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# Proton-Proton Scattering at 14.5 Mev

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The scattering of 14.5 Mev protons by protons has been studied by using a coincidence counting method. The 14.5 Mev protons were obtained from the 37-inch synchrocyclotron at Berkeley. The measurements of the differential scattering cross section are absolute and extend from 10° to 45°. The accuracy was not high, about ten percent, because the pulsed nature of the synchrocyclotron beam introduced a large background of accidental counts. At small angles the scattering is significantly larger than that predicted by $S$ wave scattering only. This indicates the effect of $P$ wave scattering such as that due to a repulsive potential well. The results are not inconsistent with those found at 8 and 10 Mev.

WHEN a deflected beam of 14.5 Mev protons was obtained from the 37-inch synchrocyclotron at Berkeley, it became desirable to study the scattering of protons from protons by means of the same experimental techniques which had previously been developed and used at Princeton, where 8 Mev protons were available. The results obtained at that energy[1] were most consistent with the scattering predicted by the $S$ wave contribution only.[2] The accuracy was not great enough to exclude $P$ wave scattering effects except for those predicted by the neutral meson theory. The same equipment was subsequently used at Berkeley with 10 Mev protons, and more precise data were obtained.[3] These results have been analyzed by Peierls and Preston,[4] and by Foldy.[4]

Peierls and Preston find from these data a mean range of the proton-proton force of 2.5 $\times 10^{-13}$ cm, and that the $P$ scattering is compatible with a repulsive square well of this range and of 10 Mev in magnitude. However, Foldy has criticized this analysis and expressed disagreement with the above conclusions.

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[1] R. R. Wilson and E. C. Creutz, Phys. Rev. **71**, 339 (1947).
[2] Breit, Thaxton, and Eisenbud, Phys. Rev. **55**, 1018 (1939).
[3] R. R. Wilson, Phys. Rev. **71**, 384 (1947).
[4] R. E. Peierls and M. A. Preston, Phys. Rev. **72**, 250 (1947); L. L. Foldy, Phys. Rev. **72**, 125 (1947).

At 14.5 Mev the $P$ wave effects predicted by the various theories should be much more pronounced than at the lower energies and it was hoped that even rough measurements would be useful. The method used, essentially that previously employed, was a coincidence counting arrangement in which the narrow incident proton beam was scattered by a very thin nylon foil. When a proton is scattered from one of the hydrogen nuclei in the nylon foil, that hydrogen nucleus or proton will then recoil, traveling in a direction perpendicular to the direction of the scattered proton. Two proportional counters were mounted on a movable table, as shown in Fig. 1, such that if the scattered proton entered the *defining counter*, the associated recoil proton would surely enter the *monitoring counter* and then register a coincidence.[5] On the other hand, if the proton was scattered from another element in the foil, or had been scattered from the beam defining slit, no coincidence would be recorded since such a scattering process would not be accompanied by a recoil proton at 90°. The details of the equipment and method have been described in another article.[1] The second alignment procedure described in reference (1) was used in the present experiment. The electronic circuits were similar to those used at Princeton but were more elaborate. They were borrowed from the Los Alamos Laboratory for the experiment. The amplifiers were the Elmore model 500 with a time of rise of roughly 0.2 microseconds. The proportional counters were filled with a mixture consisting of ninety-five percent argon and five percent carbon dioxide at a total pressure of about 25 cm Hg. The bias voltages of the discriminators were set as low as was possible without getting too many accidentals. Higginbotham scaling circuits were used to record the number of pulses in each proportional counter as well as the number of coincidences. The proton beam current integrating system was changed somewhat from that used at Princeton and it will be described later in this article.

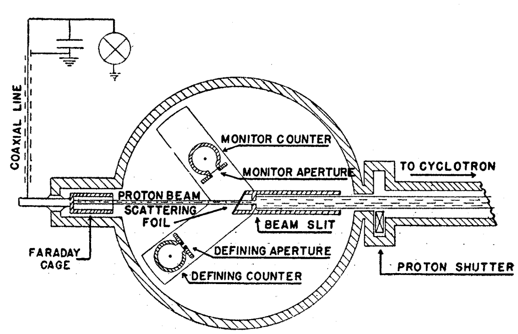


FIG. 1. Schematic drawing of the scattering chamber and integrating system.

