# Elastic Scattering of 20.6-Mev Protons by Deuterons*†

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(Received August 23, 1954; revised manuscript received November 17, 1954)

The absolute differential cross section for the elastic scattering of 20.6-Mev protons by deuterons was measured by using the external beam of the U.C.L.A. synchrocyclotron. A triple-coincidence proportional counter telescope, with variable absorbers between the second and third counters and differential pulse-height discriminators (set by a new method) on the first two counters, was used to select the desired particle by range and specific ionization. Deuterium gas at atmospheric pressure provided the target for the proton beam, which was collimated to $\frac{1}{8}$ in. diameter, with a maximum angular divergence of $\frac{1}{2}°$. An interchangeable slit system gave angular resolutions of 0.9° or 1.8°. Absolute measurements were made at 22 angles from 12° to 164° (center-of-mass) with an accuracy varying approximately from 1 percent to 3 percent, depending upon the angle. The cross section shows the familiar deep minimum (near 130° in the present case), but in addition a shallower minimum near 18°, due to Coulomb-nuclear interference. This latter minimum should allow fitting the data with a unique set of phase shifts, unlike previous nucleon-deuteron scattering experiments, and thus provide a more stringent test for theories.

## I. INTRODUCTION

THE study of the scattering of nucleons by deuterons could be expected to yield information on (1) the character of the force between neutrons, as compared with that between protons; (2) the exchange properties of nuclear forces; and (3) the existence and nature of three-body forces.

Because of the importance of these subjects, a considerable amount of work already has been done in this field. Differential cross sections for *p-d* and *n-d* elastic scattering[1] have been measured over a wide range of energies. While the inelastic scattering has received much less attention, a little information is available on the $d(p,2p)n$ and $d(n,2n)p$ reactions.

A large quantity of theoretical work has also been done. In the intermediate energy region some theoretical work is available on *n-d*[2–6] and *p-d*[7–14] (often with *n-d* included) elastic and inelastic[15–17] scattering. Phase shifts from *p-d* experiments appear to differ from those obtained from corresponding *n-d* scatterings only by an amount attributable to the Coulomb barrier. This evidence for charge symmetry is not very decisive, however, because of the inaccuracy of the experiments. It seems worthwhile to make better experimental comparisons in this intermediate energy region, where the charge symmetry assumption can be tested for several angular momentum states, and where the most accurate *n-d* experiments can be done, using monoenergetic neutrons from the $T(d,n)He^4$ reaction.

Indeed, the recent calculations of Christian and Gammel[14] seem to show that a comparison of only quite accurate *n-d* and *p-d* experiments could yield much information on the *n-n* force. They find that the *n-n* and *p-p* forces are relatively unimportant compared with the triplet even parity *n-p* force. However, this result may stem at least partially from their choice of slow-neutron scattering lengths on which to base phase shifts, whereas a different set of scattering lengths is also allowed by experiments.[18]

It is an important characteristic of the nucleon-deuteron scattering work published so far that each experiment could be fitted by two sets of phase shifts, corresponding to the ambiguity in the scattering lengths. While such an indeterminateness is inherent in *n-d* scattering (unless the experiment could be performed with polarized neutrons) a unique set of phase shifts would be obtainable from *p-d* scattering, if the region of interference between Coulomb and nuclear forces were accurately observed. So far, *p-d* experiments have either not been extended to low enough angles, or have been too inaccurate at low angles to provide the needed additional condition which would remove this ambiguity.

* This work was supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

† A more complete account of this work is given by D. O. Caldwell and J. R. Richardson, University of California, Los Angeles, Technical Report No. 22, 1954 (unpublished).

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1 A complete bibliography of theoretical and experimental papers is given by D. O. Caldwell and J. R. Richardson, University of California, Los Angeles, Technical Report No. UCLA-22 1954 (unpublished).

2 R. A. Buckingham and H. S. W. Massey, Proc. Roy. Soc. (London) **A179**, 123 (1941).

3 H. S. W. Massey and R. A. Buckingham, Phys. Rev. **71**, 558 (1947).

4 M. Verde, Helv. Phys. Acta **22**, 339 (1949).

5 M. M. Gordon and W. D. Barfield, Phys. Rev. **86**, 679 (1952).

6 A. H. de Borde and H. S. W. Massey, as quoted in *Progress in Nuclear Physics* (Pergamon Press, Ltd., London, 1953), Vol. 3, pp. 267–268.

7 C. L. Critchfield, Phys. Rev. **73**, 1 (1948).

8 H. S. W. Massey and R. A. Buckingham, Phys. Rev. **73**, 260 (1948).

9 R. Thomas, Phys. Rev. **76**, 1002 (1949).

10 J. L. Gamel, Phys. Rev. **78**, 321(A) (1950), and Ph.D. thesis, Cornell University, 1950 (unpublished).

11 G. Breit, Phys. Rev. **80**, 1110 (1950).

12 Buckingham, Hubbard, and Massey, Proc. Roy. Soc. (London) **A211**, 183 (1952).

13 A. L. Latter and R. Latter, Phys. Rev. **86**, 727 (1952).

14 R. S. Christian and J. L. Gammel, Phys. Rev. **91**, 100 (1953).

15 H. Höcker, Physik. Z. **43**, 236 (1942).

16 B. H. Bransden and E. H. S. Burhop, Proc. Phys. Soc. (London) **A63**, 1337 (1950).

17 R. M. Frank and J. L. Gammel, Phys. Rev. **93**, 463 (1954).

18 Wollan, Shull, and Koehler, Phys. Rev. **83**, 700 (1951).

Thus it would seem that $p$-$d$ and $n$-$d$ experiments more adequate than those heretofore compared are needed to provide a test of the charge symmetry hypothesis, or even to establish which set of phase shifts is the correct one. A similar conclusion can be reached for the aim of determining the exchange character of nuclear forces. Since the deuteron provides a relatively big target, even fairly low-energy nucleons are scattered in states of angular momentum greater than zero, and hence the existence of exchange forces has been fairly well established by low-energy nucleon-deuteron scattering. However, the more difficult distinction among types of exchange forces requires more complete experimental and theoretical work.

At present, three main theoretical approaches are available for attempting to distinguish among force types by comparison with intermediate energy nucleon-deuteron scatterings, those of (1) Massey and his co-workers,[2,3,6,8,12] (2) Verde[4] and Gammel,[10] and (3) Christian and Gammel.[14] While the present experiment will provide the first comparison with all three methods, it is too much to expect from the theories that a comparison with any of them will provide a definite answer as to the type of exchange force present. The present difficult calculations are incomplete and use potentials which do not give satisfactory answers for intermediate energy nucleon-nucleon scattering, but a more serious trouble may be the omission of a three-body force.

The recent work of Drell and Huang[19] raises the hope that calculations can be carried out soon which will make feasible the obtaining of information about three-body forces from nucleon-deuteron scattering. Generalizing the Lévy[20] two-body potential for many-body forces, they calculated the total energy per nucleon as a function of nuclear density, and found an energy minimum of about the right value at a reasonable nuclear density. Since they find the repulsive three-body force to be almost entirely responsible for nuclear saturation, it would seem likely that such a force would show up in nucleon-deuteron scattering, if the calculations have any relation to reality. At intermediate energies the effects of a possible three-body force may have been masked by employing so many parameters to fit inadequate data. Comparing the predictions of a theory which includes a three-body force with the present experiment could be particularly interesting, since the kinetic energy involved is much like that within a nucleus.

