Differential Cross Section for Proton-Helium Scattering near 17.5 Mev*

KARL W. BROCKMAN, JR.
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
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The differential cross section for the elastic scattering of 17.45±0.2-Mev protons by helium has been measured at 33 angles between the center-of-mass angles 6.4 to 168 degrees. An external beam of protons from the Princeton cyclotron was scattered by helium gas in the interior of the Princeton 60-inch precision scattering chamber, scattered particles being detected in a potassium iodide scintillation counter. Values found for the cross section are considered to have an over-all accuracy of 2% except at the smallest angles where the error was larger due to experimental difficulties. The resulting data have been analyzed in terms of phase shifts of the S, P, D, and F waves with the following results: S, $-100.7°$; $P_{3/2}$, $81.2°$; $P_{1/2}$, $36.4°$; $D_{5/2}$, $157.8°$; $D_{3/2}$, $10.9°$; and F, $1.2°$. These values provide a least-squares fit to the experimental curve.

I. INTRODUCTION

EXPERIMENTS on the elastic scattering of protons by helium have been performed at different energies during the past several years. The effort that has gone into this study has been rewarded by the information it has given concerning the level structure of Li^5 and the nature of spin orbit interaction. While there were some earlier proton-helium scattering experiments,[1–4] those on which the latest analyses are based are the ones by Freier, Lampi, Sleator, and Williams[5] between 0.95 Mev and 3.58 Mev, by Kreger, Jentschke, and Kruger[6] at 5.78 Mev, and by Putnam[7] at 9.48 Mev. Analyses of these results in terms of nuclear phase shifts were performed for the work of Freier *et al.* by Critchfield and Dodder[8] and for that of Kreger *et al.* and of Putnam by Dodder and Gammel.[9] The phase shifts have been interpreted in terms of energy levels of the compound nucleus Li^5 according to the Wigner-Eisenbud formalism by Adair[10] and by Dodder and Gammel,[9] and more recently they have been treated in terms of a potential interaction between the proton and the alpha particle core by Sack, Biedenharn, and Breit.[11] The only experiment at energies greater than those mentioned is that by Cork[12] at 31.6 Mev; however, there has been no published analysis of those data.

The experiment described in this paper seeks to extend the information gained from the lower energy work by using incident protons of energy near 17.5 Mev. The differential cross section was measured with an over-all absolute accuracy of approximately 2% between center-of-mass angles 6° and 168°, and the results have been analyzed in terms of the nuclear phase shifts.

II. DESCRIPTION OF EXPERIMENT

Measurement of the cross section was carried out by fairly standard techniques using helium gas as the target and detecting the scattered protons in a potassium iodide scintillation counter. The 17.5-Mev incident protons were accelerated by the Princeton frequency modulated cyclotron and were focused on the entrance slit of a scattering chamber 60 inches in diameter placed about 20 feet away in which the measurement was performed. This chamber is shown schematically (plan view) in Fig. 1, with the experimental setup for gas scattering. It was constructed at this laboratory by Yntema and White[13] for the precision measurement of angular distributions and has been described in detail by them. Its vacuum can has a 60-inch interior diameter and contains a circular table 57.27 inches in diameter equipped with radial arms to which detection apparatus may be attached. Lines on the edge of the table graduate its circumference in degrees, and by observing the graduations through a window in the vacuum can with a fixed microscope, the angular position of the counter arm may be known to within 2 minutes of arc as the table is rotated about its axis.

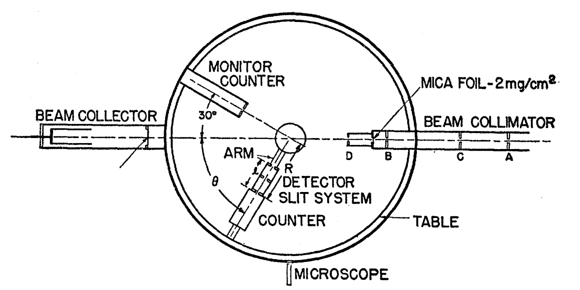

FIG. 1. 60-inch scattering chamber.

