TABLE I. *Information relative to the power of the method to resolve gamma-ray lines.*

Energy of gamma-ray $=h\nu$ in Mev	3.0	5.0	10	16
Energy of photoproton $=E_H$ in Mev	0.4	1.4	4	7
h.w. of E_H due to straggling in percent of E_H	7	5	4	3.5
h.w. of E_H in kv due to energy spread for all ψ	60	190	650	1370
h.w. of $h\nu$ in percent of $h\nu$	5	8	14	19
h.w. of $h\nu$ in kv taking $75° < \psi < 105°$	60	150	400	800

means that the source must have a strength of at least two millicuries in the gamma-ray line being investigated.

Whether or not two gamma-ray lines can be resolved by the method, can be determined from the width of the probable energy values of the photoprotons to be expected from a single line. Table I contains the essential information (neglecting instrumental error, which can be made small). The width at half-maximum ordinate (designated in the table by h.w.) is a convenient measure of the difference in the energy of two lines which can be just resolved.

Thus one sees that by using an angular restriction (Fig. 1) it would be possible to resolve lines differing in energy by 60 kv at 3 Mev or 800 kv at 16 Mev. This is probably the best that can be done by any method at present, particularly for the lower energies. There is also a distinct advantage in having the gamma-ray energy depend upon the mean of a distribution rather than its end point (as in the case of the Compton recoils[12] because it makes unnecessary an estimate of the instrumental probable error. Another advantage is the comparatively small dependence on angular variation, so that good results can be obtained under very difficult geometrical conditions. Obviously, the method is only applicable to gamma-radiation of energy greater than 2.2 Mev.

We are very grateful to Professor E. O. Lawrence and to Professor J. R. Oppenheimer for many discussions of this work. Thanks are due to Dr. F. N. D. Kurie for helpful criticism. The experimental work was supported by the Josiah Macy, Jr., Foundation and the Research Corporation and the Chemical Foundation.

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[12] J. R. Richardson and F. N. D. Kurie, Phys. Rev. **50**, 999 (1936).

FEBRUARY 1, 1938 PHYSICAL REVIEW VOLUME 53

The Scattering of Protons by Protons

L. R. HAFSTAD, N. P. HEYDENBURG AND M. A. TUVE
Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.

(Received December 13, 1937)

Our measurements of proton-proton scattering during 1936 established the existence of large *nuclear forces* between protons at close distances, in addition to the usual Coulomb forces. These nuclear forces give rise to scattering in excess of the Coulomb prediction, appreciable at 700 kilovolts and very marked at 900 kv. In the energy region between 200 kv and 600 kv the amount of scattering to be expected on the basis of *attractive* nuclear forces is radically different from that to be expected on the hypothesis of *repulsive* nuclear forces since in the first case a decrease and in the second an increase, with respect to the classical scattering, is predicted. We have accordingly extended our measurements to include this energy region, and have obtained results which can only be explained by the assumption of a strong *attractive* force of short range acting in addition to the repulsive Coulomb forces between the particles. The magnitude of the nuclear force required is in approximate quantitative agreement with that deduced from our results of 1936, experimental difficulties due to the low residual energies of the scattered particles, and the very small numbers of counts in some regions of voltage and angle (as low as three percent of the Coulomb prediction) preventing a high precision in these results below 600 kv.

INTRODUCTION

MEASUREMENTS on the scattering of protons by protons made in this laboratory last year[1] showed a considerable excess in the scattering at angles around 45° over that which would be expected for ordinary Coulomb interaction between the particles as assumed by Mott.[2] By a careful mathematical analysis,

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[1] Tuve, Heydenburg and Hafstad, Phys. Rev. **50**, 806–825 (1936).

[2] Mott, Proc. Roy. Soc. **A126**, 259–267 (1930).