## II. EXPERIMENTAL APPARATUS

### A. General Considerations

The necessity for carrying the $p$-$d$ scattering measurements down to low enough angles to include the Coulomb-nuclear interference region is evident from the preceding discussion. Since the maximum angle at

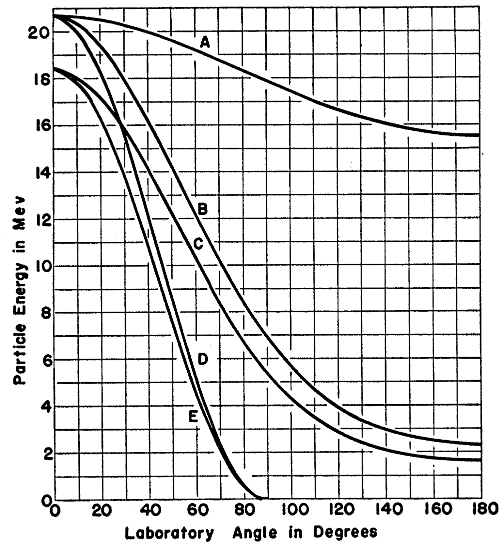


FIG. 1. Particle energy *vs* laboratory angle: (A) protons scattered from nitrogen, (B) protons scattered from deuterons, (C) maximum energy of protons from $d(p,2p)n$, (D) protons scattered from protons, and (E) recoil deuterons from $p$-$d$ scattering.

which Coulomb scattering is important, as given roughly by the square root of the ratio of the barrier to the kinetic energy, is 9° in the laboratory system for 20 Mev, the apparatus was designed to work down to 8°. This minimum angle corresponds to a center-of-mass angle of 12° for protons and 164° for deuterons. For center-of-mass angles larger than 120°, it was desirable to count the recoil deuterons to avoid the multiple scattering losses which could result from counting low-energy protons.

As can be seen from Fig. 1, at any angle the desired particle had to be separated from four other particle groups. To do this, a triple-coincidence proportional counter telescope was used with absorbers between the second and third counters. A particle separation by range was provided by choosing the absorbers so that the desired particle was near the end of its range in the third counter; the resulting large pulse was then distinguished with an integral discriminator. Differential discriminators were used on the first two counters, in order to provide a separation on the basis of the specific ionization of the particles. While a simpler separation of particles would have been provided by counting both the scattered proton and recoil deuteron in coincidence, reliable low-angle data could not have been obtained in that way.

### B. Scattering Chamber Arrangement

The electrostatically-deflected, 21-Mev proton beam of the 41-inch U.C.L.A. synchrocyclotron was made approximately parallel by a double-focusing wedge magnet in the cyclotron field. The external beam, which came in 20-$\mu$sec bursts, 1000 times a second, was brought out

[19] S. D. Drell and K. Huang, Phys. Rev. **91**, 1527 (1953).
[20] M. M. Lévy, Phys. Rev. **88**, 725 (1952).

TABLE I. Analyzing slit dimensions.

| Slit | Width Std.dev. in inches | No. of meas. | Height Std.dev. in inches | No. of meas. |
|---|---|---|---|---|
| Front narrow | $0.051552\pm0.000059$ | 112 | | |
| Rear narrow | $0.052269\pm0.000075$ | 119 | $0.59234\pm0.00016$ | 51 |
| Front wide | $0.101023\pm0.000041$ | 56 | | |
| Rear wide | $0.101879\pm0.000044$ | 60 | $0.59249\pm0.00010$ | 51 |

between 18-inch water walls about ten feet to the scattering chamber.

The scattering chamber itself was a brass casting appropriately machined to provide an axis of rotation perpendicular to the beam axis.

### C. Collimator

In the collimator all nondefining diaphragms were made of carbon to reduce both the scattering and the neutron background. To further reduce scattering, these diaphragm edges were beveled. Most of the unused external beam was stopped by a carbon insert in the flange which joined the collimator to the cyclotron, and most of the rest on an insert just ahead of the first defining hole. The first defining hole was 0.1248 in. in diameter and the second, 0.1236 in. Their $\frac{1}{32}$-in. thick brass defining edges were 14.22 inches apart, giving a maximum angular divergence of the beam in the chamber of $\pm0.50°$. However, the part of the beam selected by the collimator was so nearly parallel that beam pictures showed essentially all the beam to be contained within an angular divergence of $\pm0.2°$. Between the two defining holes were three nondefining holes spaced by aluminum sleeves so as to fulfill the criteria necessary to make the collimator effectively wall-less. A final 0.170-inch diameter antiscattering hole was added 1.790 in. beyond the second defining hole to limit the spray of protons off the last defining diaphragm to a cone of half-angle 4.7°.

The collimator extended as far as possible into the chamber, the second defining hole being 2.841 in. from the chamber center, in order to make small angle measurements possible, permit a small Faraday cup opening, and reduce the penetration of the first counter slit by low-angle protons.

To keep small the loss of beam from multiple scattering, 0.0005 in. Mylar was used for the foil (just ahead of the first defining hole) which separated the cyclotron vacuum from the chamber.

After preliminary mechanical and optical alignment the final check on the adjustment of the second defining hole was made by exposing photographic paper, placed directly behind a centering needle, to the proton beam. By measuring with a traveling microscope the position of the needle shadow with respect to the beam circle, the beam-centering could be checked to within 0.002 in. Similar beam pictures provided also the final alignment of the whole chamber.

TABLE II. Constants of the slit geometry.

| Slits | $r_1$ in. Std.dev. in. | $r_2$ in. Std.dev. in. | $HD_FD_R/r_1r_2$ cm/sterad | Std.dev. |
|---|---|---|---|---|
| Narrow | $3.2289\pm0.0011$ | $4.3895\pm0.0004$ | $0.28604\times10^{-3}$ | $\pm0.19$ percent |
| Wide | $3.2284\pm0.0011$ | $4.3885\pm0.0004$ | $1.09325\times10^{-3}$ | $\pm0.047$ percent |

### D. Analyzing Slits

To keep corrections for finite angular resolution small at small angles and to maintain reasonable counting rates at larger angles, two interchangeable sets of analyzing, or counter, slits were used, of angular resolution $\pm0.921°$ and $\pm1.800°$. It was necessary to resort to the unusual expedient of putting the rear slit of either set between the second and third counters, in order to have simultaneously a practical slit geometry, a small minimum angle, a good angular resolution, a large solid angle, a triple-coincidence counting system, and a small chamber.

The slits were made of commercial bronze (90 percent Cu and 10 percent Zn), since the relatively high density and low $Z$ of copper are desirable for reducing slit penetration. Such penetration was further diminished by milling down each slit plate around the opening to 0.030 in., a stopping thickness for 20-Mev protons.

The results of measurements on the analyzing slits are given in Table I, along with the number of final measurements of each dimension.

The distance between the slits ($r_1$) and the distance from the scattering center to the last slit ($r_2$) were measured in the Standards Laboratory of the U.C.L.A. Engineering Department with a Pratt and Whitney Electrolimit Gage, which read directly to 0.00005 in., and Johansson Precision Gage Blocks. A weighted average of the various determinations appears in Table II, along with the constant part of the solid-angle-scattering-length factor, $HD_FD_R/r_1r_2=1/G$, where $D_F$= front slit width, $D_R$= rear slit width, and $H$= rear slit height.