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Protons enter the chamber through a system of collimating slits. As shown in the figure, slits A and B, circular apertures 3.17 mm in diameter and 30 inches apart, define the proton beam while holes C and D of larger diameter serve as antiscattering baffles. A 2-mg/cm^2 mica foil placed between B and D isolated the vacuum of the cyclotron and beam tube from the target gas which filled the scattering chamber. The alignment of the scattering chamber was such that the axis of these collimators intersected and was perpendicular to the axis of rotation of the chamber's table.

A scintillation counter, consisting of a potassium iodide crystal fixed to the face of an RCA type $C7151$ photomultiplier tube, was set up on an arm of the scattering table to detect the scattering events. Pulses from the counter were amplified in a 501 amplifier and recorded with an Atomic Instruments scaler and register. An integral discriminator in the scaler was biased to eliminate low-lying background pulses due to gamma rays.

A rectangular slit with vertical sides, placed on the counter arm approximately 6 inches in front of the counter's aperture, defined the scattering region seen by the counter. With the table set at its zero graduation mark, the axis of these two slits was made to coincide with that of slits A and B; then the angle of rotation of the table from this position was the laboratory scattering angle. The space between the rectangular slit and the counter opening was enclosed with a brass cylinder to prevent protons scattered from other regions of the chamber than that defined by the slits from entering the counter; this tube carried a third slit of sufficient size not to interfere with the defining action of the other two as an antiscattering baffle.

The dimensions and spacings of the counter opening and the rectangular slit fix the values of the thickness of the gas target and the solid angle subtended by the counter opening from the region of scattering. The product of these two values averaged over the scattering path may be given approximately as

$$(Ad/Rl)\csc\theta,$$

where A is the area of the counter opening, d is the width of the rectangular slit, l is the distance between these two slits, R is the distance of the counter from the axis of rotation of the table, and θ is the scattering angle. The accuracy of the approximation depends on the dimensions used. For the work described here, it was good within 0.2% between the angles of 25° and 155°, and outside of this region corrections to the formula were applied. At angles less than 12°, where the change of cross section with angle is rapid, it was necessary to correct the data also for the curvature of the measured cross section on account of the finite angular resolution of the slits. The corrections were greatest at the smallest scattering angle (5°), where they amounted to about 12%, and dropped off rapidly with increasing angle; by 10° they were less than 1%.

Use of the two slit geometry and the variation of the size of the cross section at the different scattering angles caused it to be necessary to use three sets of the parameters A, d, l, and R to obtain reasonable counting rates in the course of the data taking. While an l of about 6 inches was used for all measurements, a value of R (about 11 inches) was used for the range of angles 55° to 155° smaller than that taken for the rest of the angles (18 inches) in order to increase the counting rate in that region. At angles less than 12°, it was necessary to decrease the width d and the diameter of the counter opening to about half their values at the larger angles (approximately 1 cm for each of these dimensions at the large angles) in order to decrease the counting rate. Slit dimensions were measured with a traveling microscope to within ± 0.001 cm, and R and l were measured with accuracies better than 0.01 inch with a 20-inch vernier caliper that could be read to 0.001 inch.

The density of the scattering centers in the gas target was found by measuring the temperature and pressure of the gas. Helium in the chamber was assumed to be in thermal equilibrium with the chamber walls and the reading of a mercury thermometer in good thermal contact with the chamber lid was taken as the gas temperature. Gas pressure was measured with a mercury manometer which was read with a precision cathetometer. The pressures used were generally between 25 and 50 cm although for a few runs smaller pressures were used, the minimum being about 14 cm. Commercially obtained helium gas used for the experiment was found to be of sufficient purity that no further purification was required. The assumption that impurities were absent was checked in the scattering at the smallest angles, where their effect should be greatest, by observing that there was no difference between runs in which the gas was admitted to the scattering chamber through a liquid air charcoal trap and runs in which no purification was used. In order to keep the helium free of impurities, the chamber was outgassed for at least 24 hours before scattering runs, then flushed with helium and re-evacuated before the target gas was admitted. The chamber's leak rate was measured and the gas was used only as long as the impurity level due to leakage remained negligibly small. Critical impurity levels had previously been determined by measuring the scattering from air.

