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ENERGY DEPENDENCE OF PROTON-PROTON SCATTERING, 18.8 to 31.8 MEV

Bruce Cork

May 15, 1950

Berkeley, California

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-3-

ENERGY DEPENDENCE OF PROTON-PROTON SCATTERING, 18.8 to 31.8 MEV

Bruce Cork

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May 15, 1950

Abstract

Measurements have been made of the absolute differential cross section of proton-proton scattering at 90° in the center of mass system. The energy of the incident protons was varied from 31.8 Mev down to 18.8 Mev, and an energy interval of ± 1.0 percent was selected by means of a deflecting magnet. Apparatus using a proportional counter and a triple coincidence method was used to reduce the background. Measurements were made simultaneously, using the apparatus¹ for measuring the angular distribution at 31.8 Mev and a single charge integrator for collecting the incident proton beam.

The cross section at 90° c.m. varies approximately as the reciprocal of the energy of the incident protons over the range investigated. Data are presented to show this dependence. Comparison is made with a Yukawa potential well, and with the tensor model selected by Christian and Noyes.

¹ Bruce Cork, Lawrence Johnston, Chaim Richman, to be published in the Physical Review, UCRL-482.

ENERGY DEPENDENCE OF PROTON-PROTON SCATTERING, 18.8 to 31.8 MEV

Bruce Cork

May 15, 1950

Introduction.

Measurements of the proton-proton differential cross section at 31.8 Mev^{1,2,3}, showed that the shape of the scattering cross section curve was compatible with a pure S wave. However, the magnitude of the cross section was approximately 1.3 times the value extrapolated from the low energy data^{4,5} assuming a square well of depth 10.5 Mev, range e^2/mc^2 , and S wave scattering only. A more singular potential well, such as a Yukawa well has been selected⁶ to be consistent with the angular distribution observed at 31.8 Mev, assuming that the D wave scattering predicted for such a potential does not appear.

Measurements have been made by Herb, Kerst, Parkinson and Plain⁴ over the range 0.860 Mev to 2.392 Mev; by Blair, Freier, Lampi, Sleator and Williams⁵ over the range 2.42 Mev to 3.53 Mev, and by others⁷⁻¹² up to energies of 14.5 Mev. Measurements have been made in the region of 240 Mev by Oxley¹³ and in the region of 170 Mev to 340 Mev by Wiegand and Chamberlain¹⁴. The Berkeley 32 Mev linear accelerator has features which allow investigation of the region below 32 Mev.

² W. K. H. Panofsky, F. L. Fillmore, to be published, UCRL-481.

³ R. Christian and H. P. Noyes, to be published, UCRL-554.

⁴ R. G. Herb, D. W. Kerst, D. W. Parkinson and G. J. Plain, Phys. Rev. 55, 998 (1939).

⁵ J. M. Blair, G. Freier, E. E. Lampi, W. Sleator and J. H. Williams, Phys. Rev. 74, 553 (1948).

⁶ Chew and Goldberger, Phys. Rev. 75, 1637 (1949).

⁷ May, Powell, Proc. Roy. Soc. A 190 170 (1947).

⁸ R. R. Wilson, Phys. Rev. 71, 384 (1947).

⁹ R. R. Wilson and E. C. Creutz, Phys. Rev. 71, 339 (1947).

¹⁰ R. R. Wilson, E. J. Lofgren, J. R. Richardson, T. B. Wright and R. S. Shankland, Phys. Rev. 71, 560 (1947).

¹¹ I. H. Dearnly, C. L. Oxley and J. E. Perry, Phys. Rev., 73, 1290 (1948).
J. Rouvina, private communication.

¹² Frank Faris, Byron Wright, private communication.

¹³ C. L. Oxley, Phys. Rev., 76, 461 (1949).

¹⁴ C. Weigand and O. Chamberlain, UCRL-553, to be published.

Method.

It was convenient to use the angular distribution apparatus¹ that was used at 31.8 Mev, to extend the measurements down to 25 Mev. The thickness of the aluminum window separating the hydrogen from the argon filled proportional counter limited the low energy range to 25 Mev for scattering angles of 90° in the center of mass system. To extend the measurements to still lower energy, a 90° coincidence method was used.

This apparatus was arranged so that the incident beam first passed through the angular distribution scattering chamber, then through the 90° coincidence chamber, and finally on into the charge integrator. This procedure allowed a direct comparison of the two geometries in the high energy region, and normalization of the 90° coincidence data to the 31.8 Mev data.