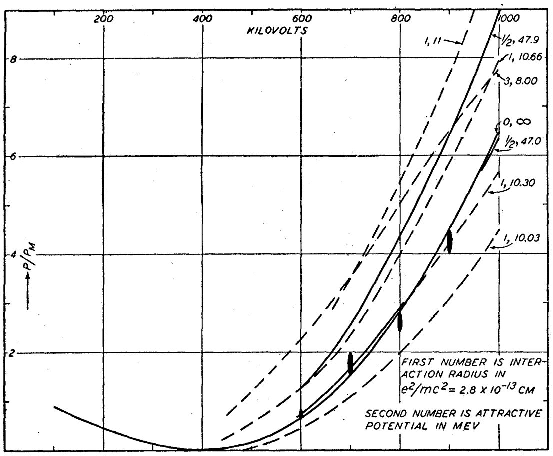

FIG. 1. Theoretical variation of P/P_M, with energy at scattering angle of 45° (ovals obtained from second set of data of T.H.H. using theoretical angular distribution curves fitted to experiment at higher scattering angles) [after Breit, Condon, and Present].

Breit, Condon and Present[3] were able to show that, while either strong repulsive or strong attractive forces in addition to the ordinary Coulomb force could account for the observed excess scattering at 45° at the various voltages, agreement with the experimental results as a function of angle (15° to 50°) at the various voltages was obtained only on the assumption of an *attractive* force of short range (under 10^{-12} cm). If such an attractive force exists between two protons, then one may expect that for some specific combination of the impact parameters the effect of the repulsive Coulomb force should be approximately canceled by the short range attractive force, and at this point a decrease in the number of scattered particles should be observed. This expectation is, of course, largely independent of any specific type of theoretical analysis of the problem. The results of the analysis of Breit, Condon and Present are summarized in Fig. 12 of their paper which is reproduced here as Fig. 1. The ordinates P/P_M are the ratios of the number of scattered protons actually observed or expected on the assumption of attractive forces to the number which would be expected on the basis of repulsive Coulomb forces alone as assumed by Mott. It is seen that the experimental points agree satisfactorily with the theoretical curves in the region above 600 kv, but that no data were available in the neighborhood of the predicted minimum at 400 kv which might serve to verify the deduction made from the higher voltage observations that the "new" force encountered in very close collisions, and superposed on the Coulomb repulsion, is an attractive force and not a suddenly increased repulsion (as for elastic spheres).

The observations of last year were made with the use of an ionization chamber attached to a linear amplifier. This combination was chosen because it permits particles of different kinds, or different energies, to be readily distinguished, and thus reduces the danger of misleading results due to spurious counts. However, this apparatus suffers from the disadvantage that it responds only to particles which are able to produce several thousand ions within the collecting chamber, and therefore fails to detect, with certainty, protons with a residual range, after energy-losses on scattering and on penetrating the ionization-chamber window, of less than about three millimeters. In the case of protons scattered at 45°, which retain only half of the incident energy, the limit for safe detection was reached at 600 kv, and consequently no observa-

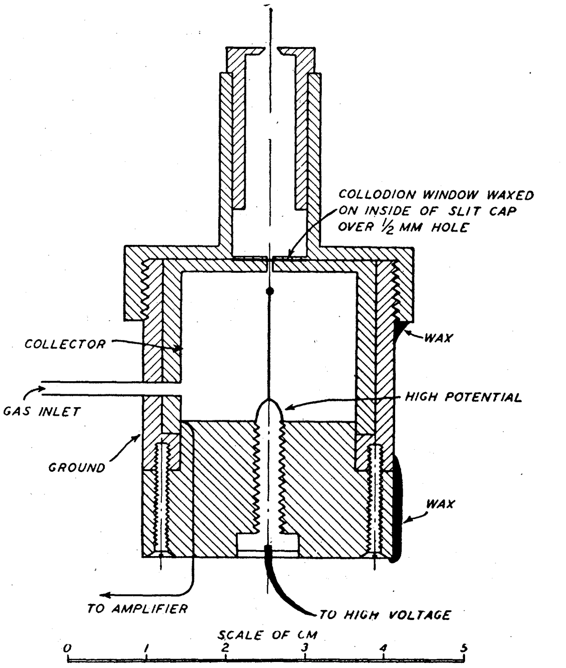

FIG. 2. Geiger point-counter.

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[3] Breit, Condon and Present, Phys. Rev. **50**, 825–845 (1936). See also, Sexl, Naturwiss. **50**, 795–796 (1936).

tions by this method were attempted at lower voltages.

Since it was especially desirable to establish definitely the existence or nonexistence of the minimum required by the assumption of an attractive force, measurements on proton scattering have now been extended down to 220 kv by the use of the less reliable, but highly sensitive, Geiger point-counter for the detection of the scattered particles.