[5] The monitor counter was actually adjusted at $89\frac{1}{2}°$ with respect to the defining counter to allow for a relativistic effect on the angle between scattered and recoil protons. Since the monitor counter subtended an angle of 7°, this adjustment was not essential.

The scattering foil, nylon $(C_{12}H_{22}N_2O_2)_x$ about $2\times 10^{-4}$ cm thick, was placed at the center of the scattering chamber and mounted so that the normal to the plane of the scattering foil made an angle of 30° with the direction of the incident proton beam which was 2.0 mm in diameter. (Fig. 1.) The scattered protons entered the "*defining proportional counter*" through a circular aperture of 2.47 mm diameter which was 7.8 cm from the center of the scattering foil. The aperture of the monitor counter, which was mounted so that it received the recoil protons at 90° with respect to the defining counter, had an oval aperture $\frac{3}{16}$ in. wide and $\frac{5}{16}$ in. high, and it was 3.7 cm distant from the scattering foil. Of course, the recoil and scattered protons could not be distinguished, but, for the purposes of this paper, those protons which entered the defining counter will be called scattered protons and those which entered the monitor counter will be called recoil protons.

The solid angle of the monitor counter was large to insure that the recoil protons associated with all protons entering the defining counter would enter the monitoring counter. However, for the smallest angles at which the scattering was studied, i.e., 10° and 12° with respect to the incident proton beam, the vertical aperture of the monitor counter was not large enough and thus, for geometrical reasons, in a small proportion of cases for protons which entered the defining counter the associated recoil protons could not enter the monitor counter. One can readily demonstrate that in the plane of scattering (the horizontal plane) the spreading of the recoil protons at the monitor counter due to the finite size of the scattering area and the defining aperture is less than 75 percent of the total width of the monitor aperture and that it does not change rapidly with the angle. Hence, there was no loss due to the horizontal spreading at any angle. On the other hand, the vertical spreading of the recoil protons at small scattering angles was corrected as follows: The incident proton beam of circular cross section was separated into six narrow vertical sections of equal base length. Corresponding to each of these sections the vertical density distribution at the monitor aperture of recoil protons corresponding to scattered protons uniformly entering the circular defining aperture was numerically and geometrically calculated. The distributions from each of the narrow beam sections were then added together to give the final vertical recoil distribution at the monitor aperture. This is shown in Fig. 2. The effect of multiple scattering on the distribution was determined in the same way that is discussed at length in reference (1) and was found to be negligible. The vertical arrows in Fig. 2 indicate the positions of the top and bottom of the monitor counter. The fractional correction to be added to the observed coincidence rate is the ratio of the area outside the arrows to that included inside the arrows. At 10° this correction amounts to $(13\pm1)$ percent. Similar numerical calculations showed the correction to be $(8\pm1)$ percent at 12°, $(3\pm1)$ percent at 14°, and less than 0.2 percent at 18°. Since the final results have statistical errors of about 10 percent, it was felt that the above degree of approximation for the correction was adequate.

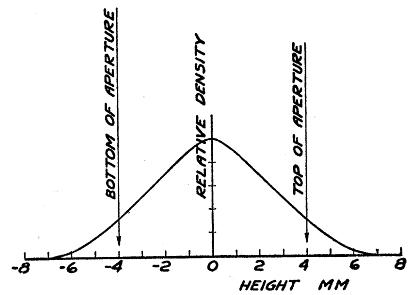


FIG. 2. The distribution of protons in the vertical direction along the aperture of the monitor counter. The protons striking outside the arrows would not enter both the defining and monitor counters, and hence would not cause coincidences.