Protons not scattered by the helium were collected in a Faraday cup housed in a compartment at the rear of the scattering chamber. The charge collected in the cup was measured with a current integrator described in the Yntema and White paper[13] to give the number of protons incident on the gas target during a scattering run. The compartment containing the cup was sealed off from the helium filling the chamber with a 1-mil aluminum foil and was drawn to a vacuum of 10^{-5} to prevent loss of charge from the Faraday cup by ion currents. A magnetic field of 1000 gauss in the region of the mouth of the cup was used to suppress secondary electron currents. To be sure that the spread of the beam due to multiple scattering in the gas and the foils was not so large that the cup failed to collect all the protons, the scattering of protons by a heavier gas (air), in which the beam spread increases rapidly with pressure, was measured at different gas pressures. The linearity of the relation between the measured scattering and the pressure assured that the collection was complete. Loss of protons due to this spread when the target was helium, in which multiple scattering is much less than in air, was estimated to be less than 0.2%.

The energy of the incident protons was determined by measuring their range in aluminum. Range measurements were made on protons scattered through a small hole in the chamber wall at $-10°$ by a platinum foil lowered into the beam between gas scattering runs, and the particles were detected in a proportional counter which was biased to detect only the particles producing maximum ionization. By this means the energy of the incident protons could be found within 80 kev. It was further determined that the mean energy of the protons delivered by the cyclotron varied over an interval 0.16 Mev wide. From these measurements and considerations of the factors causing variations of the energy, the energy of the experiment is quoted as 17.45±0.2 Mev.

TABLE I. Experimental values for the differential cross section for the scattering of protons by helium at 17.5 Mev, and the values for the cross section computed from the phase shifts that provide a least-squares fit.

	Experimental values		Calculated values	
θ_{cm} (degrees)	σ_{cm} (mb/sterad)	Estimated error %	σ_{cm} (mb/sterad)	% deviation
6.38	2510	3	2400	−4.5
7.62	1200	2.5	1141	−5.2
8.87	700	2.0	682.4	−2.5
10.11	475	2.0	463.2	−2.4
11.36	365	1.5	355.4	−2.6
12.60	308	1.2	299.1	−2.9
15.08	253	1.2	250.9	−0.7
17.56	235	1.2	233.9	−0.3
21.28	225	1.2	223.7	−0.4
24.98	219	1.1	216 9	−0.8
31.13	205	1.3	203.9	−0.4
37.23	186	1.2	187.4	0.9
43.29	165	1.3	168.1	2.0
49.28	140	1.3	147.3	5.1
55.20	120	1.2	125.9	4.9
61.05	98.2	1.4	104.9	6.8
66.82	79.9	1.3	85.07	6.5
72.50	64.7	1.4	67.07	3.7
78.09	48.8	1.5	51.33	5.2
83.58	37.0	1.5	38.08	2.9
88.96	27.1	1.5	27.42	1.2
96.31	16.7	1.6	16.68	−0.1
103.46	10.4	1.6	10.31	−0.8
110.38	7.57	1.8	7.586	0.2
117.08	7.64	1.7	7.752	1.4
123.58	10.2	1.6	10.10	−1.1
132.49	16.0	1.9	16.00	−0.2
141.06	23.1	1.9	23.62	2.1
145.20	27.5	1.9	27.66	0.7
149.28	31.2	1.6	31.67	1.4
157.22	39.3	2.0	39.10	0.5
164.96	45.4	1.8	45.06	0.8
168.01	45.9	1.5	46.88	2.1