As will be found below, the results obtained with the Geiger counter detection technique are as yet not satisfactory from a quantitative standpoint. However, since the qualitative fact of the existence of the "scattering minimum" required by the assumption of attractive forces is so directly and strikingly demonstrated by the observations so far obtained, and since it will not be possible to repeat these observations for some time, it seems desirable to report our results in their present form.

Apparatus and Technique

A new scattering apparatus was built following the observations made last year. This was done to improve the alignment of the detector with respect to the incident beam, to provide a less troublesome ground joint for rotating the detecting chamber, and to provide a more accurate angular scale with a vernier for measuring the position of the detector. The dimensions of the new slit-systems, for the incident beam and for the detector, were not changed significantly from those of last year.[1]

The detector for the scattered protons consisted of a Geiger point-counter, with a 3-stage amplifier of the type by Johnson and Street,[4] which was available in the laboratory. The output of the amplifier was connected to a scale-of-eight thyratron recorder of a design due to Giarratana.[5] A cross section of the Geiger counter is shown in Fig. 2.* A platinum wire 0.002 inch in diameter, with a bead about three times this diameter, formed on the end of the wire in an oxygen gas flame, was used in the counter. The chamber was operated at a helium pressure of 13 cm of mercury. A collodion[6] window of about 1 mm stopping power was placed over the aperture of the counter to close the chamber from the scattering volume. It was found difficult to make a bead on the platinum wire which had satisfactory operating characteristics. Various techniques for making points were tried[7] without consistent results. It is possible that the use of other circuits[8] would have been more successful.

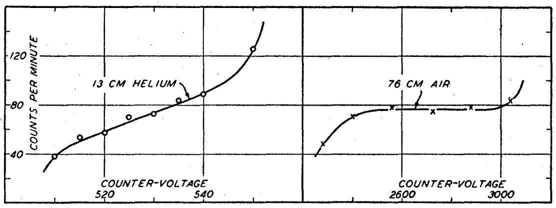

FIG. 3. Characteristics for Geiger point-counter.

In general, while a good voltage "plateau" was relatively easily obtainable at high operating pressures, as shown in Fig. 3, it was practically impossible to obtain a satisfactory plateau at the low pressures we were constrained to use because of our thin windows. This fact in itself was sufficient to prevent us from obtaining a measure of the scattering on an absolute scale. However, it is probable that no large error is introduced by this difficulty for though, as shown in Fig. 3, there was usually no definite plateau at the low pressure, a setting nevertheless could be made on the point of inflection which could be reproduced from day to day with an accuracy of perhaps 25 percent. Relative values, taken during a single run, were of course much more accurate, since, with a stabilized counter voltage, no appreciable variation in the counting rate for any given voltage setting was observed. The data were always taken as *ratios*, the 25° value usually being adopted as the standard for each day's comparisons.

A more subtle difficulty was encountered in the fact that, for most Pt points, when the output

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[4] Johnson and Street, J. Frank. Inst. **215**, 239–246 (1933).

[5] Giarratana, Rev. Sci. Inst. **8**, 390–393 (1937).

* The cross hatching should have been omitted in Fig. 2 between the inner face marked "collector" and the outer brass case. The collector was a thin-walled brass cup spaced from the outer case by a groove in the hard rubber end-plug at the bottom.

[6] We have found ordinary pharmacist's "New Skin" highly satisfactory for windows.

[7] J. R. Dunning and S. M. Skinner, Rev. Sci. Inst. **6**, 243–246 (1935); H. Geiger, *Handbuch der Physik*, Vol. 22, part 2, p. 155.

[8] H. V. Neher and W. W. Harper, Phys. Rev. **49**, 940–943 (1936); N. S. Gingrich, R. D. Evans and H. E. Edgerton, Rev. Sci. Inst. **7**, 450–456 (1936); and G. Brubaker and E. Pollard, Rev. Sci. Inst. **8**, 254–258 (1937).

from the Geiger counter was carefully observed with cathode-ray monitor at low counting rates, a single isolated "count" would often appear as a ragged group of four or more peaks usually partly unresolved. Such a peak would register as an indefinite number of counts on our "fast" thyratron recorder, thus leading to false results. This difficulty was particularly marked when air was used in the Geiger counter. The effect would probably not be observed when using electrometers or other slower methods of detection. The point which was finally used (in helium) showed sharp, clean kicks and not more than one "residual" count in five minutes.