The proton-proton coincidences in the proportional counters, together with the individual counting rates in each counter, were observed at each scattering angle $\theta$ during a series of ten minute runs of the cyclotron. During each ten minute run, the proton beam was maintained at as constant intensity as possible. In order to normalize each run, however, and reduce the measurements to an absolute basis, it was necessary to measure the integrated proton beam current during each ten minute observation. This was accomplished by permitting the primary proton beam, after it had passed entirely through the scattering chamber, to enter a Faraday cup collector. The Faraday chamber was connected to a standard mica condenser through a concentric solid core dielectric cable (8PGU) and the potential of this system relative to ground was measured by a quadrant electrometer. The capacitance of the entire system relative to ground was 0.101 microfarads. The electrical connections are shown in Fig. 1. It was determined that the coaxial cable did not contribute any leakage current due to the effects of the slow neutrons from the cyclotron. The condenser was a standard (Pye) instrument chosen because of its low leakage rate and small soakage charge. The system was checked for both leakage and soakage at frequent intervals and these effects were found to be negligible in comparison to the other uncertainties of measurement. A quadrant electrometer was connected heterostatically with the needle at 90 volts above ground. The deflections were measured by a lamp and scale arrangement; a typical deflection of the light spot during a ten minute run being about 7 cm on the scale at a meter from the electrometer mirror. The condenser was ungrounded at the beginning of each run and the observation consisted of recording the position of the light spot at the end of the ten minute interval, and then determining the zero position by again grounding the condenser system and reading the deflection immediately afterwards with the grounding switch again open to eliminate contact potential differences. As a control, the electrometer was observed during runs when the shutter of the scattering chamber was closed so that no protons could enter, and it was always found that the deflections were negligible. The integrating system was calibrated before each set of runs with an RCA instrument which applied a known voltage to the standard condenser. The RCA instrument in turn was calibrated several times against a standard potentiometer. The day-by-day calibrations of the system were remarkably uniform, because the graph of the electrometer deflections *vs.* applied voltage was strictly linear in the range of operations.

The calibration data were plotted on a graph giving deflection of the light spot against applied calibration voltage. The best straight line drawn through all the calibration points gives: 1 cm deflection = 0.01238 volts. This figure combined with the capacity of the integrating system yields: 1 cm deflection = $1.250\times10^{-9}$ coulombs collected, which is equivalent to $N_p=7.81\times10^9$ protons in the incident beam per cm deflection. The uncertainty in $N_p$ is about 2 percent.

The beam from a synchrocyclotron comes in short bursts about 50 microseconds long and with a recurrence rate of about 600 per second. This produced a very high rate of counting during the pulse for any appreciable average counting rate and so the number of accidental coincidences was significant. The correction for the accidentals is complicated because the background counts in the proportional counters, many times the counts resulting from protons scattered by protons, were caused in part by protons and in part by neutrons. Unfortunately, the neutron pulse, which probably comes from protons striking the dees or deflector, was not of the same length as the deflected proton pulse.

If one assumes that the neutron pulse has a square shape and is of length $\delta$ and that the proton pulse has a similar shape but of length $f\delta$, then one can derive a correction formula in the usual way to get:

$$n_a=\frac{2\tau}{R\delta}\left[n_1n_2+\left(\frac{1}{f}-1\right)n_1{}^pn_2{}^p\right] \qquad (1)$$

where $n_a$ is the number of accidentals per second, $n_1$ and $n_2$ the total counting rates in each channel, $n_1{}^p$ and $n_2{}^p$ the counting rates in each channel due to protons only, $\tau$ the resolving time of the coincidence system, and $R$ the repetition rate. This formula is at least dimensionally correct and since in practice the lumped constant $2\tau/R\delta$, and $f$ were determined under nearly the same conditions that data were taken, the formula can be expected to be a good approximation. The lumped constant $2\tau/R\delta$ was determined to be $(1.0\pm0.1)\times10^{-5}$ seconds$^{-1}$ by observing the accidental rate when the proton beam was shuttered off just before entering the scattering chamber. The background counting rates in the proportional counters were then due altogether to the neutron bursts and the second term in Eq. (1) was zero. The fraction $f$ was determined by misaligning the proportional counters such that the angle between them was sufficiently far from 90° so that no true coincidences should have occurred. Several ten minute runs were made during which $n_a$, $n_1$, and $n_2$ were recorded. After each of these runs, the proton beam was shuttered off and a two-minute run was made to determine the counting rate of the proportional counters due to neutrons only. Subtracting these rates from $n_1$ and $n_2$ gave $n_1{}^p$ and $n_2{}^p$ respectively. It was then possible to solve (1) for $(1/f-1)$. The average result of several runs was $(1/f-1)=3.0\pm0.4$ or $f=0.25\pm0.02$.