The 90° coincidence apparatus is shown in Figs. 1 and 2. To reduce the number of background counts, one of the 90° proportional counters was arranged as a double counter telescope. Thus scattered protons were counted by a triple coincidence. The coincidence geometry is defined by the entrance apertures of each of the counters and the position of the incident beam. These apertures were of rectangular cross section 1 in. x 2 in. and located at a distance of 7-1/2 in. from the center of the scattering region. The scattered beam which could be accepted by the coincidence geometry was $45^\circ \pm 4^\circ$ maximum and $45^\circ \pm 2^\circ$ mean angle in the laboratory system of coordinates.

Energy Selection and Measurement.

The proton beam from the Berkeley 32 Mev linear accelerator¹⁵ was collimated and then deflected in an analysing magnet. Approximately 6 meters of further collimation gave a beam of 1 cm diameter and an angular divergence

¹⁵ H. Bradner, R. Crawford, H. Gordon and J. R. Woodyard, Phys. Rev. 73, 534A (1948).

-6-

of $\pm .001$ radians. The energy spectrum was measured by observing the current at the charge integrator as a function of the deflecting magnet field.

The absolute energy was determined by measuring the deflection¹⁶ of the proton beam in the magnetic field. The energy of the coincidence protons scattered at 90° c.m. was also measured by determining their range in aluminum. Using the range data¹⁷ extrapolated from low energies, the energy of the incident protons for the above deflecting magnetic field was observed to be $31.6 \pm .3$ Mev.

Incident protons of energy less than 31.8 Mev were obtained by operating the linear accelerator in a manner different from the normal adjustment. Since beam currents of approximately 10^{-12} amperes were adequate to give a satisfactory counting rate, it was possible to adjust the energy of the injected protons and the voltage gradient at the output end of the linear accelerator so that a good beam of protons with energy as low as 18.8 Mev would result. By adjusting the magnetic field of the analyzing magnet to the appropriate value, protons with an energy spread of ± 1.0 percent were incident at the scattering chamber. The mean energy of the incident protons was calculated from the deflection of the protons in the magnetic field, and these values, corrected for the energy loss in the nylon foil and hydrogen, are the values used in Table I. Changes in the magnetic field over the range of energies used could be measured with an accuracy of $\pm 1/3$ percent. Thus the mean energy could be determined to $\pm 2/3$ percent.

Counters.

Each proportional counter consisted of a rectangular chamber 1-1/2 in. x 3 in. x 4 in. with a .002 in. diameter wolfram wire mounted along the major

¹⁶ R. R. Wilson and E. C. Creutz, Rev. Sci. Inst. 17, 385 (1946).

¹⁷ Livingston and Bethe, Rev. Mod. Phys. 9, 263 (1937).

TABLE I

Measured Values of $\left(\frac{d\sigma}{d\Omega}\right)_{90^\circ \text{c.m.}}$ As A Function of the
Energy of the Incident Protons.

Runs designated "A" are with angular distribution singles geometry, runs designated C are with double coincidence angular distribution geometry, and runs designated T are triple coincidence geometry.

Energy MeV	$\frac{1}{E} \times 10^3$	Run	Q Coulombs $\times 10^{-12}$	$\left(\frac{d\sigma}{d\Omega}\right)_{90^\circ \text{c.m.}}$ millibarns	Statistical Error %	RMS N %	Assigned Absolute Probable Error %	Relative Errors
31.8	31.45	A		14.3	± 0.7		± 1.8	0
31.8	31.45	1C	2250	14.4	± 2.2	± 2.4		
31.45	31.8	1T	2250	14.5	± 2.8	± 3.1		
31.45	31.8	2T	856	14.3	± 4.1	± 2.6		
31.8	31.45	3A	1285	14.4	± 0.9	± 1.3		
31.8	31.45	3C	2185	14.3	± 1.4	± 1.5		
31.45	31.8	3T	3850	14.35	± 2.4	± 1.9		
31.45	31.8	Normalized Triple		25.45	-	-	± 2.2	0
25.45	39.30	4A	2890	18.32	± 0.7	± 1.1		
25.45	39.30	4C	2890	18.4	± 1.2	± 1.4		
25.45	39.30	Weighted Mean		18.36	-	-	± 2.1	± 1.4
25.2	39.68	4T	5780	18.7	± 1.7	± 1.9	± 2.6	± 2.0
21.9	45.66	6T	1925	22.8	± 2.5	± 2.1	± 2.3	± 2.1
18.8	53.19	7T	1713	27.2	± 2.5	± 2.2	± 2.4	± 2.2

axis. (Fig. 1) The scattered protons entered a .002 in. duraluminum foil mounted on the broad side of the counter. In the double counter these protons went on into the second counter, with no foil separating the two counters.