When the Geiger point-counter was tested in the scattering chamber, it was found that there were too many background counts, these being of the same order as the scattered protons at 45°. Most of these counts were due to stray x-rays from the high voltage accelerating tube, and were eliminated by building a lead shielding box $2\frac{1}{2}$ cm thick around the scattering chamber. There still remained from 2 to 5 counts per minute which varied linearly as the number of protons entering the scattering chamber. These counts could be observed independently of the scattered protons by setting the detector at 90° to the incident beam. Counts at 90° might be due to protons scattered from heavy atoms present as a contaminating vapor or gas in the chamber. This possibility was eliminated by closing off the chamber from the pumps and, without introducing hydrogen, observing the scattering at some smaller angle. No increase in the residual counts was observed at 20° even after the chamber had remained sealed off for 30 minutes or more. The observed counts might also be due to "delta-rays" from the incident beam. Since these electrons should have small energies, a magnetic field at the counter slit-system should deflect them out before they entered the counter. The number of counts remained the same, however, with the magnetic field present. It was finally found that these counts could be eliminated by placing a thin opaque foil over the counter aperture. This indicated that the counts were due to ultraviolet light being produced by the proton beam passing through the hydrogen in the scattering chamber, this ultraviolet light producing photoelectrons in the sensitive region of the counter. We then evaporated a thin aluminum coating onto the collodion window of the counter; this increased the stopping power of the window by less than one mm while the background counts were reduced to less than one count in five minutes.

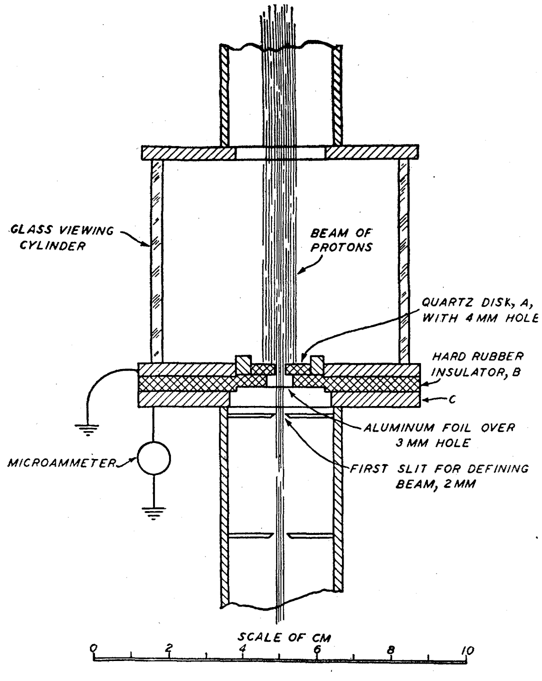

FIG. 4. Proton current monitor.

The operating conditions in the scattering chamber were similar to those of last year. Hydrogen at 12-mm pressure purified by passing through a palladium tube (at a few hundred degrees centigrade) was used in the scattering chamber. The zero angular position of the detecting chamber was determined by running a scattering curve on either side of the zero, the angle about which the two curves are symmetrical being adopted as the zero angle and the vernier being then set to read zero at this position. The mechanical zero of the instrument agreed with this position within the limits of measurement.

In an effort to overcome the difficulty of not being able to record the scattering and to monitor the beam-current into the scattering chamber simultaneously throughout a run, an arrangement shown in Fig. 4 was installed. The scattering chamber was insulated by the