The accuracy of the alignment of the slits was checked for the following slit characteristics: height, left-right positioning, lengthwise and sidewise tilting, rotation, and slit edge nonuniformity. The total errors these introduced into $G$ amounted to 0.004 percent for the narrow slits and 0.002 percent for the wide. The left-right positioning, rotation, and slit nonuniformity contributed also to errors in the scattering angle of 0.036° for the narrow and 0.042° for the wide slits. The amount by which the slit axis did not quite pass through the chamber center was measured and allowed for in setting the counter angle zero. When the error for setting the zero is added quadratically to those for setting the counters at any desired angle and for the slit alignment, the resulting error in angle is 0.063° for the narrow and 0.066° for the wide slits.

The antiscattering baffle ($B$ in Fig. 2) attached by dowel pins to each front slit plate was aligned and checked in the same way as the slits. The baffle de-

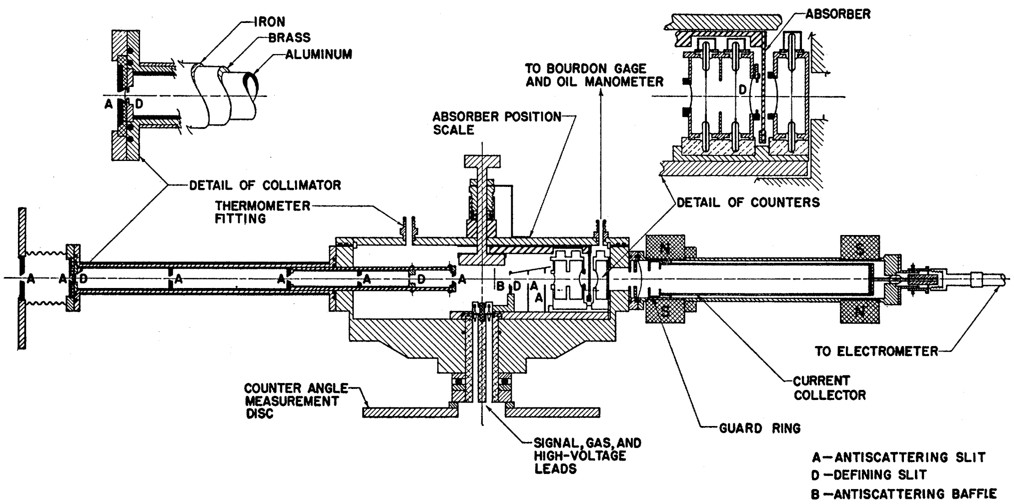


FIG. 2. Sectional view of the scattering chamber and details of the triple coincidence proportional counter telescope.

creased slit-edge penetration by cutting off low-angle protons and also helped prevent protons scattered off the last defining slit of the collimator from getting into the analyzing slit system. At counter angles of 15° and larger, the last antiscattering hole on the collimator also prevented direct slit-slit scattering, but between 15° and 10° the baffle alone was effective. At 8° direct slit-scattered protons could get through the front analyzing slit, but not past further antiscattering slits between the front analyzing slit and the first counter window.

### E. Absorbers

The absorbers between the second and third counters, used to provide particle selection by range, were mounted on the rim of a sector, as shown in Fig. 2. The set of absorbers desired could be turned into position by means of a Wilson seal, and all parts determining this position were held in place by dowel pins. Photographic checks with the beam showed that the 10° wide foils were positioned to an accuracy of better than 0.5°, whereas the third counter window was 5° wide.

The 99.4 percent pure aluminum foils were weighed and measured with sufficient accuracy so that variations in surface density for foils of the same nominal thickness could be taken as a measure of the variations in foil thickness. A safety factor of three standard deviations of this foil thickness variation was allowed in determining the thickness of absorber to be used. Much larger allowances had to be made for the angular resolution of the counters (see Fig. 1) and for straggling. For the latter, an integral range distribution was obtained,[21] permitting one to find the number of mg/cm$^2$ of Al which have to be subtracted from the mean range in order that not more than 0.1 percent of the particles of the desired energy are lost by straggling. Since the mean range used at a given angle was that corresponding to the largest angle (or lowest energy) the counter slit system could see, the particle loss in the absorbers due to straggling was negligible.

Loss of particles in the absorber because of multiple scattering was also negligible, mainly because the third counter window was quite large compared with the analyzing slits, the absorber was close to the window, and the window was made very thick (about 50 mg/cm$^2$), so that the largest part of the multiple scattering took place in the window itself. Calculations of multiple scattering with energy loss were made using a power law for $-dE/dx$ in the Rossi-Greisen[22] formulation to give $\langle\phi^2\rangle = 0.045(E_f^{-0.22} - E_i^{-0.22})$, where $\phi$ is the rms projected scattering angle in radians and $E_i$ is the proton energy in Mev before, and $E_f$ after, passing through the Al. Even though this gives an overestimate of $\phi$, the loss was still found to be negligible.

### F. Counters

Because the second slit was placed between the second and third counters (see Sec. IID), the multiple scattering loss between the slits had to be considered carefully. Loss was due mainly to the first counter window and to a lesser extent to the counter gas; the contributions of the deuterium and the second counter window, which was right next to the second slit, were quite small. From multiple scattering[23] calculations it was found that the loss could be made negligible if (1) the first counter window was 0.00025-in. duraluminum, (2) the counter gas was at $\frac{1}{2}$ atmosphere, (3) the narrow slits were not used for particles of energy less

[21] D. O. Caldwell, Phys. Rev. **88**, 131 (1952) and in more detail D. O. Caldwell, University of California, Los Angeles, Technical Report No. 9, 1952 (unpublished).

[22] B. Rossi and K. Greisen, Revs. Modern Phys. **13**, 267 (1941).

[23] W. T. Scott, Phys. Rev. **85**, 245 (1952).

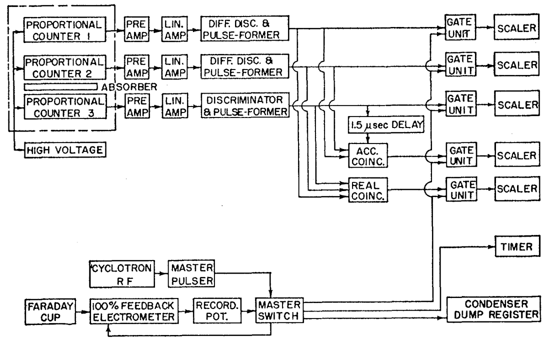


FIG. 3. Block diagram of the electronic system.

than about 15 Mev, (4) the wide slits were not used for particles of less than about 7-Mev energy, and (5) the beam at the second slit was much larger than the slit, to provide compensating scattering into the slit opening.

Since there was no window between the first and second counters, it was necessary to be sure that one did not affect the other. When a source was placed so that several thousand alpha particles a second traversed the first counter but did not quite enter the second, the counter rate in the second was just background, and none of these few counts were in double coincidence. On the other hand, when the source was moved closer, essentially all the counts from the second counter were in coincidence with those from the first.

### G. Electronics

A general idea of the electronics system[24] may be obtained from Fig. 3. The speed of the counting system was limited by the Bell-Jordan amplifiers, and was set by the length of shorted delay lines chosen in the discriminators to form the uniform pulses used in the rest of the system. In normal operation, then, both the real and accidental coincidence units had resolving times of $0.71 \pm 0.04$ μsec. A 1.5-μsec delay line in the third channel of the latter thus assured that all accidental coincidences recorded resulted from real coincident events in the first two counters and a random event in the third (see Sec. IVA).