The signals from each of these counters were amplified by an amplifier having a gain of 3000 and a band width of 0.9 megacycles. The output of each amplifier was coupled to a discriminator and gate circuit that generated a 0.7 microsecond pulse. These gated pulses associated with the various counters were then coupled into a triple coincidence circuit which recorded the coincidence scattered protons.

Corrections.

The resolving time of the counter circuits was measured with a double pulse signal generator and observed to be 4 microseconds. The counting rate of each counter was kept at a sufficiently low rate so that the correction for counts being missed by the triple coincidence circuit was less than 1/2 percent. This low counting rate also resulted in the corrections for accidental coincidences being less than 1/4 percent.

The individual counting rates were kept approximately constant by varying the magnitude of the incident beam current. Thus the corrections to the the relative cross section are very small due to counter resolving time.

As an additional check on the accidental coincidence rate, double coincidences were measured between one of the telescope counters and an auxiliary counter, measuring protons scattered from the same incident beam. This counter was arranged so that it had approximately the same counting rate as the other counter, but scattered protons could not be in real coincidence.

All protons incident at the counters have greater than 8.0 Mev energy in the laboratory system. Multiple scattering of 8.0 Mev protons by 20 cm

-9-

of hydrogen has been estimated using Williams¹⁸ formula and found to have a root mean square scattering angle of 0.07° . This correction when applied to the coincidence geometry is estimated to be less than 1/2 percent.

The root mean square multiple scattering angle in two of the .002 in. duraluminum foils (chamber exit foil and counter entrance foil) is estimated to be 1.5° at 8.0 Mev. The counter aperture was sufficiently large, compared to the entrance aperture, so that protons scattered by these foils would be counted, unless they were scattered at an angle of greater than 6.0° . Assuming a gaussian distribution, the probability of scattering greater than 7.0° is 6×10^{-5} . No correction was made for multiple scattering by the foils.

An estimate of the correction for multiple nuclear scattering is made as follows:

The cross section for single nuclear scattering of 8 Mev protons by protons was observed⁹ to be $60.5 \times 10^{-27} \text{ cm}^2$ at 90° c.m. Assuming the cross section is an order of magnitude greater than this in the forward direction in the laboratory system, the probability of an 8.0 Mev proton making an elastic collision in the 20 cm of hydrogen and possibly not being counted is estimated to be less than 1/3 percent. No correction was made for multiple nuclear scattering.

The position of the incident proton beam was observed at the charge integrator by means of a photographic emulsion. It was observed that multiple scattering in the hydrogen did not cause a significant number of protons to be missed by the Faraday cage. Although a systematic investigation of the reliability of the charge integrator was made at only 31.8 Mev, the charge integrator was arranged so that secondary electrons from the entrance foil or

¹⁸ E. J. Williams, Proc. Roy. Soc., 169, 531 (1939).

-10-

from the Faraday cage would have to traverse a guard cylinder of 16 cm length and 6 cm diameter, operated at a potential of negative 150 volts relative to the foil and cage. In addition, two small permanent magnets were arranged to give a magnetic field of 50 gauss at the target end of the Faraday cage.

During the scattering experiments, the pressure was measured in the region of the Faraday cage and was always less than 10^{-5} mm of mercury.

Procedure.

The scattering chamber was evacuated and observed to be vacuum tight. Hydrogen was then admitted through a palladium tube until the pressure was slightly greater than one atmosphere. The excess hydrogen was then permitted to escape from the chamber via an oil-lock tube which regulated the pressure and prevented back diffusion of air into the system. The pressure was calculated from the measurements of the height of the oil in this oil-lock column, the density of the oil, and the barometer reading. The temperature of the hydrogen was determined by measuring the temperature of the scattering chamber. It was possible to operate the proportional counters well up on the plateau for counting protons and still have a negligible number of background counts, using the triple coincidence method. The threshold for counting gamma-rays was determined for each counter, and then each counter was operated well above this point.

Each run was made by opening a beam shutter and operating until a charge of 920.7×10^{-12} coulombs was collected on the Faraday cage. These runs were of approximately 20 minutes duration for protons of 31.8 Mev incident energy. This corresponds to a beam current of approximately 10^{-12} amperes. The incident beam current was reduced at lower energies in order that the counting rate would be approximately constant. The proton plus background

-11-

counts of each counter were recorded as well as the triple coincidence and the accidental double coincidence counts. The corrections described above were then made.