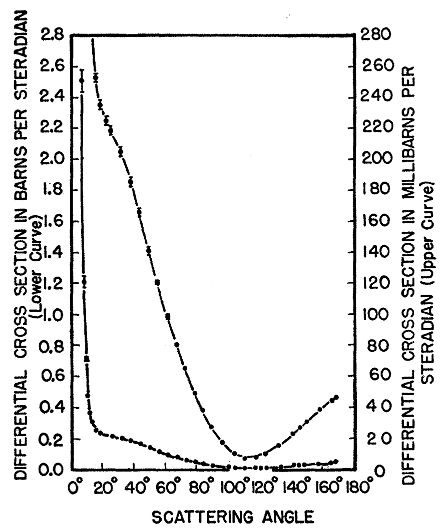

FIG. 2. Center-of-mass differential cross section for scattering of 17.45-Mev protons by helium. (Upper curve is 10 times the lower curve.)

The experiment consisted of the measurement of the differential cross section at 33 angles ranging from 5° to 164° in the laboratory system. At each of these angles between 5000 and 50 000 scattering events were counted. Background measurements were required in the extreme forward and backward directions. At the back angles, the energy of the scattered protons is low, and at the low discriminator biases necessary to record the proton pulses, some of the gamma ray background was included. These background pulses were counted separately by closing off the forward slit of the detection system with an aluminum shutter, thus removing the proton pulses. At angles less than 17° some protons scattered from structures in the chamber could enter the detector. This background was measured by evacuating the chamber and taking vacuum counts. Spread of the beam due to multiple scattering in the helium gas would tend to increase this small-angle background somewhat. How much was not determined though the effect was believed to be small, and consequently the error that was estimated for these points was increased.

The cross section and scattering angles were transformed into the center-of-mass coordinate system by means of a Lorentz transformation in order to account for relativistic effects. The differences between this and the nonrelativistic transformation amounted to only about 1% at most, however.

Results of the experiment are listed in Table I, which gives the center-of-mass differential cross section in millibarns per steradian for the various center-of-mass angles at which the measurements were made. The estimated error at each point is also included. A graph of the results is shown in Fig. 2, where the cross section has been plotted twice with the scale of the upper curve ten times that of the lower one. In Fig. 3, the cross section at 17.5 Mev is shown along with the results of some of the other experiments to show how they lie with respect to one another.

The errors arising in the measurements have been estimated as follows: error in the determination of the number of protons incident on the target, $\pm 0.5\%$; error due to variations of the energy of the incident protons during the experiment, $\pm 0.5\%$; error in the product of solid angle and target thickness due to errors in measurement and slit edge penetration effects, $\pm 0.3\%$; error in measurement of gas density, $\pm 0.1\%$. The statistical error arising in the counting of the scattering events varies from point to point, and lies within the range 0.5% to 1.6%. Thus it is estimated that the cross section has been found in general with an accuracy of better than 2%. Slightly greater errors have been estimated for the two smallest scattering angles where the corrections applied to the data were large.

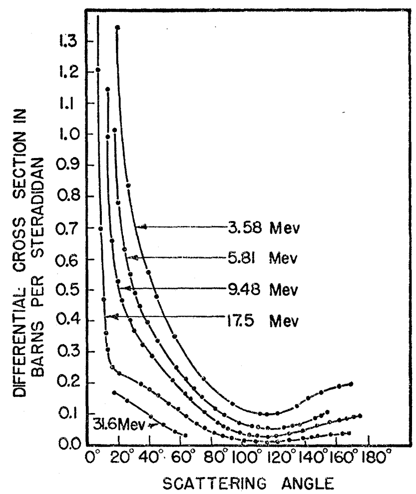

FIG. 3. Differential cross section for scattering of protons by helium at several energies.