Two forms of gating were employed: (1) all scalers could be gated on at the beginning of a selected charging cycle of the beam-integrating condenser and off at the end of the same or another cycle, and (2) the scalers could be made to count only during cyclotron beam on-times. This latter gate[25] reduced the chances of getting spurious counts not initiated by the beam by a factor of roughly 60/1000.

The usual checks were made to be sure that the electronic system was linear, that there were not unequal delays in the three counting channels, that the resolving time was not so short that desired counts were being missed, and frequently that the 1–3 and 2–3 doubles rates were the same as the 1–2–3 triples rate. Nightly checks were made on the gain of the system, amplifier-discriminator linearity, gating pulse setting, and scaler operation.

Special mention must be made of the method used to set the discriminators, since it was quicker and more accurate than conventional methods. Approximate settings for the first two counting channels could be obtained from any prior run by using a curve like Fig. 4 of the energy loss distribution in a counter, as calculated from Symon's[26] theory. After making a run to get the approximate counting rate at that angle, the lower level of the first channel discriminator was set arbitrarily higher, and another run was made. Suppose we were counting 16-Mev protons and raising the discriminator to a setting of 200 had decreased the counting rate by 30 percent. Figure 4 shows that this discriminator setting of 200 must have corresponded to a 20-kev energy loss in the counter. Since the energy loss distribution essentially begins (0.1 percent curve) at 14 kev and ends (99.9 percent curve) at 52 kev, the lower level discriminator had to be set below $200(14/20) = 140$ and the upper level had to be set above $200(52/20) = 520$. The second channel was set in the same way, but the third channel, because of the wide range of energies in the third counter due to straggling, had to be set by taking a conventional bias curve. However, by using the energy loss distribution together

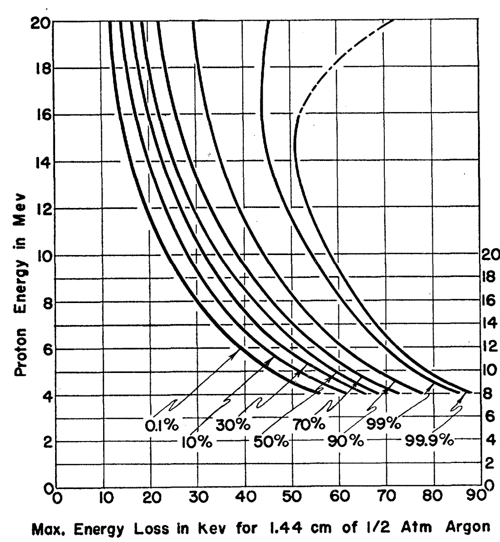


FIG. 4. Energy loss distribution in a counter *vs* proton and deuteron energy. For a given percentage of monoenergetic particles, each curve represents the maximum energy loss *vs* particle energy.

[24] The authors wish to thank C. Wilkin Johnstone and Richard J. Watts of the Los Alamos Scientific Laboratory for generously supplying circuits, information, and advice.

[25] We are indebted to Louis K. Jensen for designing, building, and maintaining this unit, as well as an excellent pulse generator that received continual use.

[26] K. R. Symon, Ph.D. thesis, Harvard University, 1948 (unpublished), as quoted by B. Rossi, *High-Energy Particles* (Prentice-Hall Inc., New York, 1952), pp. 32–35.

with the straggling calculations,[21] plots of minimum energy loss *vs* counter angle for protons and deuterons could be obtained. It was then easy to set the third channel discriminator initially and to pick a minimum of settings to determine the counting rate plateau. The whole procedure, as well as the stability of the electronics, was frequently checked by predicting a first or second channel discriminator setting for a certain percentage particle loss and then making a run to see if that loss was obtained.

### H. Current Integration

Considering the collection of the beam, its integration, and the calibration of the integrator, we shall first be concerned with difficulties which can occur in beam collection. Such errors can be caused by (1) ionization in the region of the Faraday cup, (2) leakage in the cup or connecting cable, (3) acquisition or (4) loss of secondary electrons, (5) pickup and rectification of ac, (6) collection of ions by the electrical leads outside of the cup, (7) loss of electrons from the exterior of the cup by gamma ejection, (8) loss of part of the beam, and (9) having a low-energy component of the beam which does not produce countable scattering events.

The probability of a 20-Mev proton forming an ion pair in passing through the 9-in. long Faraday cup, kept at a pressure of less than $1\times10^{-5}$ mm Hg, is only 0.03 percent, which is then an upper limit on the error due to ionization.

The electrometer used to integrate the beam was the 100 percent feedback type, which maintained the Faraday cup near ground potential and thus minimized leakage which was indeed found to be negligible.

The acquisition by the cup of secondary electrons produced by protons going through the 0.002-in. duraluminum foil at the chamber exit was eliminated by having between the foil and cup entrance a field of 1250 gauss (produced by a magnetron magnet outside the cup housing), and a grounded guard ring. Yntema and White,[27] in extensive tests on a similar system, found no effect of secondary electrons on the charge collected for cup potentials several thousand times as large as any encountered in the present experiment.

To prevent the escape from the cup of secondary electrons produced by the stopping of the proton beam (a) a magnetic field was present at the cup entrance; (b) another field (produced by a 1900-gauss magnetron magnet outside the cup housing) was placed at the end of the cup, where the beam stopped; (c) the cup was made unusually long; and (d) the entrance to the cup was partially enclosed. The latter two features decreased the solid angle for escape and minimized the influence of any slight potential difference between the cup and the region outside of it.

That pickup and rectification of ac were not a source of error was borne out by the agreement between calibrations made with and without the cyclotron rf on. To achieve this result, however, it was necessary to use *L-C* filters at both ends of the cable.

Similarly, calibrations made with the cyclotron beam on and off showed that ion collection by the cable and other radiation effects were not sources of error. The beam scattering loss at the Faraday cup entrance was found to be negligible, and indeed essentially all of the beam reached the back of the cup.

The last error considered is that of having a part of the beam penetrate a portion of the collimating diaphragms and lose so much energy that the scattering events it produced not be counted. This low-energy component was largely eliminated by the last collimator antiscattering hole and the chamber exit hole, which was made as small as it could safely be. Slit penetration was decreased by using brass (see Sec. IID) slits of just a stopping thickness and by precollimating the beam. Although the integral range curves taken to measure the beam energy (see Sec. IVC) showed no evidence for such a harmful low-energy component, the total error assigned to the beam collection, 0.3 percent (0.5 percent at a few angles), is mainly to allow for such an effect.

Since the details of the calibrations of the current integrator will be published elsewhere,[28] it is necessary to mention here only that a current-time method was used which provided accurate calibrations over the range of charging currents from $10^{-10}$ to $10^{-11}$ amp. Only the 8° data were taken with smaller currents. Three independent checks on the absolute values of the calibration constants and the consistency of over three hundred calibrations made during the course of the experiment led to the assignment of standard errors for the calibrations of from 0.2 percent for currents around $10^{-10}$ amp to 1 percent for currents smaller than $10^{-11}$ amp.

### I. Vacuum System

While separate mechanical pumps were used for the deuterium and counter filling systems, the main mechanical and diffusion pumps were used on both the scattering chamber and Faraday cup, or either one separately. The whole main system could reach $3\times10^{-5}$ and the Faraday cup alone, $9\times10^{-6}$ mm Hg. With liquid nitrogen, the whole system could get down to $9\times10^{-6}$, and the cup alone, $2\times10^{-6}$. For the first few hours after shutting the chamber off from the pumps, the pressure increased $3\times10^{-4}$ mm/min, while for longer periods the rate of rise was slower.