Results.

The proton-proton differential cross sections for 90° in the center of mass coordinates are given in Table I and Figs. 3 and 4. The energies of the incident protons, and the reciprocals of the energies are likewise tabulated.

The tabulated errors for the measured cross section are the statistical errors which were calculated by using the reciprocal of the square root of the number of counts. The probable errors due to temperature and pressure measurement were $\pm 1/3$ percent. The probable error of the absolute cross section due to charge measurement was measured at 31.8 Mev and observed to be less than $\pm 1/2$ percent, and the assigned probable errors of the absolute cross sections are tabulated.

The curve of Fig. 3 is normalized for the measured cross section of $14.3 \times 10^{-27} \text{ cm}^2$ at 31.8 Mev, and all other points are plotted relative to this value. This procedure was more convenient than carefully evaluating the triple coincidence geometry.

The mean energy of the incident protons tabulated in Table I is the value calculated from the deflection in the magnetic field. The probable error in energy for each adjustment of the magnetic field is $\pm 2/3$ percent.

Table II is a summary of the calculated values of the differential cross section for proton-proton scattering at 90° c.m. The third column is a tabulation of the values calculated by Christian and Noyes, assuming a tensor model.

The curve of Fig. 3 is plotted through the values listed in Table III calculated by Christian and Noyes, assuming a Yukawa well of range $= 1.417 \times 10^{-13} \text{ cm}$,

TABLE II

Calculated values of the differential cross section for proton-proton scattering at 90° c.m.

Energy Mev	$\frac{1}{E} \times 10^3$	$\left(\frac{d\sigma}{d\Omega}\right)_{90^\circ}$ cm. Christian and Noyes	Millibarns			
			Yukawa		Square	
			S	S and D	S	S and D
5	200	100.21	100.37	99.63	99.60	99.64
10	100	52.05	53.51	52.73	50.70	52.73
15	66.6	34.23	35.40	34.33	31.72	34.33
20	50	24.95	25.84	24.58	21.85	24.58
29.4	34.01	16.11	16.62	15.15	12.47	15.15
32	31.25	14.59	15.00	13.51	10.89	13.51

TABLE III

Calculated values of the function \bar{K} using the method of Blatt and Jackson.

Energy Mev	Christian and Noyes	Square S	\bar{K} Yukawa	
			S	S and D
5	6.018	6.052	6.025	6.052
10	8.318	8.540	8.113	8.235
15	10.424	11.165	10.053	10.354
20	12.416	13.932	11.894	12.524
29.4	15.908	19.536	15.248	16.660
32	16.843	21.188	16.188	17.846

-14-

and depth of 49.35 Mev. These are the parameters determined by Chew and Goldberger⁶ selected to be consistent with the angular distribution observed at 31.8 Mev, assuming that somehow the D-wave scattering predicted for such a potential does not appear. Fig. 4 is a summary of the measured values of the differential cross section for proton-proton scattering at 90° c.m. as a function of the reciprocal of the energy of the incident protons.

Table IV and Fig. 5 are a summary of the values of the function \bar{K} defined by Blatt and Jackson¹⁹. The straight line labeled Blatt and Jackson, Fig. 5, is the best straight line fit for $K = 3.755 + 0.4603E$ determined from low energy proton-proton scattering data.

It is concluded that at present no potential model has been discovered having any effective range long enough to fit the low energy data, that also predicts negligible D-wave scattering at 32 Mev. Hence, there is no existing theoretical basis for such an S-wave model. The tensor model of Christian and Noyes³ has been arranged to satisfy the experimental data at 250 Mev and 340 Mev, as well as the low energy data.

Acknowledgments.

It is a pleasure to express my thanks to Profs. Luis Alvarez and W. K. H. Panofsky for encouragement to continue this problem. Also, I am grateful to Prof. Geoffrey Chew, Mr. Richard Christian, and Mr. H. P. Noyes for stimulating discussions, and for calculation of the values of the function \bar{K} . The linear accelerator crew under the direction of Mr. Robert Watt played an important role in making all the necessary adjustments for changing the energy and for satisfactory operation of the Linear Accelerator. The

¹⁹ J. D. Jackson and J. M. Blatt, Rev of Mod. Phys. 22, 77 (1950).

TABLE IV

Summary of measured values of the differential cross section for proton-proton scattering at 90°c.m. and calculated values of \bar{K} assuming the measured cross sections.