III. PHASE SHIFT ANALYSIS

An important step to be taken, if possible, in the interpretation of nuclear scattering data is the analysis of the differential cross section in terms of phase shifts. If one uses the notation of the papers of Critchfield and Dodder[8] and Dodder and Gammel,[9] the expression for the differential cross section in terms of the phase shifts and as a function of the scattering angle and the incident energy is the following:

$$k^2\sigma(\theta)=\Bigg|-\frac{\eta}{2}\csc^2\left(\frac{\theta}{2}\right)\exp\left[i\eta\ln\csc^2\left(\frac{\theta}{2}\right)\right] +\sum_{l=0}^{\infty}\left[(l+1)\exp(i\delta_l^{+})\sin\delta_l^{+}+l\exp(i\delta_l^{-})\sin\delta_l^{-}\right] \times\exp(i\phi_l)P_l(\cos\theta)\Bigg|^2+\Bigg|\sum_{l=0}^{\infty}\left[\exp(i\delta_l^{-})\sin\delta_l^{-} -\exp(i\delta_l^{+})\sin\delta_l^{+}\right]\exp(i\phi_l)\sin\theta P_l'(\cos\theta)\Bigg|^2. \quad (1)$$

When a set of several phase shifts is required to fit the expression to an experimental curve, the problem of doing so becomes quite difficult because of the complexity of the formula. This is especially the case when the data are quite far removed in energy from previously analysed results, for then it is hard to guess where to look for the new solutions. The situation is complicated further by the possibility of the existence of more than one set of values for the phase shifts that fit the data, for in that case one must pick the physically significant set. In the work described here, one particular set of phase shifts was found, and from the manner in which it was determined, it is reasonable to think that it is the solution corresponding to reality. The method was as follows:

For the case of 17.45-Mev protons, the product of the wave number of the protons and the nuclear radius is about 2.4; therefore, one expects large S, P, and D phase shifts and an F phase shift that is small. Since F wave effects were assumed to be small, the first step was to locate the vicinity of the solution in terms of a set of five phase shifts for the partial waves S, $P_{\frac{3}{2}}$, $P_{\frac{1}{2}}$, $D_{\frac{5}{2}}$, and $D_{\frac{3}{2}}$. To do this, expression 1 was equated to the experimental cross section at five particular angles and a solution of the resulting set of five equations in the five unknown phase shifts were sought. The equations were set up in the variables described in the paper of Critchfield and Dodder,[8] with a suitable extension to include the two D phase shifts, using the following scattering angles: 90°, 54°44′, 125°16′, 25°, and 150°. The first three angles were chosen because at those angles the corresponding equations become considerably simpler. Now these equations, being nonlinear, are quite difficult to solve, and indeed the solutions were never found, but from them came estimates of the phase shifts. The procedure was roundabout. Values for the two P phase shifts were assumed and introduced into the equations; then it was possible to solve the equations for the remaining phase shifts and an additional pair of parameters that indicated how close the original guesses of the P phase shifts had been. Another pair of P phase shifts was then tried and so on until it appeared that a guess close to the solution had been made. The guesses for the P phase shifts were not made blindly, however, and it is here that the lower energy results were used.

A result of the work of Dodder and Gammel[9] is a graph of the logarithmic derivative of the two P-wave functions at the nuclear boundary *versus* energy. To the extent that the situation represented by these curves is that of resonance scattering from single $P_{\frac{3}{2}}$ and $P_{\frac{1}{2}}$ levels in the compound nucleus, the graphs are linear and may thus be easily extrapolated to predict what occurs at a higher energy. This then was the procedure for obtaining the original guesses of the P phase shifts used in solving the phase shift equations. By the extrapolation, the values of aY (nuclear radius $a=2.9\times10^{-13}$ cm times the logarithmic derivative Y) were -20.4 for the $P_{\frac{3}{2}}$ wave and -4.2 for the $P_{\frac{1}{2}}$ wave. Then, using the formula