TABLE I. *Experimental results on scattering of protons by protons.*

VOLTAGE (kv)	ITEM	ANGLE AND RELATIVE MOTT VALUE									REMARKS
		20° 362	25° 107	30° 44.0	35° 20.2	40° 11.3	45° 8.18	50° 7.91	55° 9.95	60° 13.4	
220	Counts per min.	...	106	42	18	9.1	4.1	2.4	1.0	...	Current about 8×10^{-10} ampere
	Total counts	...	860	417	381	182	83	48	10	...	
	$(P/P_M)_{25}=1.00$	...	1.00	0.95	0.90	0.81	0.51	0.30	0.10	...	
	$(P/P_M)_{25}=0.87$	...	0.87	0.83	0.78	0.70	0.44	0.26	0.09	...	
335	Counts per min.	...	135	47.5	16.5	6.4	3.4	4.0	4.3	...	Current reading not satisfactory
	Total counts	...	2426	523	330	128	68	40	43	...	
	$(P/P_M)_{25}=1.00$	...	1.00	0.86	0.65	0.45	0.33	0.40	0.34	...	
	$(P/P_M)_{25}=0.75$	...	0.75	0.64	0.49	0.34	0.25	0.30	0.26	...	
450	Counts per min.	...	123	38.4	11.1	3.0	0.55	2.1	5.0	...	Current about 4.3×10^{-9} ampere
	Total counts	...	2458	384	221	59	10	21	50	...	
	$(P/P_M)_{25}=1.00$	...	1.00	0.76	0.48	0.23	0.058	0.23	0.44	...	
	$(P/P_M)_{25}=0.61$	...	0.61	0.46	0.29	0.14	0.03	0.14	0.27	...	
550	Counts per min.	...	125	44.3	17.3	7.0	4.2	...	...	...	Current about 6.2×10^{-9} ampere
	Total counts	...	1756	421	173	140	84	...	...	...	
	$(P/P_M)=1.00$	...	1.00	0.86	0.73	0.53	0.44	...	...	...	
	$(P/P_M)=0.58$	...	0.58	0.50	0.42	0.31	0.25	...	...	...	
640	Counts per min.	154	45.2	17.3	8.1	6.0	5.9	3.2	...	5.5	Current about 3.9×10^{-9} ampere
	Total counts	3085	362	346	161	126	123	13	...	55	
	$(P/P_M)_{25}=1.00$	1.01	1.00	0.95	0.95	1.26	1.71	0.96	...	0.97	
	$(P/P_M)_{25}=0.56$	0.57	0.56	0.53	0.53	0.71	0.96	0.54	...	0.54	

hard rubber disk *B* and was connected through a microammeter to ground. The proton beam was partially defined by the hole in the quartz disk *A*, then passed through the thin aluminum window in the plate *C* and through the slit system of the scattering chamber. The true total current into the scattering chamber cannot be measured in this way because of secondary electrons from the aluminum window (and because the hole in our quartz window was slightly larger than the hole into the scattering chamber). However, it was found that the current into the chamber was proportional to this current so long as the current density remained reasonably uniform throughout the cross section of the beam. The arrangement accordingly served as a fairly satisfactory monitor on the beam current during a run.

RESULTS

A summary of the data obtained is given in Table I. Since for reasons given above it appears unwise to attempt to get absolute magnitudes from these results, only *relative* values are given. In order to show the degree of statistical validity of the results, the total number of counts, as well as the counting rate per minute is recorded. Current measurements, when satisfactory, are given in the supplementary column. Relative Mott values, giving the expected variation of counts with angle for Coulomb forces, are shown at the top of the table.

Two alternative possibilities arise in attempting to compare the observed data with theory. Since for small angles the scattering depends chiefly on Coulomb forces, the Mott ratio for small angles will be unity, and relative values such as the above might be correctly normalized by assuming a Mott ratio of unity for some angle sufficiently small. Observations below 25° not being available, the data may be *arbitrarily* normalized at this angle and, the results, though in error by an appreciable amount, will give the correct trend with voltage. Mott ratios normalized in this way are given in Table I labeled $(P/P_M)_{25}=1$ and are plotted in Fig. 5.

The alternative possibility arises in recog-

TABLE II. *Proton-scattering data, 45° value against energy of proton.*

Observed ratio	Voltage (kv)							
	220	335	450	550	640	725	820	910
$S_{45°}/S_{25°}$	0.039	0.025	0.0045	0.034	0.038	...	...	...
$S_{45°}/S_{20°}$	...	...	...	...	...	0.067	0.113	0.167

nizing the error involved in the above normalization and using the estimate of the nuclear force obtained by Breit, Condon and Present[3] to calculate a more nearly correct value for the Mott ratio at 25°. This is done in the table and labeled $(P/P_M)_{25}=0.87$ to 0.56, respectively, but is not plotted since it leads to a confusing overlapping of curves. It is perhaps of interest to note that with this closer approximation, the Mott ratio for 45° drops to the very low value of 0.03 at 450 kv.