### J. Deuterium System

To eliminate all impurities initially except normal hydrogen, the deuterium gas was forced to diffuse through the walls of a heated tube of palladium.

[27] J. L. Yntema and M. G. White, U. S. Atomic Energy Commission Report NYO-3478, 1952 (unpublished).

[28] H. N. Royden and D. O. Caldwell, Rev. Sci. Instr. (to be published).

The two tanks of deuterium from the Stuart Oxygen Company which were used for nearly all of the data were later analyzed mass-spectrographically by the Consolidated Engineering Corporation. The more impure of the two was found to contain only 0.04 percent air and 0.02 percent water, so the *Pd* tube was almost superfluous. The H,D analysis, which had a limit of error of less than 0.05 mole percent, showed one tank contained 99.20 mole percent D and the other 99.25 percent.

After the chamber was filled, the gas pressure was determined relative to the atmospheric pressure by means of a small *U*-tube manometer containing Octoil-*S* diffusion pump oil.

The temperature of the gas at the time the pressure was measured was determined to an accuracy of about $\pm 0.03$ percent, where the large error results from the uncertainty that temperature equilibrium was established to better than 0.1°.

Temperature and pressure readings were made at the beginning and end of the period during which a gas filling was used, and the resulting difference in $T/P$ values, along with the measured chamber leak rate, were used to assign $T/P$ values for each run, according to the time elapsed since the chamber was filled. Since $T/P$ changed by about 0.006 percent per hour and the fillings were used for one and sometimes two nights, the $T/P$ value for most runs was known to at least 0.1 percent.

## III. EXPERIMENTAL CHECKS

Of the many experimental checks which were made, the most important was that on the reproducibility of the data afforded by having taken a number of short runs at each angle, and also, for the majority of angles, by having taken data at the same angle on different nights, sometimes weeks apart. For each angle, then, two statistical errors in the data could be computed: a Poissonian one based on the total number of counts, and a Gaussian one based on the reproducibility of the data. These two errors were compared by a chi-square test, and with very few exceptions it was found that the data reproducibility depended only upon the number of counts. The few exceptions were mainly runs during which a faulty relay erratically threw extra counts into the scalers. While a good average background was found to correct for this, the individual runs showed too much variation and have been assigned appropriately larger errors.

Another check on data reproducibility was provided by counting both scattered protons and recoil deuterons at nearly the same center-of-mass angle, since there were important differences in the two types of measurements. For instance, a background subtraction was necessary when counting deuterons. Because of the broadness of the energy loss distribution (see Fig. 4), not all the inelastic protons having a range equal to or longer than that for the deuterons could be excluded by their energy loss in the first two counters. Therefore, a background was measured by using absorbers just thick enough to stop the deuterons. Since the group of protons from deuteron breakup being counted had a slightly higher energy than the group which actually constituted the background, it was necessary to reset the discriminators a little. These new settings were obtained easily using the energy loss distribution and third counter minimum energy loss curves discussed in IIG.

The agreement of the two deuteron check points with the proton data is an especially good test of the background measurement, since these points lie near the main minimum in the cross-section curve, where the inelastic scattering is relatively large compared with the elastic. Indeed, the main group of deuteron points join smoothly onto the proton points right in the minimum, and the point at 130° had a much larger background than did any other deuteron measurement. The deuteron check point at 89.9°, which is close to a proton point at 91.9°, lies on a smooth curve drawn through the proton data.

A further difference in the proton and deuteron measurements at the two check points is that in one case the proton had a considerably higher energy than the corresponding deuteron, and in the other case the deuteron had over twice as much energy as the corresponding proton. In fact, these were, respectively, the lowest deuteron and proton energies used in the experiment. Since the root mean square multiple scattering angle varies approximately inversely as the particle energy, if there were any appreciable multiple scattering loss at any angle, it should have showed up in these two cases.

Since at a fixed energy the multiple scattering loss would have been greater with the narrow slits than with the wide, both the proton and deuteron measurements at a laboratory angle of 20° were made with narrow and wide slits as a further check. For the deuterons, the narrow slit result (4.7 percent statistical error) was 1.2 percent higher than the wide (1.6 percent), while for the protons, the narrow slit cross section (1.4 percent) was 0.87 percent lower than the wide (0.63 percent).

Some check on multiple scattering loss in the gas was provided by a run made with the chamber filled to only half an atmosphere and using narrow slits at 20°, at which angle the proton energy was the lowest used with those slits. Since scattering from the collimating slits to the analyzing slits also would have made the half-atmosphere result larger, an upper limit on both effects is given by the fact that the full-atmosphere cross section (1.4 percent statistical error) was 0.22 percent lower than that obtained with half an atmosphere (1.0 percent).

Another good check on slit-slit scattering was accidentally provided by a shift in the direction of the external beam, which caused a large increase in the number of protons striking the edges of the last collimator defining hole. Some of these protons, scattering off various metal surfaces, found their way into the first and second counters. However, these protons either could not get through the second analyzing slit, or they had lost too much energy to get through the absorber, for measurements made after the chamber was realigned to the new beam direction agreed within statistical error with those made before realignment. Despite the fact that the first and second counter singles rates decreased by a factor of over two after realigning, the cross section for 12.5° deuterons obtained before (1.3 percent statistical error) agreed to within 1.4 percent with that obtained after (1.1 percent) realignment, and similarly the 10° proton cross sections agreed within 0.82 percent for statistical errors of 1.9 percent and 1.4 percent.

Thus slit-slit scattering was not a source of error in the cross-section measurements, except for deuterons at 8° where direct slit-scattered protons could get through the first analyzing slit (see IID). When counting protons at this angle, the only effect was to increase the singles rates in the first two counters, but with deuterons the absorber was thin enough to admit some of these slit-scattered protons. Since the ratio of background to total counts was six times as large at 8° as at 10°, this high background increased the statistical error. Furthermore, since it was found that the slit-scattered proton background decreased rapidly with energy, a correction had to be made by filling the chamber with ordinary hydrogen and making runs with the same absorbers and discriminator settings as were used when taking deuteron and background counts. A rather large error was assigned for this correction.

While background measurements were made for all deuteron runs, only a few were taken for proton runs. The proton backgrounds were nearly always found to be negligible, indicating the absence of (1) slit-slit scattering, (2) scattering from heavy contaminants, (3) false triple coincidences from neutron recoil background, and (4) electrical noise counts. The only exceptions found were obviously due to the last of these causes.

These proton background measurements served also as a check on the method of determining accidental coincidences, since with stopping, or background, absorber in place the triple coincidence and accidental coincidence counts were about equal.

However, the accidental coincidence correction was quite small even at the lowest angles, because the beam current had to be reduced (by reducing the hydrogen supply for the cyclotron arc) to prevent counting losses. Runs were made of cross section *versus* beam current to determine the maximum singles counting rate which could be tolerated before losses occurred.

Runs at any angle which were made with different beam currents served as a test of the current integrator calibration, since each run was assigned its calibration constant on the basis of the charging time of the integrating condenser. A further check was provided by making runs with two different (0.1 $\mu f$ and 0.01 $\mu f$) condensers. Regardless of having different currents or condensers, the cross-section values always agreed within statistical errors.