$$aY=\frac{ka}{FG[1+(F/G)\cot\delta]}+ka\frac{F'}{F},$$

where k is the wave number, δ the phase shift, and F, G, and F' are Coulomb wave functions tabulated by Breit and his collaborators,[14] the $P_{\frac{3}{2}}$ phase shift, δ_1^+, and the $P_{\frac{1}{2}}$ phase shift, δ_1^-, were determined to be 67° and 32°, respectively. From this starting point, the solution that was obtained for the set of five equations was: $\delta_0=-107.6°$, $\delta_1^+=72°$, $\delta_1^-=36°$, $\delta_2^+=150.6°$, $\delta_2^-=7°$. This solution was not really good, for while the scattering curve plotted from it followed the experimental cross section fairly well for much of the range of angles, deviations as great as 25% occurred in the backward direction. Nevertheless, it provided a reasonable starting point for a more refined calculation, since the cross section at the back angles is particularly sensitive to the phase shifts.

A search was then made for a set of phase shifts providing a least squares fit to the experimental curve. Using an International Business Machines card-programmed electronic calculator, an iterative procedure was employed in which the phase shifts were changed from the initial value along the line of maximum gradient of the relative deviations from the experimental values. Six phase shifts were used to fit the data, the five previously used and δ_3, the phase shift for F-wave scattering with the constraint that the $F_{7/2}$ phase shift should be equal to the $F_{\frac{5}{2}}$ phase shift. The results were the following: $\delta_0=-100.7°$, $\delta_1^+=81.2°$, $\delta_1^-=36.4°$, $\delta_2^+=157.8°$, $\delta_2^-=10.9°$, and $\delta_2=1.2°$. Table I also gives the values of the cross section calculated using these phase shifts and the percent deviation from the experimental results. On examination of these values it is seen that the fit leaves something to be desired, for while the rms error is only 2.88%, there is a large systematic deviation (to about 7%) around the angles 43° to 83°. Aside from the possibility of a systematic experimental error, there are two possible causes for this deviation that come to mind. The first is that not enough phase shifts were used to fit the data. This could be investigated by first splitting the F-wave phase shifts to allow for the effects of spin orbit interaction, then, if necessary, adding some G-wave scattering. It was not considered worthwhile, however, to do this at this time. The other possible cause of deviation is that at this energy it might be necessary to consider relativistic effects. The phase shift analysis is based on nonrelativistic theory and for this experiment v/c was about 0.2.

Of course, there also remains the possibility that the phase shifts found were spurious and do not correspond to physical reality. It is the belief of the author, however, that the chance is very good that they are physically significant. The reason for this is that the S and P phase shifts were found in the regions in which they were to be expected from considerations of the results of the lower energy experiments. As has already been seen, these previous results were used directly in finding the approximate P-wave solutions, and the final results did not differ too greatly from the predictions. The values of the logarithmic derivative times nuclear radius (aY) corresponding to the final results were -33.3 for the $P_{\frac{3}{2}}$ wave and -6.1 for the $P_{\frac{1}{2}}$ wave. These values are less than those obtained from the extrapolation of the graph of Dodder and Gammel, which would be expected if higher lying P levels were affecting the scattering. This is not an unlikely situation. The S-wave phase shifts for the lower energy work have been found to follow closely the pattern to be expected in scattering from an impenetrable sphere of radius 2.6×10^{-13} cm. It is not possible to check the results of the present experiment quantitatively with this model because of the lack of the proper wave functions, but it may be stated that the value found is in the proper region for agreement with the model.

The D-wave situation is surprising and ambiguous. Since the formula for the cross section in terms of the phase shifts [Eq. (1)] is a function of double the phase shift angles, values of a phase shift differing by 180° give identical values for the cross section. Thus another possible value for δ_2^+ is $-22.2°$, and without additional information one cannot choose between this value and the previously given one (157.8°). In the light of previous results, however, one would be inclined to pick the value 157.8° since this would be the case of the inverted doublet for D states which was indicated in the analyses of Dodder and Gammel. If this is true, $D_{\frac{5}{2}}$ resonance scattering would occur at some lower energy, thus pointing to the existence of a $D_{\frac{5}{2}}$ level in the Li^5 compound nucleus, and thus confirming the expectations of Dodder and Gammel.