The first scattering curves were taken before the photoelectrons discussed above were eliminated by coating the counter window with an opaque layer of aluminum. The curve for 220 kv in Fig. 5 was taken under these conditions. At this energy a small proton beam current could be used because of the larger scattering at lower energies. Therefore the photoelectric effect, which varied linearly as the current, was sufficiently small to be neglected. At 335 kv the photoelectric correction was already appreciable. Hence the curves at this voltage and for all higher voltages were taken with the evaporated aluminum window giving a background count of less than one in five minutes.

The 220-kv curve breaks off rather rapidly beyond 40°, for beyond this angle most of the protons do not have sufficient range after passing through the counter-window to actuate the point-counter. The curve at 335 kv was carried beyond 45° to show that at this angle all protons were counted. The symmetry about 45° of the ratio to Mott is clearly shown by the 450-kv curve.

The ratios of counts at 45° to those at 20° (or 25°) at voltages from 220 kv to 900 kv are given in Table II. The values for 220, 335, 450, 550, and 640 kv were taken from Table I. Higher voltage ratios were separately determined this year for this curve. In Fig. 6 these data have been plotted giving ratios to Mott, the value of R at 20° (or 25°) being taken as 0.75 which was the average value found last year for the region 15° to 25°. The points for last year using the linear amplifier for detecting the scattered protons are also given in Fig. 6. It may be noted that these old points are displaced slightly from the values given last year. This is due to a correction which has been applied, based on new information on the stopping power of aluminum

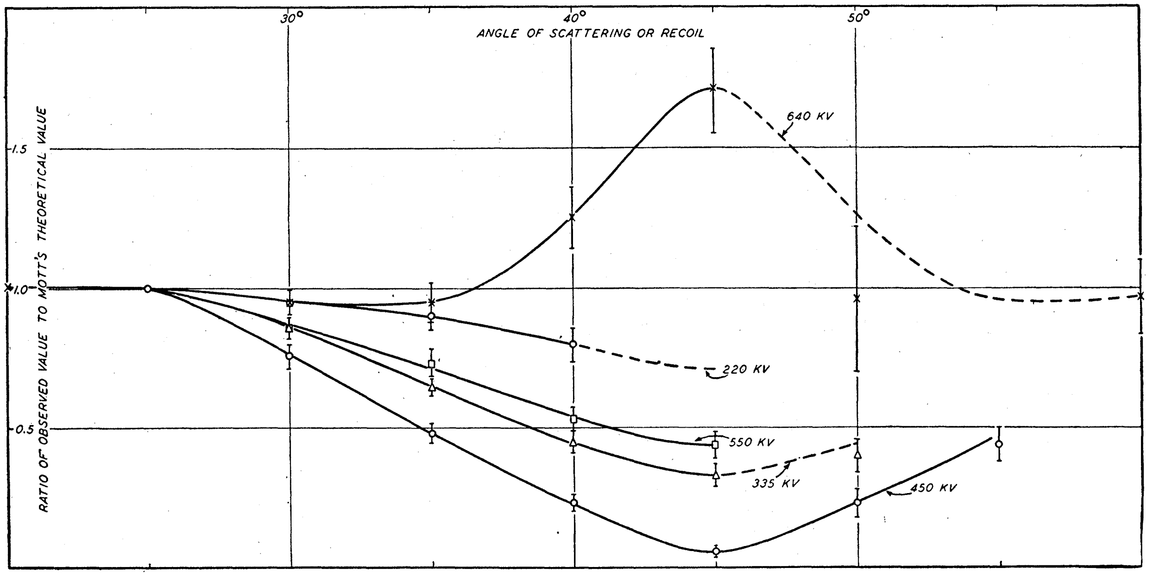

FIG. 5. Proton-proton scattering (ratios adjusted to unity at 25°).