The cross section at a given angle was measured also as a function of time to check on amplifier gain changes, counter gas contamination, and scattering from air. As mentioned above, the last of these was also tested by background measurements. Still another check was made by using an appropriate absorber to measure scattering from air at 25° periodically during a night of data taking. By measuring also the cross section for scattering at that angle with only air in the chamber, the increase in air concentration could be determined directly and checked with the measured leak rate of the chamber. In general, the effects of air scattering were found always to be very small.

Two conventional checks are to measure a cross section at the same angle on both sides of the beam, and to measure a cross section someone else has already determined. The former was done at 45°, and the agreement of the two determinations within 0.15 percent is better than the statistical accuracy warrants. The latter was done by determining the $p$-$p$ scattering cross section at a laboratory angle of 20° to compare with some small angle measurements being made at this laboratory by H. N. Royden. For the present, the result, 24.0 mb/sterad in the center-of-mass system, can be compared with a value of 23.9, obtained by interpolating between the 18.3-Mev and 32-Mev measurements, as fitted[29] by a Lévy potential. The agreement is much better than the uncertainty in the interpolated value.

## IV. RESULTS

### A. Corrections to the Data

Two corrections to the data have been discussed sufficiently already. These are the background subtraction made (see III) for all deuteron and a few proton runs, and the deuterium temperature/pressure ratio assignment (see IIJ) for each run. A 0.07 percent van der Waals' correction was also made to all the pressures.

The same rate of change of temperature/pressure was used to determine the rate of increase in scattering from air contamination. Corrections had to be made only for proton runs at angles of 17.5° or less, and the largest correction was only 0.34 percent (at 8°). The experimentally confirmed (see III) smallness of this effect was due, at small angles, to using deuterium fillings for only a short time, and at larger angles, to discriminating against the higher energy air-scattered protons.

[29] A. Martin and L. Verlet, Phys. Rev. 89, 519 (1953).

A similar small (0.45 percent in the worst case) correction had to be made at proton angles of 20° or less for scattering from the 0.8 percent ordinary hydrogen impurity in the deuterium (see IIJ). To obtain a good correction, the $p$-$p$ scattering cross sections were taken from an interpolation between the curves given by Martin and Verlet[29] (see III), and the percentage of $p$-$p$ protons excluded by the absorbers at each angle was determined by folding the nearly gaussian distribution in range due to straggling[21] with the trapezoidal distribution due to the angular resolution of the analyzing system (see IVC).

Still another source of unwanted counts was the extra particles obtained because the analyzing slits could not be perfectly absorbing. The correction was small, varying from 0.41 percent for 8° protons to 0.17 percent for 45° deuterons, primarily because of the excellent energy resolution of the absorber system (see also IIC and D).

An opposite correction to the preceding three was that for the loss of particles in the absorbers due to single scattering and absorption. However, only the absorption was important in the total corrections, which varied from 1.02 percent for 8° protons to 0.08 percent for 90° protons.

All the data also were corrected for electrometer zero drift, the final value of the drift being read on the Brown Recording Potentiometer (see Fig. 3) immediately after each run. Because the runs were kept short, the drift correction rarely was as large as 1 percent.

All data were corrected for accidental coincidences by means of a coincidence circuit like that used for real triples, but which registered whenever pulses from the first two counters occurred simultaneously with a delayed pulse from the third counter. This method was necessary because $\frac{1}{5}$ to $\frac{1}{2}$ (depending on the angle) of the pulses from the first two counters were in double coincidence, since (1) these counters had a much larger solid angle than the second analyzing slit (see IID), and (2) only they received metal-scattered protons (see III). Since the number of accidental counts for $n$ counters of resolving time $\tau$ having $N_n$ counts in a time $t$ when used with a square-pulsed beam of period $p$ and on-time $\delta p$ is $A_n = nN_1N_2\cdots N_n(\tau/t)^{n-1} \times[\delta^{1-n}-(n-1)\tau/(np\delta^n)]$, it was readily shown, using measured singles and doubles counts, that $A_2 \gg A_3$. The value for $A_2$ calculated from this formula, which was derived following a method used by Feather,[30] gave good agreement with the electronic result when the latter was corrected by the factor $\delta p/(\delta p-d)$ to account for the probability that counts were missed because the delay line kept the accidental system dead for a time $d$ during the first part of the beam pulse.

The final correction to the data was for the finite width and height of the incident and scattered beams. A second-order geometry analysis was kindly supplied by C. L. Critchfield, and some fourth-order terms in the rear slit height were added to it for this particular geometry. The corrections ranged in magnitude from 3.83 percent for 8° protons to 0.03 percent for 85° protons.

### B. Summary of Errors

Summarizing the errors in the differential cross section, $\sigma_0(\theta_0)=TC\sin\theta_0/KGPFIQ$, we can first dispose of $K$, which includes the gas constant, Avogadro's number, and the electronic charge, all contributing essentially no error here.

The ratio of gas temperature to pressure, $T/P$ usually was known with a standard error of 0.1 percent, while the fraction, $F$, of the gas which was deuterium was determined with a limit of error of 0.05 percent (see IIJ).

Two errors (see IIH) have been assigned in the number of incident particles: (1) an allowance of 0.3 percent (0.5 percent in a few cases) for possible errors in beam collection, and (2) errors varying from 0.2 percent to 1 percent in the determination of the charge per cycle (of which there were $I$), $Q$.

Four sources of error must be considered in using $\sin\theta_0/G$ to determine the portion of the scattered beam seen by the counting system. First, the combined errors in the measurement of the geometrical constants of which $G$ is comprised and in the alignment of the counter slit system amount to only 0.047 percent for the wide slits and 0.19 percent for the narrow (see IID). However, the uncertainties in $\theta_0$, the laboratory angle, while only 0.063° for the narrow slits and 0.066° for the wide, give errors in the cross section varying from 0.13 percent to 0.079 percent, as computed from $\Delta\sigma/\sigma=2\Delta\theta_0/\sin2\theta_0$ for deuterons and $[(\cot\theta_0)+\sin\theta(3.5+\cos\theta)/(2+\cos\theta)^2]\Delta\theta_0$ for protons (where $\theta$ is the center-of-mass angle). The third error arises from the uncertainty in the centering of the incident beam (see IIC), which amounted to 0.064 percent/$\sin\theta_0$, except for runs made with a shifted beam (see III), for which the error has been doubled. The fourth error comes from the correction for finite beam size (see IVA) and varies from 0.36 percent to 0.003 percent. It stems largely from taking derivatives of the imperfectly known cross section, but also an error of 6 percent of the correction was assigned for the effects of neglected higher order terms and of the approximate treatment of the incident beam.

There were several small contributors to the error in $C$, the number of properly scattered protons counted. One was the background correction (see III) made for a few proton runs, for which an error of $\frac{1}{3}$ the correction has been assigned, and for all deuteron runs, for which an error of about 5 percent of the correction has been included to allow for possible effects of the small energy difference between the actual and measured back-

[30] N. Feather, Proc. Cambridge Phil. Soc. 45, 648 (1949).

grounds. A larger error was assumed for the unusual 8° deuteron background.

Since the correction for accidental coincidences was usually much less than 1 percent and approached 2 percent at only one angle, the error assigned to it of 10 percent for $\theta_0 \leqslant 25°$ and 20 percent for $\theta_0 > 25°$ was not important. Also small were the errors due to the corrections for scattering from air contamination, taken to be $\frac{1}{3}$ of the correction and amounting to 0.11 percent in the worst case, and for scattering from ordinary hydrogen, which yielded a maximum error in the cross section of 0.06 percent. An error of 0.3 percent in the worst case resulted from assuming a 30 percent uncertainty in the correction for particle loss in the absorbers, mainly to allow for possible inaccuracies in the absolute values of the theoretical absorption cross sections.