In a typical cyclotron run of ten minutes duration, the data taken consisted of the number of counts in each channel, i.e., $n_1$ and $n_2$, the total number of coincidences, and the electrometer deflection. A blank run of one or two minutes duration during which the shutter was placed in the proton beam was made immediately following most runs. From these data, it was possible to calculate $n_1{}^p$ and $n_2{}^p$ and, by using Eq. (1), the number of accidental counts could be determined and subtracted from the observed number of coincidences to give the true coincidences. Because of the pulsed nature of the beam, the average value of the corrections was rather high, in many cases being about twenty-five percent of the observed coincidences.

In order to assign an absolute value to the scattering cross section it was necessary to know the number of hydrogen nucleii in the nylon scattering foil per square centimeter normal to the beam. This was determined from interferometer measurements of the thickness and a knowledge of the density and composition of the nylon foil.[6]

The Jamin interferometer index was set on the center of a system of white light fringes and then

[6] The foil was obtained from the DuPont Company, Wilmington, Delaware.

the foil, still mounted on its holder, was placed in one of the light paths so that the light passed through the same area of foil and at the same angle as did the protons in the scattering experiment. The compensator shift necessary to bring the fringe system back to index was recorded as $c$. The fringes were not as sharp as previously because of the inhomogenity of the foil, but the position of the center could be estimated. The compensator was calibrated with sodium light, a shift $c'$ corresponding to one sodium light fringe. In five trials, $c$ was found to be $0.810\pm1.6$ percent and $c'$ to be $0.364\pm1.4$ percent where the errors are r.m.s. deviations from the mean. The index of refraction, $n$, was determined by a comparison of samples of the same foil with calibrated oils using a geologist's polarizing microscope. These comparisons gave for $n$ values of $1.545\pm0.003$ and $1.520\pm0.003$ for the two directions of polarization. An average of $n$ equal to $1.533\pm0.004$ was used. The estimated probable error is based upon the intervals between the refractive indices of the liquids between which the nylon was bracketed. If $\lambda$ is the average wave-length of sodium light the thickness of the foil in the direction of the proton beam is given by $t=c/c'\lambda/(n-1)=2.46\cdot10^{-4}$ $\pm2.3$ percent cm.

The number of hydrogen nuclei per square centimeter, $N_H$, will be given by $N_H=tdh/m$, where $d$ is the density of nylon, $h$ is the fraction of hydrogen in the nylon by weight, and $m$ is the mass of the hydrogen atom. The density was determined by comparing the weight in air and the weight in water (with a wetting agent) of 3 samples of the same material using a micro balance. Each of these trials gave 1.13 g/cm$^3$ with an uncertainty due to weighing of $\frac{1}{2}$ percent. There is an additional uncertainty of about $\frac{1}{2}$ percent due to water content of the foil. This estimate of the error due to water content is based upon the increase in weight of a vacuum dried sample exposed to humid air. The fraction of hydrogen in the nylon was determined by weighing the water of combustion of weighed samples, which were dried in a vacuum desiccator before combustion with dry oxygen.[7] Two trials gave 0.0986 and 0.0972 with an estimated probable error of $\pm1$ percent. From the formula $(C_{12}H_{22}N_2O_2)_x$ one can compute $h=0.0980$. The DuPont Company reports $h=0.101$ from the weights of the reactants in the nylon polymer. All four of the above determinations were averaged with equal weight to give $h=0.099\pm1$ percent. These data give a value for $N_H$ of $(1.64\pm2\frac{1}{2}$ percent$)\times10^{19}$ hydrogen atoms per square centimeter normal to the beam.

