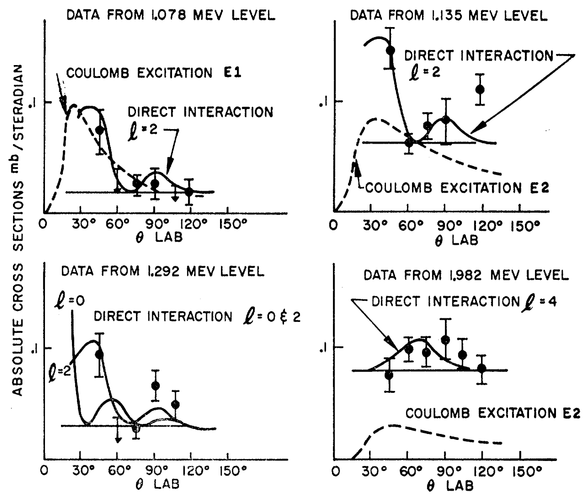

FIG. 4. Theoretical curves calculated for the angular distributions of inelastically scattered protons in In^{115}. The direct interaction curves are calculated for $r_0=1.9\times10^{-13}$ cm. An arbitrary isotropic background has been added. The $E1$ Coulomb excitation curves are claculated for a reduced transition probability corresponding to the single-particle limit $B(E1)/e^2=0.8\times10^{-26}$ cm^2. The $E2$ Coulomb excitation curves are calculated for a reduced transition probability $B(E2)/e^2=0.1\times10^{-48}$ cm^4 as estimated from the properties of neighboring nuclei. For comparison, the experimental points of Fig. 3 are repeated.

$B(E2)/e^2=0.008\times10^{-48}$ cm^4. In this instance, collective effects are expected to enhance the transition. Indium is in the region of the periodic table in which nuclei have approximately spherical equilibrium shapes and collective excitations take the form of vibrations. If one neglects the coupling between the intrinsic nuclear motion and the vibrations, one can obtain an estimate of the reduced quadrupole transition probability from the vibrational parameters of neighboring even-even nuclei. Using the one-phonon quadrupole excitation probabilities of the even-even cadmium isotopes,[13] one obtains a reduced transition probability of approximately $B(E2)/e^2=0.1\times10^{-48}$ cm^4, again neglecting spin factors of the order of unity. Theoretical distributions calculated with this value are shown in Fig. 4 for the 1.135- and 1.982-Mev levels. The $E2$ process could contribute more or less to the cross sections of the four states, but the shapes of the measured distributions for levels 2 and 3, in particular the minima at about 75 degrees, indicate the importance of other mechanisms in the excitation of these states.

On the basis of the statistical model, the angular distribution for a reaction proceeding through the compound nucleus is expected to be symmetric about 90 degrees if the compound nucleus is formed in a region of many broad overlapping states whose various phase relations cancel each other. For a nucleus as heavy as Sn^{116} at an excitation of 18 Mev, the compound nucleus might be expected to be of this nature. The shape of the distribution for the 1.982-Mev level and perhaps for the 1.078-Mev level could be accounted for by this mechanism or by a combination of this mechanism and

TABLE I. Percentage change in inelastic cross sections for 25% error in background estimate.

θ (deg)	Levels in Mev 1.98	1.29	1.14	1.08
117.5	8	...	6	55
90	4	9	15	36
45	35	45	20	46

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$E2$ Coulomb excitation. Under the statistical assumption, interference effects between these processes will cancel, and the asymmetric distributions for levels 2 and 3 cannot be accounted for in this way. The most likely alternative explanations are the breakdown of the statistical assumption in this region, with the reaction proceeding through the compound nucleus and with interference effects causing the asymmetric distributions, or the breakdown of the compound nucleus assumption, with a direct interaction process becoming important.

An estimate of the expected contribution of compound nucleus formation to the reaction can be made from the cross section for compound nucleus formation calculated from the penetration of the Coulomb barrier.[15] If one estimates the level densities of the various relevant residual nuclei from the Fermi gas model, one can calculate the expected proton-to-neutron emission ratio.[16] This approximation is undoubtedly not accurate in this energy range but can serve as an orientation with respect to magnitudes.

The expected total cross section for proton emission to all available levels can be estimated in this way to be roughly 0.05 millibarn. By estimating average values for the measured cross sections extrapolated through 180 degrees, one obtains a total proton emission cross section of roughly 3 millibarns. It thus appears likely that the contribution to the distributions from compound nucleus formation is small.

Direct interaction, the third process considered, results in distributions characterized by large forward maxima for low angular momentum transfers. The angular distributions are functions of the orbital angular momentum transfer involved in the interaction, and an interaction radius parameter $r=r_0A^{\frac{1}{3}}\times10^{-13}$ cm. The parameter r_0 is usually somewhat larger than the value for the nuclear radius obtained from other methods.[17]

The spin and parity of the 1.292-Mev level have been determined[6] from the β decay of Cd^{115} as $11/2^+$. Thus, the direct interaction process can take place only with even l values 0, 2, . . . , etc. The best fit to the experimental distribution, using a radius parameter in the usual range for direct interaction, is obtained with $r_0=1.9$. The shape of the experimental distribution can be accounted for by either an $l=2$ interaction or some combination of $l=0$ and 2 interactions. The curves are shown in the figure as computed from the theory of Austin *et al.*[18] They are plotted with an isotropic background added.

The results of attempts to fit the other distributions using the same value of the radius parameter r_0 are also shown in the figure. One obtains values of 2 and perhaps 0 for the 1.078- and 1.135-Mev levels. The 1.982-Mev level distribution is more or less isotropic, although it could have a small amount of $l=4$ or higher.

These values should not be taken too seriously, since the theory is not expected to give precise angular distributions in a region where interference effects with competing processes are likely to be important. This fact, coupled with the experimental uncertainties, makes any assignments rather doubtful. Qualitatively, however, it is reasonable to expect that the forward maxima of the experimental distributions can be accounted for by an interaction mechanism of this type.

In conclusion, it appears more likely that the distributions with the characteristic forward maxima for three out of four levels are caused by a direct interaction process rather than by chance phase relations among the levels in the compound nucleus. This and the large magnitudes of the cross sections, in comparison to the expected compound nucleus values, indicate that the direct interaction process is probably important in the formation of these states.

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