Ref.	Source	E Mev	Error %	$\frac{1}{E} \times 10^3$	$\left(\frac{d\sigma}{d\Omega}\right)_{90^\circ}$ cm	Probable Error %	Calculated \bar{K}
5	BFLSW	2.42			156.6	± 2.1	4.86 ± 0.05
5	BFLSW	3.04			142.1	± 1.8	5.15 ± 0.06
5	BFLSW	3.27			134.3	± 1.4	5.24 ± 0.06
5	BFLSW	3.53			129.4	± 1.4	5.36 ± 0.07
19	RWH	2.42			--		4.90 ± 0.05
19	RWH	3.04			--		5.17 ± 0.05
19	RWH	3.28			--		5.26 ± 0.06
19	RWH	3.53			--		5.41 ± 0.06
19	MP	4.2			--		5.83 ± 0.30
19	M	4.94	± 0.04		--		6.02 ± 0.18
11	DOP	7.03	± 0.06		66.5		7.63 ± 0.11
9	WC	8.0	± 0.1		60.46	± 3.5	8.00 ± 0.40
10	WLRWS	14.5	± 0.7		33.4	± 2	10.78 ± 0.80
11	Rouvina	3.435	± 1.4	291.1	133.4	± 2.4	5.30 ± 0.067
		6.846	± .58	146.1	146.48	± 1.4	6.86 ± 0.122
		7.514	± .53	133.1	68.87	± 1.3	7.18 ± 0.130
12	FW	12.4	± 2.0	80.64	40.3	± 2.0	9.683 ± 0.2
	Cork	18.8	± 0.7	53.19	27.2	± 2.4	11.67 ± 0.27
		21.9	± 0.7	45.66	22.8	± 2.3	12.91 ± 0.27
		25.2	± 0.7	39.68	18.7	± 2.6	14.65 ± 0.33
		25.45	± 0.7	39.30	18.36	± 2.1	14.84 ± 0.27
		31.45	± 0.7	31.79	14.45	± 2.2	16.73 ± 0.30
		31.8	± 0.7	31.45	14.3	± 1.8 1.5	16.76 ± 0.25 0.21
1	CJR	31.8	3	31.45	14.3	± 1.8 1.5	16.76 ± 0.25 0.21
2	PF	29.4	± 0.7	34.0	16.0	± 3.0	15.84 ± 0.39
13	Oxley	250.		4.0	"8"		
14	Chamberlain	170.		5.88	4.0		
		340.		2.94	4.0		

-16-

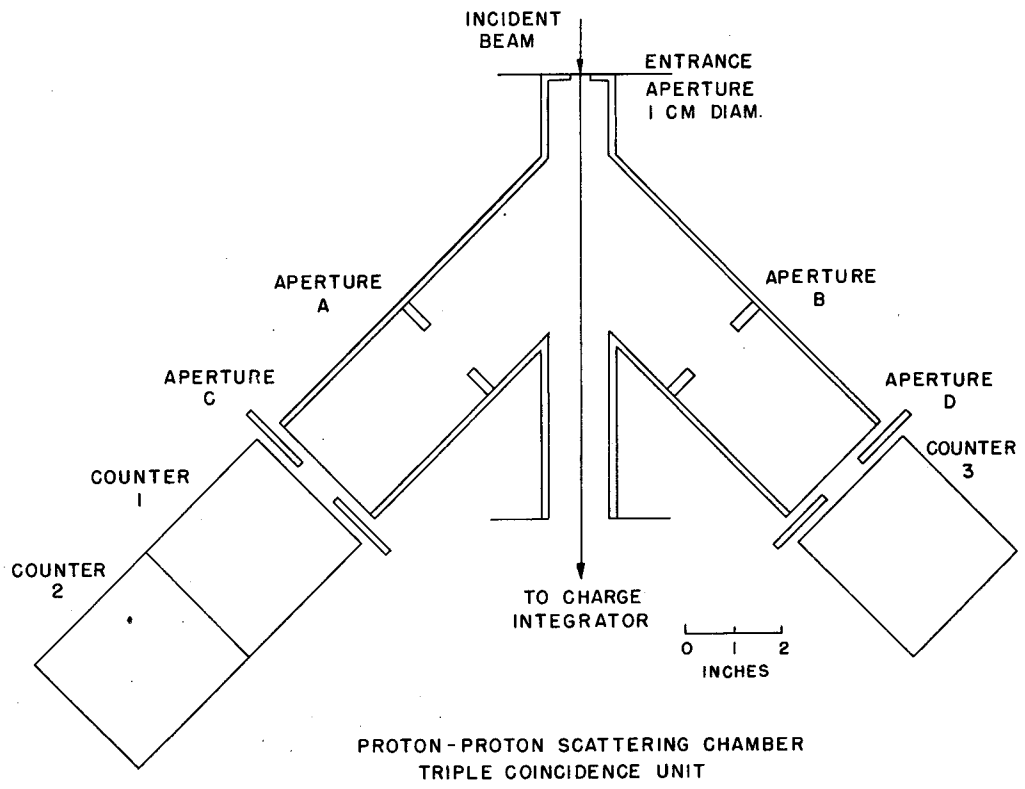
design and maintenance of the counting apparatus was done by G. O. Essex and A. J. Stripeika under the supervision of H. D. Farnsworth.