Two errors must be considered in regard to slit-edge penetration. First, an error of $\frac{1}{2}$ the correction for penetration of the analyzing slit edges has been assigned because there is a lack of good experimental verification of the treatment, and this gives a 0.2 percent error in the worst case. Secondly, by a calculation similar to that for the analyzing slits, it was found that only 0.11 percent of the scatterings counted could have been produced by lower energy protons which had partially penetrated the collimating slit edges, and these events could not have caused an error in the cross section greater than 0.006 percent. Note that an error has already been assigned in the beam collection (see IIH) to account for protons which could have lost so much energy that their scattering events would not have been counted.

It was not necessary to assign any error for the small and accurate electrometer zero drift correction, for counting losses (see III), nor for multiple scattering losses (see IIE, IIF, and III).

The main source of error in $C$ and in the whole cross section determination was the Poissonian nature of the number of counts, the relative error in the most complicated case being given by

$$\frac{[(C_g+A_g)/I_g^2+(C_b+A_b)/I_b^2)]^{\frac{1}{2}}}{(C_g-A_g)/I_g-(C_b-A_b)/I_b},$$

where the subscript $g$ refers to the measurement of the gross counts and $b$ to the measurement of background alone, and $C$ designates total counts (of which $A$ were accidentals) in $I$ condenser cycles. A tabulation of this statistical error and the relative standard deviation in the cross section at each angle resulting from quadratically combining all the errors considered above may be found in Table III. These errors apply to the absolute values of the cross sections, since each determination was an absolute measurement. The cross sections and angles have been transformed to the center-of-mass system relativistically, but these differ little from the classical values.

TABLE III. Experimental data. The following data for the angular distribution of protons elastically scattered from deuterons is for a proton laboratory energy of 20.57±0.11 Mev. The errors, as well as the differential cross-section values, are absolute, and are expressed as percentage standard deviations.

| Lab angle (degrees) | C.m. angle (degrees) | C.m. cross section (mb/sterad) | Percent statistics | Std. error (percent) |
|---|---|---|---|---|
| 8.0-$p$ | 12.07 | 93.92 | 2.7 | 3.1 |
| 10.0-$p$ | 15.03 | 72.93 | 1.2[a] | 1.8 |
| 12.5-$p$ | 18.80 | 69.56 | 1.4 | 1.7 |
| 15.0-$p$ | 22.53 | 72.37 | 0.93[a] | 1.2 |
| 17.5-$p$ | 26.26 | 75.22 | 0.83[a] | 1.1 |
| 20.0-$p$ | 29.97 | 77.27 | 0.53 | 0.83 |
| 25.0-$p$ | 37.37 | 70.77 | 0.89 | 1.1 |
| 35.0-$p$ | 51.87 | 52.19 | 0.90 | 1.0 |
| 45.0-$p$ | 65.95 | 36.11 | 0.83[a] | 0.96 |
| 55.0-$p$ | 79.44 | 23.27 | 1.3 | 1.4 |
| 45.0-$d$ | 89.86 | 16.70 | 1.4 | 1.7 |
| 65.0-$p$ | 92.20 | 15.49 | 1.8 | 1.9 |
| 75.0-$p$ | 104.17 | 9.66 | 1.8 | 1.9 |
| 85.0-$p$ | 115.16 | 5.62 | 2.8 | 2.9 |
| 90.0-$p$ | 120.20 | 4.51 | 2.1 | 2.2 |
| 25.0-$d$ | 129.90 | 2.64 | 2.8 | 3.1 |
| 20.0-$d$ | 139.91 | 6.62 | 1.5 | 1.9 |
| 17.5-$d$ | 144.92 | 11.44 | 1.2 | 1.4 |
| 15.0-$d$ | 149.93 | 16.97 | 1.5 | 1.9 |
| 12.5-$d$ | 154.94 | 24.28 | 0.84 | 1.3 |
| 10.0-$d$ | 159.95 | 33.94 | 1.9 | 2.5 |
| 8.0-$d$ | 163.95 | 38.65 | 4.1[a] | 4.3 |
| Proton-proton scattering check run: | | | | |
| 20.0 | 40.20 | 24.00 | 0.75 | 1.1 |

[a] An additional error due to the background had to be included in the statistical error because of the method of combining sets of data.

## C. Beam Energy Determination

In order to check the use and calibration of the absorbers as well as to determine the beam energy, three energy measurements were made during the course of the experiment by taking integral range curves with the absorbers in front of third counter, while counting protons from $p$-$p$ scattering at 20° and 25°.

There are three uncertainties in the energy: (1) the error in the mean energy determination, (2) the energy spread in the beam at any particular time, and (3) changes in the mean energy with time.

Considering the first of these, there are three errors in the determination of the mean energy, uncertainties of (a) 1.5 mg/cm$^2$ in the absorber thickness, (b) 1.5 mg/cm$^2$ in the mean-range determination, and (c) 2.3 mg/cm$^2$ in the range-energy relation, giving a total error of 0.08 Mev. The range-energy relation for aluminum was computed for a ionization potential[31] of 164±3 ev and was corrected for multiple scattering.

An upper limit of about 0.1 Mev can be placed on the energy spread in the beam, since the integral range curves could be fitted quite well by considering just straggling and angular resolution. This analysis also showed that the absorbers for $p$-$d$ scattering were being chosen properly (see IIE).

[31] D. O. Caldwell and J. R. Richardson, Phys. Rev. 94, 79 (1954).

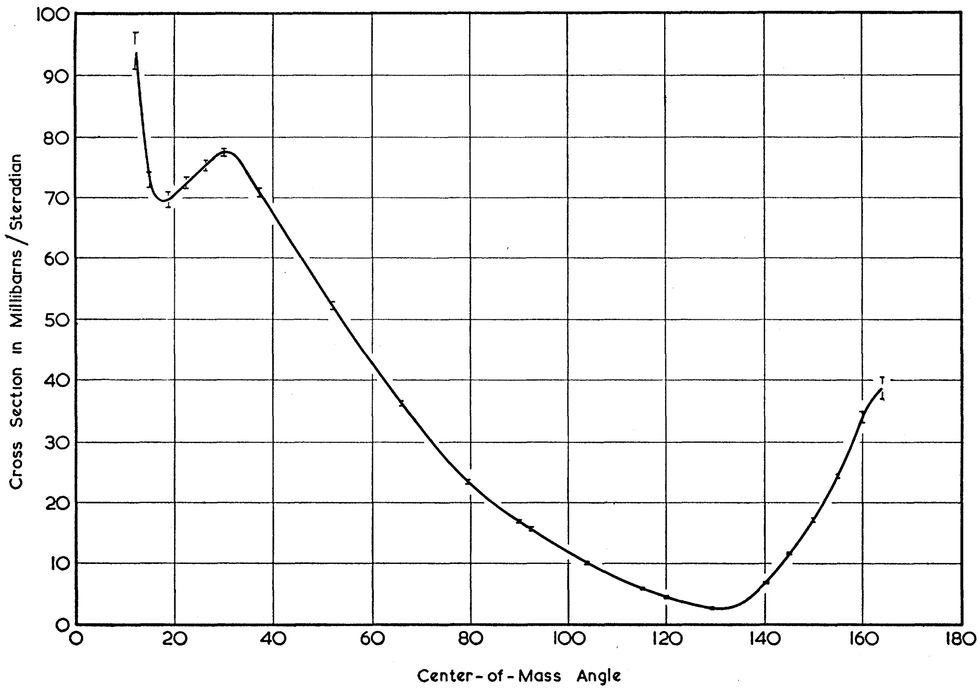


FIG. 5. Center-of-mass differential cross section for the elastic scattering of 20.6-Mev protons by deuterons.