It is clear that there is a need for more proton-helium scattering experiments in this energy region. Data at a different energy would eliminate the D-wave ambiguity merely through the necessity for the continuity of the phase shifts, and data at a number of different energies would open the door to interpretive work along the lines of that carried out for the lower energy experiments.

ACKNOWLEDGMENTS

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Directional Correlations and Electric Quadrupole Moments of Mercury Isotopes*

R. V. POUND AND G. K. WERTHEIM†

Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts and Brookhaven National Laboratory, Upton, New York

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The directional correlation of the 368-kev and the 159-kev γ rays of 44-min Hg^{199} were studied with sources in the form of liquid metal, frozen metal, and dry crystalline $HgCl_2$. The results in the liquid metal, if free of scattering and of disturbances in the intermediate state, indicate a mixing of 0.8% $E5$ with the predominantly $M4$ first γ ray, assuming the second to be pure $E2$. The disturbance observed in the frozen metal suggests a static electric quadrupole interaction $eQ(\partial^2 V/\partial z^2)/h$ of 593 Mc/sec whereas that in $HgCl_2$ suggests similar interaction of 1100 Mc/sec for the 2.35-mμsec intermediate state. If the second γ ray is a rotational transition, an intrinsic quadrupole moment determined from the intermediate lifetime can be used together with these values and the coupling observed for Hg^{201} in $HgCl_2$ to compute the electric quadrupole moment of Hg^{201}. The resulting value of $0.46_{-0.11}^{+0.28}$ barn is in excellent agreement with the spectroscopically determined value of 0.45 ± 0.04 obtained by Murakawa.

INTRODUCTION

In several instances,[1] disturbances of directional correlations of successively emitted nuclear radiations have been observed and shown to be attributable to coupling of the electric quadrupole moment of the intermediate nucleus to the field of surrounding charges. No example has so far been reported for which a reliable evaluation of the pertinent electric field gradient could be made so as to allow determination of the nuclear electric quadrupole moment of the intermediate state from the observed disturbance. It is well known that covalent effects play a dominant role in determining such field gradients in solids. In most examples so far reported, the nucleus studied is a chemical impurity in an unknown electronic state, perhaps also displaced by recoil from a normal lattice site because the gamma rays observed follow very promptly after disruptive α or β emission or electron capture. As a consequence, evaluation of a field gradient is even less reliable than in the already difficult examples of stable nuclei observed by radio-frequency spectroscopy.

The experiments to be described herein deal with a nuclear isomer, 44-minute Hg^{199}, which can be observed in chemical environments normal to ordinary mercury because γ emission can be separately selected (disruptive electron conversion ignored) and the initial 368-kev γ ray, leading to the 2.35-mμsec level[2] examined, produces small recoil. In these respects, the situation is similar to that of 48-min Cd^{111} [3,4] and of 68-min Pb^{204}.[5,6] Also highly relevant to the study of the correlation in 44-min Hg^{199} are: (1) the existence of a stable isotope, Hg^{201}, for which the nuclear electric quadrupole interaction energies are known both in a solid, $HgCl_2$ [7] and in several atomic states from optical spectroscopy[8]; and (2), the evidence that the 2.35-mμsec isomeric level studiable by these techniques presumably decays by electric quadrupole radiation.[9,10] Some results pertaining to the directional correlations of this isomer were reported by Bolotin and Wilkinson[11] but they are completely inconsistent with those to be discussed here.

EXPERIMENTAL TECHNIQUE

The apparatus used was a combined "fast" coincidence, "slow" spectrometer instrument built up at

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† Now at the Bell Telephone Laboratories, Murray Hill, New Jersey.

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