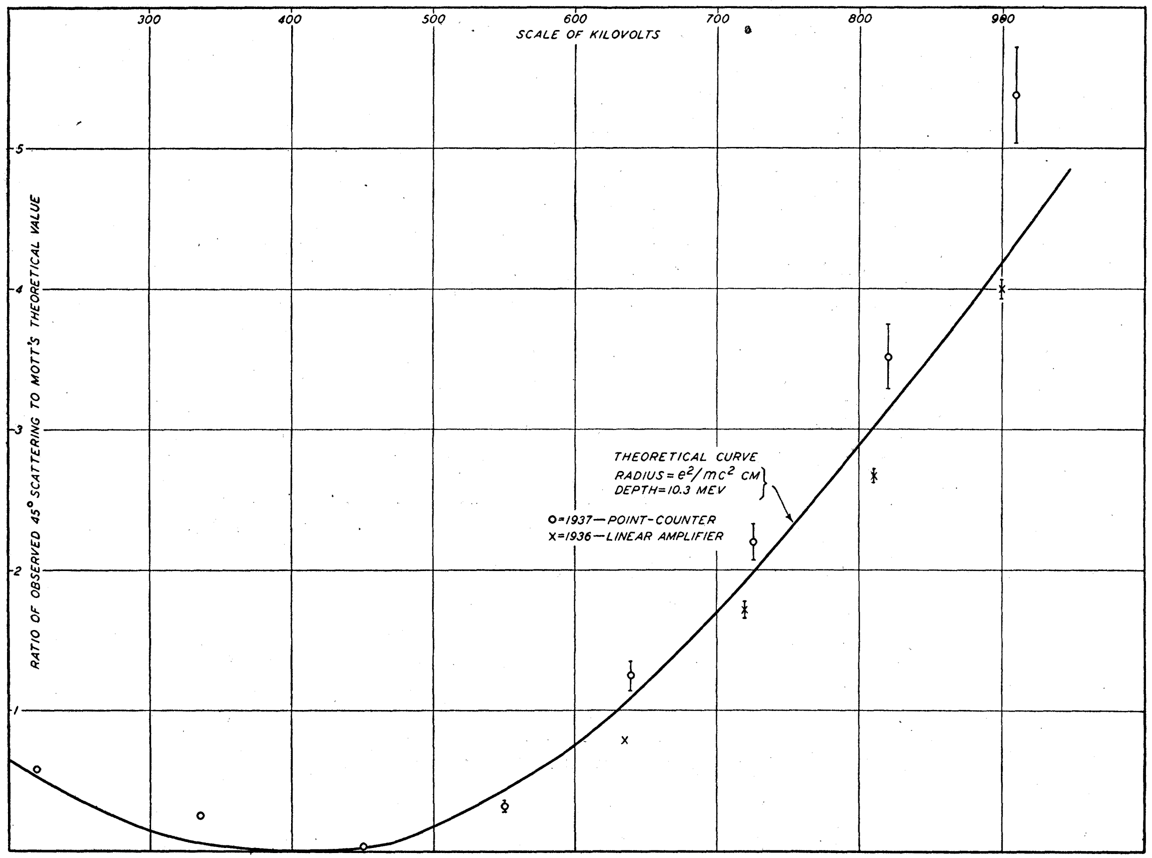

FIG. 6. Variation of scattering with voltage at 45°.

for protons.[9] The values found this year are slightly higher, one conceivable explanation for this being that with the linear amplifier as used last year some of the scattered protons were missed at 45° due to their short range at this angle. However, we feel that the point-counter technique is inherently less quantitative than the linear amplifier, and accordingly we do not consider that these point-counter observations invalidate our last year's curve in any way.

We are now engaged in repeating the curves of last year with a new technique to investigate this difference and to determine the absolute values more accurately.

DISCUSSION

Breit, Condon and Present[3] have shown that our results of last year on proton scattering could be interpreted theoretically by assuming a strongly attractive force between protons at very close distances of approach. The shapes of the curves for angular distribution of scattered protons and the variation of the scattering anomaly with proton energy was reasonably well accounted for by phase shifts in the partial wave having $L=0$ and assuming an interaction potential independent of the proton energy.