A check on this value of $N_H$ was obtained by comparing the stopping power of the foil with the stopping power of air for 4.05 cm $\alpha$'s in a pulse analyser.[8] The foil was placed at the beginning of the range of the $\alpha$'s and oriented so they went through at the same angle as the protons. It was found that, because of the inhomogenity of the foil, the $\alpha$'s emerged in two groups with a loss of range of 0.22 and 0.30 cm. If the decrease of range, $r$, is taken as the average of these figures, the number of hydrogen atoms per square centimeter will be, $N_H=hrd_aW_n/mSW_a$, where $d_a$ is the density of air, $W_a$ is the average atomic weight of air, $W_n$ is the molecular weight of nylon, and $S$ is the relative stopping power of nylon. $S$ was computed as 19.68 from the formula $(C_{12}H_{22}N_2O_2)_x$ by using atomic stopping powers tabulated by L. H. Gray.[9] From these numbers one gets $N=1.53\cdot10^{19}$, but the uncertainties in $r$ are so large that this value is given only as a gross check of the value given by the former method.

The energy of the scattered proton varies with scattering angle and incident energy as $E_0\cos^2\theta$. This made it possible to determine the incident energy $E_0$ by observations of the falling off of the coincidence rate with decreasing angle $\theta$ with a 10 mil Al foil placed behind the aperture of the monitor counter. As $\theta$ was decreased, the energies of the recoil protons decreased as $E_0\sin^2\theta$ until the energy of the recoil protons was such that only half of them would penetrate the 10 mil Al foil and cause coincidences with the associated scattered protons. This thickness of the Al foil corresponded to the recoil protons' mean range and from this their energy could be determined from the range-energy relationship for protons in aluminum. The angle at which fifty percent of

[7] This was done by Charles Koch, Chemistry Department, University of California, Berkeley, California.

[8] These measurements were made by Albert Ghiorso, Radiation Laboratory, University of California, Berkeley, California.

[9] L. H. Gray, Proc. Camb. Phil. Soc., **40**, 72 (1944).

the recoil protons penetrated the foil was determined from a curve of scattering yield plotted as a function of the scattering angle $\theta$. In the region where the range of the recoil protons was close to the thickness of the Al foil, a typical straggling curve was observed. The curve began to drop at a scattering angle of about 42.2° (the intersection of the extrapolation of the linear part of the curve and the 100 percent yield plateau). It reached zero at about 38.2°, and passed the 50 percent point at 40.2°. The Al foil, which was accurately 9.99 mils in thickness, corresponds to the range of a 6.0 Mev proton[10] and dividing this energy by $\cos^2(90-40.2)$ gives 14.5 Mev for the energy of the protons in the cyclotron beam. Since the spread of the curve was close to that expected from straggling and geometry alone, the protons in the incident beam were probably uniform in energy to within a few percent. However, the only precautions that were taken to keep the proton beam monoenergetic were to keep the running conditions of the synchrocyclotron, particularly the deflector voltage and magnetic field, as constant as possible.

The proportional counters were filled with a mixture of argon gas containing five percent $CO_2$ at a pressure of about 25 cm Hg. The counters were pumped and refilled after every second cyclotron run. Thin nylon foils ($2\times10^{-4}$ cm) behind the counter apertures separated the counter volume from the high vacuum of the scattering chamber. The very low specific ionization of the high energy protons made it difficult to obtain good counting plateaus. To correct this difficulty, aluminum absorbers of the proper thickness were placed immediately behind the counter apertures to slow down the protons to an energy of a few Mev. Thus their paths in the counters were nearer the end of their range where the specific ionization was much larger and hence the proportional counter pulses were also much larger. Because the energy of the scattered protons changed so rapidly with angle, it was necessary to use three sets of foils to cover the range of angles under investigation. For angles near 45°, both scattered and recoil protons had an energy of about 7 Mev. Hence aluminum foils of 10 mils thickness were placed behind the apertures of each counter. For scattering angles from $\theta=10°$ to $\theta=18°$, the energy of the scattered proton varied from 14 to 13 Mev. A 43 mil Al foil was used behind the aperture of the defining counter for values of $\theta=10°$, 12° and 14°; and a 38 mil Al foil was used for the data taken at 18°. On the other hand, at these angles the energy of the recoil protons varied between 0.44 and 1.5 Mev and hence no foil except the thin nylon window was used behind the monitor or recoil counter aperture.