An indication of the constancy of the beam energy under normal conditions is given by the agreement between measurements taken at the beginning 20.56 (Mev) and end (20.57 Mev) of the *p-d* data taking period. An upper limit on the energy change can be set by the third measurement (20.68 Mev), which was made after a beam shift (see III) caused the collimator to select a different part of the beam. Since none of the *p-d* data taken just before this measurement were used, the maximum change in mean energy for any accepted data can be taken as about 0.08 Mev.

Adding quadratically uncertainties (1) and (3) above gives 0.11 Mev as the standard deviation in the mean energy, and the energy spread in the beam at any time, (2) above, is thought not to have exceeded that same value. We have then as the beam energy, $20.57\pm0.11$ Mev.

## V. CONCLUSIONS

The results of this experiment, which are given in Table III and Fig. 5 seem a reasonable interpolation between the experimental work at 9.7 Mev[32] and 31 Mev,[33] except for the appearance of the Coulomb-nuclear interference minimum. While it should soon be possible to compare this experiment with the theoretical work of Massey and Gammel,[34] at the moment the only comparison that can be made is with the 20-Mev *n-d* calculation of Verde. Although a phase shift analysis ought to be made, the phase shifts converted to equivalent *n-d* ones, and these compared with Verde's phase shifts for each angular momentum, by just comparing cross-section curves it is hard to see how the present data could give any agreement with Verde's theory. For either his symmetric or neutral potential, the main cross-section minimum comes at too small an angle (about 90°, instead of 130°) and is not deep enough by an order of magnitude. Also, the theoretical backward peaks are four to six times too high. The theoretical forward peak at about 30°, where Coulomb effects are not important, is a factor of two too low for the symmetric potential and a factor of one and one-half too high for the neutral potential.

Except for checking various theoretical approaches, these data probably cannot yet be used for achieving some of the aims outlined in the Introduction. It can only be hoped that this experiment may provide some spur for the necessary theoretical work. The data can perhaps give an answer to the long-standing question as to which set of nucleon-deuteron scattering lengths is the correct one, because of the clear appearance for the first time of a Coulomb-nuclear interference minimum. This minimum should give the added condition needed to make unique the phase shifts used to fit the data. In general, this experiment should provide a more stringent test for present or future theories than do previous low or intermediate energy nucleon-deuteron scattering measurements.

[32] Armstrong, Allred, Bondelid, and Rosen, Phys. Rev. 88, 433 (1952).

[33] V. J. Ashby, University of California Radiation Laboratory Report 2091, 1953 (unpublished).

[34] H. S. W. Massey and J. L. Gammel (private communications).

### VI. ACKNOWLEDGMENTS

Beneficial discussions were had with Professor G. Breit, Professor E. Bretscher, Professor K. R. MacKenzie, Professor H. S. W. Massey, and Professor B. T. Wright; and Professor C. L. Critchfield generously supplied the second-order geometry correction. George Jones and Harry E. Handler furnished considerable aid with the electronics, as did Steve Plunkett in the design and construction of the other apparatus. Help in this construction was also given by the Physics Department Shop, under the supervision of E. M. Griffiths. Herbert N. Royden's work on the electrometer and its calibration is gratefully acknowledged, as is the extensive assistance given by Miriam Caldwell in the mathematical and computational tasks. One of us (D.O.C.) wishes also to thank Professor P. Scherrer for the hospitality of the Physics Institute of the Swiss Federal Institute of Technology during the writing of this paper.

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PHYSICAL REVIEW VOLUME 98, NUMBER 1 APRIL 1, 1955

# Decay of the 3.5-min Metastable State of $Sb^{122}$

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(Received November 4, 1954)

The radiations associated with the 3.5-min activity of $Sb^{122}$ have been studied with 180° magnetic photographic spectrometers and a ten-channel coincidence scintillation spectrometer. Two gamma rays with energies of 60.7 and 75.3 kev were detected by means of internal conversion electrons and also by means of the scintillation spectrometer. The 75.3-kev transition is the more strongly converted of the two, and it is concluded that it is the isomeric transition. The two gamma rays are emitted in cascade.

An isomeric state in $Sb^{122}$ was first reported by der Mateosian *et al.*[1] in 1947. They measured its half-life to be 3.5 min. The gamma rays associated with the 3.5-min decay have been investigated by two groups, one employing a scintillation spectrometer[2] and the other an ionization chamber.[3] The results of the scintillation spectrometer study indicated the presence of one gamma ray with an energy of 68 kev, whereas

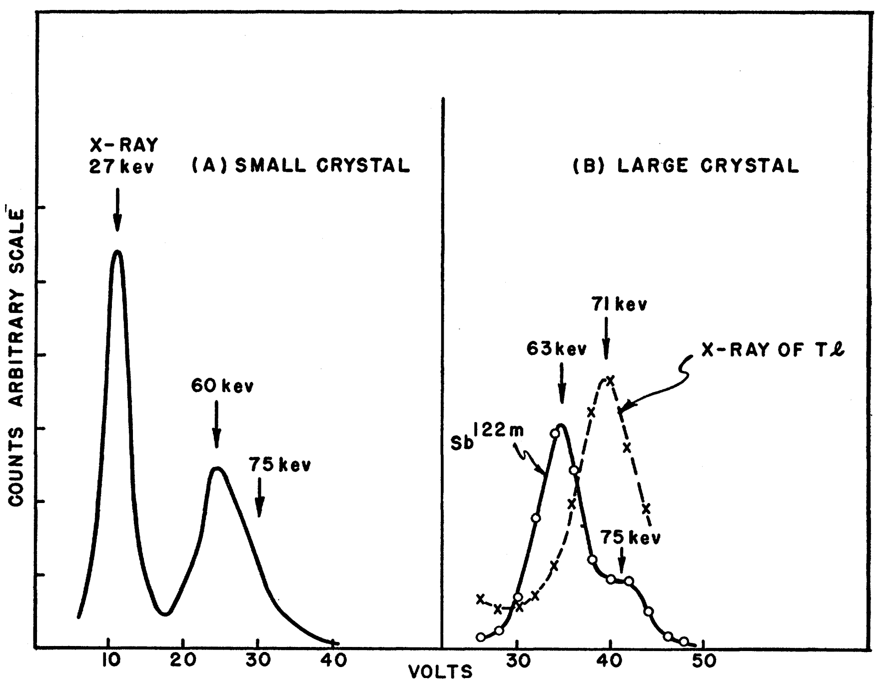


Fig. 1. NaI(Tl) pulse-height distributions of gamma rays from $Sb^{122m}$.

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* University of Michigan, Ann Arbor, Michigan.
[1] der Mateosian, Goldhaber, Muehlhause, and McKeown, Phys. Rev. **72**, 1271 (1947).
[2] E. der Mateosian and M. Goldhaber, Phys. Rev. **82**, 115 (1951).
[3] J. H. Kahn, Oak Ridge National Laboratory Unclassified Report ORNL-1089, Nov. 1951 (unpublished).