This work was sponsored under the auspices of the Atomic Energy Commission.

LMB/5-16-50
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Figure Captions

- Fig. 1 Triple coincidence geometry for proton-proton scattering measurements.
- Fig. 2 Photograph of geometry, double coincidence counter on the left.
- Fig. 3 Variation of the absolute differential cross section for proton-proton scattering at 90° center of mass as a function of the reciprocal of the energy of the incident protons.
- Fig. 4 Summary of proton-proton scattering data, 90° c.m. as a function of the reciprocal of the energy of the incident protons.
- Fig. 5 Variation of the function \bar{K} as a function of the energy of the incident protons.



MU 242

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Fig. 1

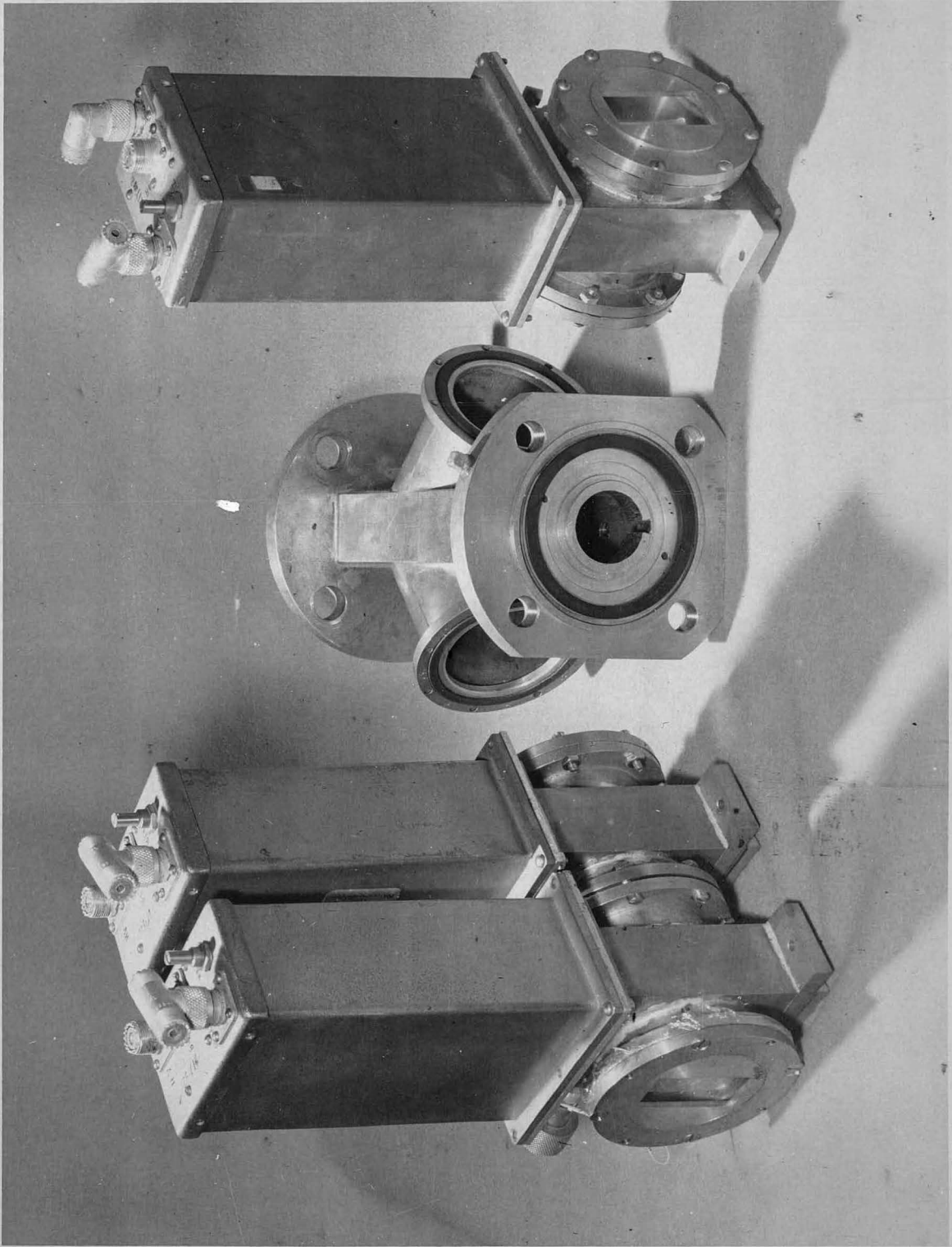
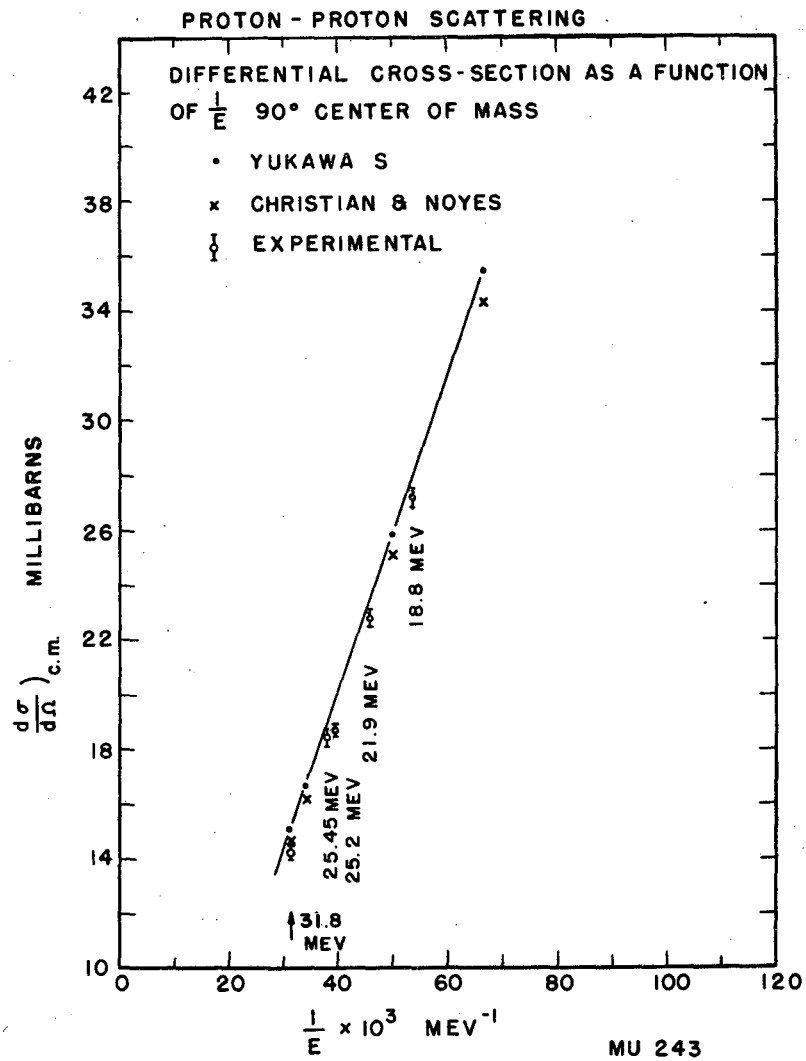