To insure that all the 0.44 Mev recoil protons associated with protons scattered at 10° were able to penetrate the nylon scatterer and the nylon counter window, those foils were made as thin as possible by repeated stretching. In addition, the scattering foil was placed at an oblique angle with respect to the incident proton beam so that as short a path as possible in the scatterer was presented to the recoil protons.

It was found that the stopping power of the scattering foil was equivalent to 0.3 cm of air, and since both this foil and the monitor counter window were made in the same way, the two foils together should have a stopping power of 0.6 cm of air and therefore should certainly pass protons of 0.37 Mev. Hence the 0.44 Mev recoil protons should have penetrated both foils easily. This was further checked by one run at $\theta=9°$ where more true coincidences were observed than at $\theta=10°$.

Many experimental troubles were experienced before reliable results were obtained. In part, the difficulties were caused by an underestimation of the accidental coincidences due to the pulsed nature of the synchrocyclotron beam; in part they were caused by an electronic difficulty that developed but which did not become apparent until it manifested itself by a short circuit that could be traced and repaired. A final difficulty was caused by the rapid variation of

TABLE I. Scattering cross sections of 14.5 Mev protons on protons.

| $\theta_{c.m.}$ | $n$ | $\sigma_{c.m.}$ | $\epsilon$ |
|---|---|---|---|
| 20° | 12 | $4.6\times10^{-26}$ cm$^2$ | $\pm0.3\times10^{-26}$ cm$^2$ |
| 24° | 20 | 3.1 | 0.2 |
| 28° | 7 | 3.6 | 0.4 |
| 36° | 11 | 3.0 | 0.3 |
| 90° | 34 | 3.34 | 0.2 |

[10] J. H. Smith, Phys. Rev. **71**, 32 (1947).

TABLE II. Scattering cross sections of 10 Mev protons[3] (for comparison).

| Date | $\theta_{lab}$ | Coincidences per proton | Coinc. per proton/$\cos\theta$ | Mean square error percent | $\sigma_{c.m.}$ | $\theta_{c.m.}$ |
|---|---|---|---|---|---|---|
| May 11 | 45° | 102.5 | 146 | 1.2 | $4.90^{*}\times10^{-26}$ | 90° |
| Foil *A* | 25° | 129 | 142 | 1.4 | 4.77 | 50° |
| | 20° | 129.5 | 138 | 1.4 | 4.63 | 40° |
| | 19° | 130 | 137 | 1.3 | 4.60 | 38° |
| June 1 | 45° | 123.5 | 175 | 0.6 | 4.90* | 90° |
| Foil *B* | 22° | 156 | 169 | 1.2 | 4.73 | 44° |
| June 16 | 28° | 53.7 | 60.8 | 1.8 | 4.72 | 56° |
| Foil *C* | 26° | 56.0 | 62.3 | 1.2 | 4.82** | 52° |
| | 18° | 57.3 | 60.3 | 1.2 | 4.68 | 36° |
| | 16° | 58.1 | 60.5 | 1.5 | 4.70 | 32° |
| | 14° | 61.0*** | 63.0 | 2.0 | 4.88 | 28° |
| | 12° | 67.8**** | 69.5 | 3.0 | 5.39 | 24° |

* The values of $\sigma$ at 45° were adjusted to 4.90 for foils *A* and *B*.
** The values of $\sigma$ for foil *C* were adjusted such that the average at 26° and 28° were equal to the value of $\sigma$ at 25° for foil *A*.
*** The measured value of 60.5 was corrected by +0.8 percent for geometrical and multiple scattering loss.
**** The measured value of 60.5 was extrapolated to 66 using a number-bias curve; then a correction of 3 percent was added for the geometrical and multiple scattering loss.