In Fig. 1, due to Breit, Condon and Present, several curves have been plotted for the theoretical variation with energy of P/P_M, where P is the scattering probability from the S wave interaction and P_M is Mott's value at 45°. Each curve is for a definite value of the parameters r_0, the radius of the potential well in units of e^2/mc^2, and E_0 is the interaction potential in Mev. The observed values of last year gave $r_0=1$, $E_0=10.30$ as the best values. From the

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[9] Parkinson, Herb, Bellamy and Hudson, Phys. Rev. 52, 75–79 (1937).

values found this year it would appear that an E_0 slightly larger than this may be necessary, but not as large as $E_0=10.66$ for $r_0=1$.

The observed values at 45° in Fig. 5 and Table I clearly show the minimum required by Breit, Condon and Present at approximately the value of energy predicted on the basis of our higher voltage data. The observed value at 45°, 450 kv, goes almost to zero. This offers a striking confirmation of the existence of a short range *attractive* interaction between protons.

It is seen from the curves in Fig. 5 that the scattering is nearly classical at 220 kv. The effect of the attractive force becomes quite appreciable at 335 kv in the region of 45°. At 450 kv and 45° scattering the effect of the attractive force almost completely neutralizes the Coulomb force. With increasing energy of the incident proton the attractive force becomes predominant, giving rise to an increase in the scattering until at roughly 650 kv it exceeds the Mott value.

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The 4.3μ Fundamental Band in the Spectrum of CO_2

DONALD M. CAMERON AND HARALD H. NIELSEN
Mendenhall Laboratory of Physics, Ohio State University, Columbus, Ohio

(Received December 14, 1937)

The fundamental absorption band due to the oscillation ν_3 in the CO_2 molecule has been remeasured and almost completely resolved into its rotational fine structure. The lines are found to fit the formula $\nu=2350.1+0.780N-0.0031N^2$. The convergence factor -0.0031 seems to fit our data a little better than the value -0.0035 given by Martin and Barker, and is in agreement with the theoretically determined value given by Adel and Dennison.

THE spectrum of carbon dioxide has been very carefully investigated in the infrared by several investigators[1] who have succeeded in resolving the majority of the most interesting bands into rotational structure. One band, however, which has been only very imperfectly resolved is that occurring near 4.3μ in the spectrum of CO_2 and due to the fundamental oscillation ν_3 of the molecule. The frequency ν_3 may be thought of as arising when the carbon atom oscillates unsymmetrically along the figure axis of the molecule relative to the center of mass of the oxygen atoms and it is accompanied by an intense change in the electric moment. The intensity of this band is in fact so intense that

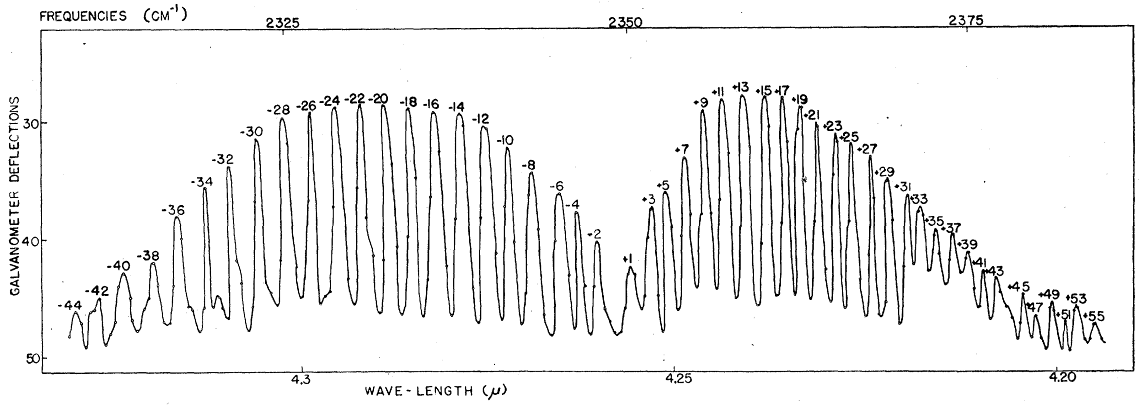

FIG. 1. Galvanometer deflections taken of the fundamental absorption band in CO_2.

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[1] P. E. Martin and E. F. Barker, Phys. Rev. **41**, 291 (1932); E. Barker and A. Adel, Phys. Rev. **44**, 185 (1933); E. F. Barker and T. Y. Wu, Phys. Rev. **45**, 1 (1934).