FIG. 2

-20-



14

Fig. 3

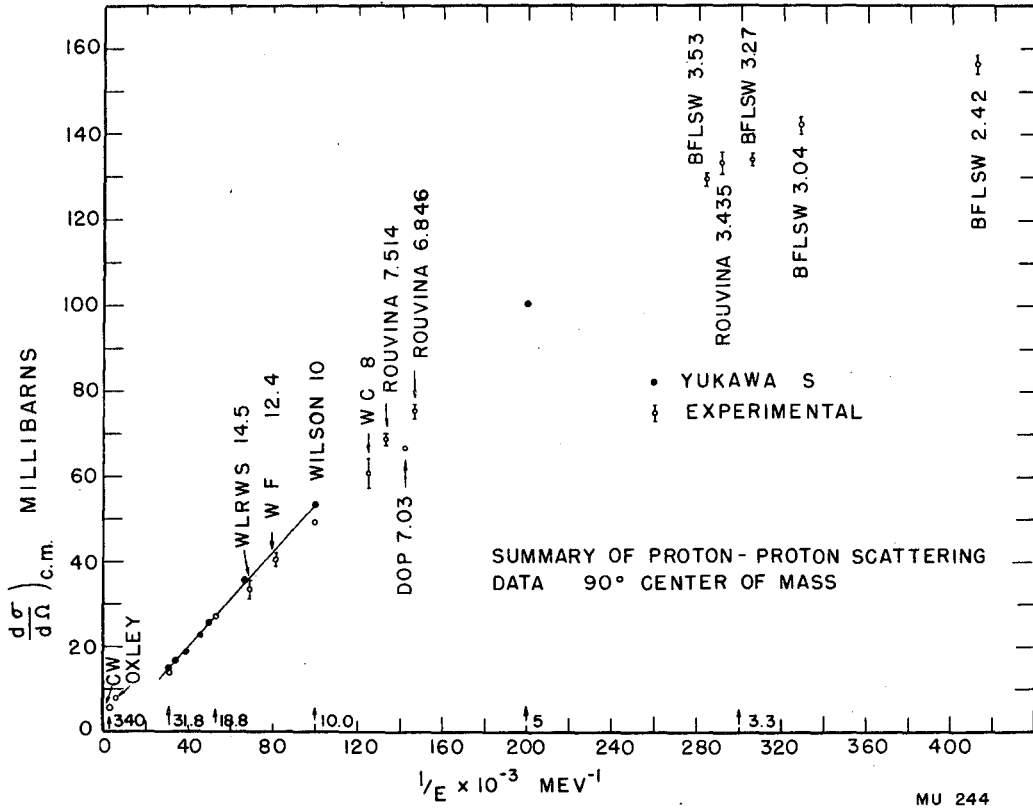
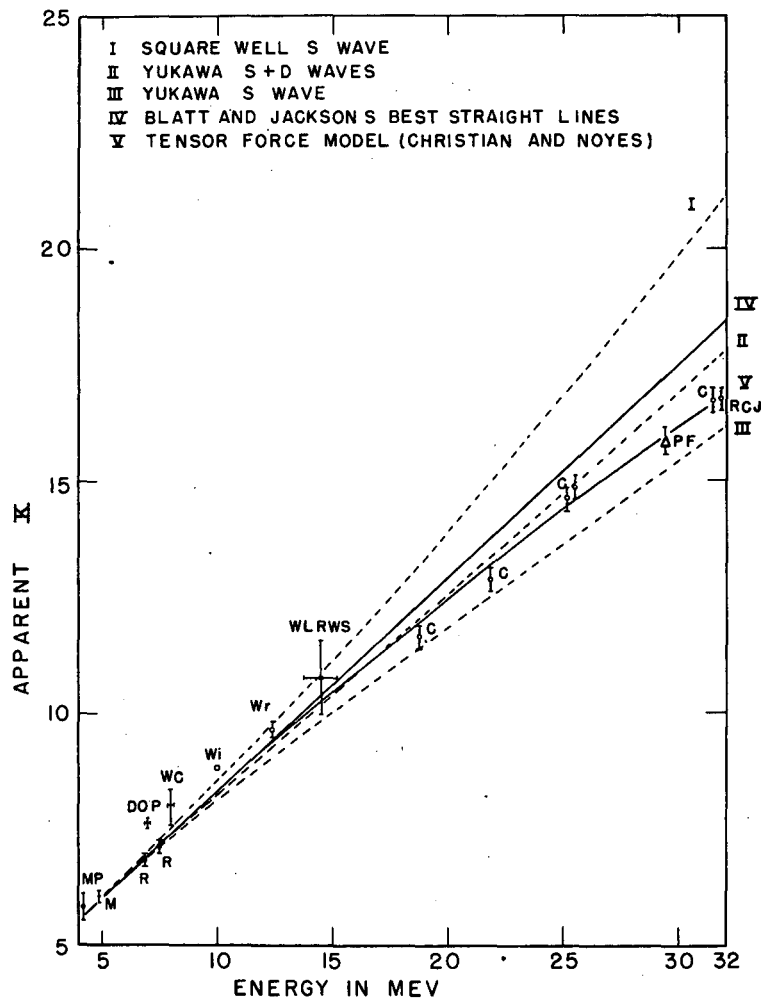


Fig. 4



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Fig. 5