pulse height with proton energy which is a function of scattering angle. The coincidence circuit resolving time $\tau$ originally used was 0.2 microsecond and the rise time of the linear amplifier was also of this order of magnitude. So long as the pulse heights in both counters were equal and large and low relative biases were used, no trouble was experienced in the coincidence circuit. However, when the pulse in one counter is very large and the other pulse is very small, then because of the rise time of the amplifier, the gate caused by the small pulse could have been delayed enough so as not to coincide with the gate caused by the larger pulse which would suffer no appreciable delay. As the scattering angle approached 10°, just such a condition occurred, since the pulses caused by the recoil protons became very large while the pulses caused by the scattered protons became very small. This condition was discovered by measuring scattering yield at a particular angle as a function of coincidence resolving time. At $\theta=45°$, where both proton pulses were the same height, the resolving time was varied from 0.1 $\mu$sec. to 0.4 $\mu$sec. without measurable effect. However, at $\theta=10°$ in changing from 0.2 $\mu$sec. to 0.4 $\mu$sec. a considerable increase in the scattering yield was noticed. At $\theta=12°$, 14°, and 18° the effect was intermediate. Hence, for small angles all data taken with the 0.2 $\mu$sec. resolving time were rejected. Since the rise time of the linear amplifiers was about 0.2 $\mu$sec., it was felt that the coincidence circuit resolving time of 0.4 $\mu$sec. was sufficiently large so that no counts were lost because of this effect of different pulse height. This fact was not established experimentally, as at 45°, because going to resolving times greater than 0.4 $\mu$sec. would have caused an excessively large accidental coincidence background and, furthermore, the equipment was not designed to produce larger resolving times.

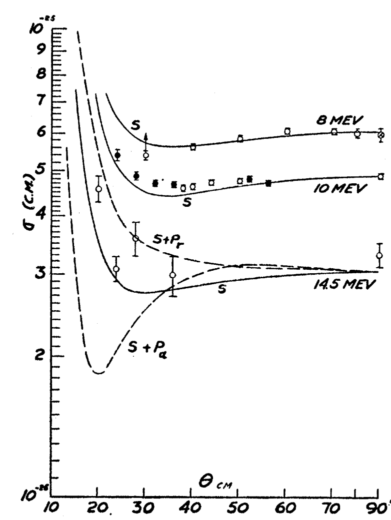


FIG. 3. The differential scattering cross section in the center of mass system as a function of the angle of scattering in the center of mass system. For comparison, the results obtained at 8 Mev[1] and 10 Mev[3] are also given. The measurements at 10 Mev are relative and have been adjusted arbitrarily at 90°. The measurements at 8 Mev are relative to the point at 90° which was determined absolutely. The solid curves represent the theoretically expected scattering on the basis of *S* wave scattering only.

Because of this fact and also the possibility that the foil window in the recoil proton counter was too thick to pass all the recoil protons at 10°, the scattering yield at 10° can be regarded as a lower limit. We feel, however, that neither of the above effects are appreciable in comparison to the final statistical probable error.

The results obtained[11] are given in Table I where $\theta$ is the scattering angle measured in the center of mass system (twice the angle actually measured), $n$ is the number of ten minute runs at each angle, $\sigma_{c.m.}$ is the absolute scattering cross section per unit solid angle in the center of mass system, and $\epsilon$ is the experimental mean square error determined from the deviations of the values given by the ten minute runs from the mean. The values of $\sigma$ are plotted in Fig. 3 as a function of $\theta$. The curves were computed by L. L. Foldy on the assumption of a square well of depth 10.5 Mev and width $e^2/mc^2$ both for $S$ wave scattering alone (solid curve), and for $S$ plus $P$ wave attractive (lower dashed curve) and repulsive (upper dashed curve). Also in Fig. 3, for comparison, are plotted the results obtained at 8 Mev[1] and 10 Mev.[3] The 10 Mev data are also given in Table II as they appear elsewhere[3] only in graphical form. A detailed theoretical analysis of the above experimental work will be included in a forthcoming paper by L. L. Foldy in this journal.

It is a pleasure to express our appreciation to Professor E. O. Lawrence for making the facilities of the Radiation Laboratory available to us.

[11] The values of $\sigma$ given in Table I are slightly different for small angles than those given by us in a preliminary report, Phys. Rev. **71**, 560 (1947) because there the wrong diameter of the defining counter aperture was used in calculating the geometrical loss correction. The correction was calculated correctly for the 10 Mev data.[3]