Small-Angle Proton-Proton Scattering at 20 Mev*

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The differential cross section for the scattering of 19.8-Mev protons by protons has been measured for angles between 18° and 35° in the center-of-mass system, detection being by photographic emulsion placed in a scattering camera. Cross sections were measured simultaneously at all angles and azimuths. A run with analyzing slits closed served to evaluate the small slit-edge correction. The accuracy of the cross-section measurements is approximately 2.5% at all angles except 18°, where the accuracy is about 3%.

INTRODUCTION

THE study of the two-nucleon system is of fundamental interest because of its connection with the problems of nuclear forces and nuclear structure. The experiment discussed here measures the differential cross section for proton-proton scattering in an angular range where the interference between Coulomb and nuclear scattering is expected to be large for the proton energy involved, 20 Mev in the laboratory system. The geometry used enables one to count protons scattered at a given angle at all azimuths, so that a reasonably large yield can be obtained with a small angular opening. The correction for variation of cross section over the angular width of the detector is thereby reduced; this consideration is important at small angles, where the variation of cross section with angle can be large.

This paper will be concerned mainly with the presentation of the experimental results. For a detailed description of the apparatus, and a more complete error discussion, reference should be made to the thesis submitted by one of the authors.[1]

APPARATUS

The present experiment used nuclear emulsions as detectors, hydrogen gas at a pressure of one atmosphere as target, and the 20-Mev external proton beam from the U.C.L.A. synchrocyclotron as proton source. The beam passed from the cyclotron vacuum through a $\frac{1}{4}$-mil Mylar foil into a permanently mounted 32-in. cast-aluminum scattering chamber (hereafter called the "large" chamber) filled with hydrogen. This entrance foil was located at the inner end of the collimating tube of the large chamber, and was followed immediately by a 0.1-in. collimating hole. The second collimating hole was located at the exit of the large chamber; an anti-scattering baffle followed this hole by about two inches. Attached to the rear of the large chamber was the "scattering camera," which provided the defining slits for the scattered beam. The incident beam passed through a 1-mil Mylar exit foil at the rear of the camera and thence through a 1-in. air gap and a similar entrance foil into a Faraday cup, which was connected by a cable to a current integrator in the cyclotron control room. The scattered protons passed through the thin rear wall of the camera into the photographic emulsion, which was held in a film-holder at the back of the camera. Figure 1 indicates schematically the arrangement of equipment.

A scintillation counter was used to monitor contaminants in the hydrogen gas. This counter, mounted in the large chamber, was set at an angle where the protons scattered from air nuclei, were well separated in energy from those scattered from hydrogen nuclei, and only the former were counted. The hydrogen pressure was measured by determining the excess of the chamber pressure above atmospheric pressure with a differential manometer, and determining atmospheric pressure with a precision aneroid barometer. A precision thermometer extending into the large chamber was used to measure the hydrogen temperature.

The brass "scattering camera" used to define the scattered beam was similar in slit geometry to that described by Faris[2] and is shown in Fig. 2. Protons scattered on the beam axis pass through an annular defining opening to the rear of the chamber, where they penetrate an 11-mil copper window and another 11-mil copper film-cover, finally reaching the 30-mil Kodak NTB nuclear emulsion, mounted on ordinary film base. Reference circles coaxial with the incident beam were put on the film by covering it with an engraved optical mask and exposing it to a flash of light, just prior to the experimental run. The average angle of scattering was thus determined by the average radius of the annular swath on the film within which protons were counted, the average radius of the annular defining slit, and the distance between the slit and the film.

The proton tracks were counted with an oil-immersion microscope. The swath width was defined by an eyepiece reticle, the swath radius by one of the aforementioned reference circles. A background run was made with identical geometry, except that the annular area defining the scattered beam was reduced to nearly

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[1] H. N. Royden, thesis, University of California, Los Angeles, January, 1957 (unpublished).
[2] F. E. Faris and B. T. Wright, Phys. Rev. **79**, 577 (1950).

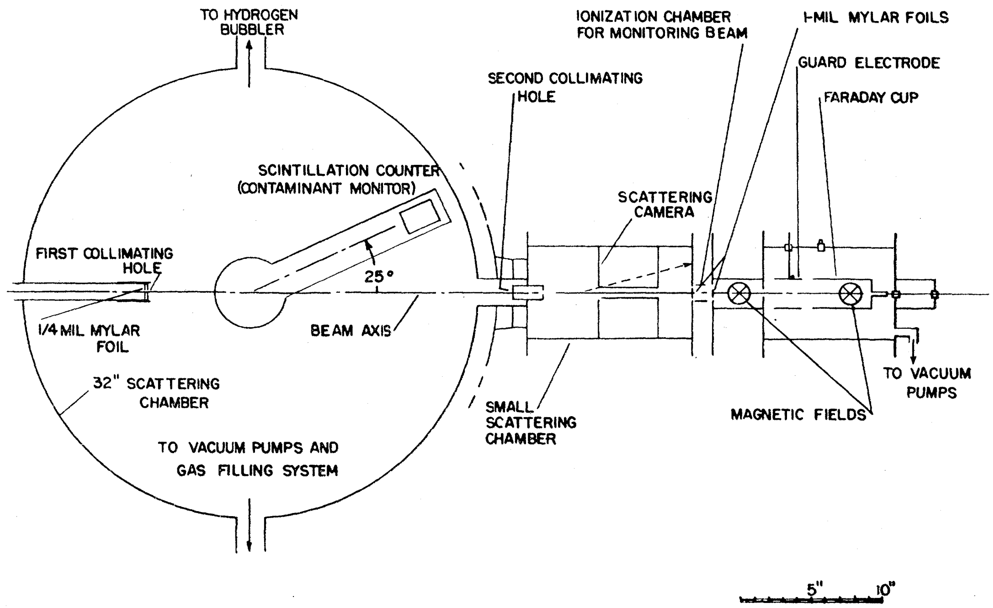

FIG. 1. Schematic view of the apparatus, showing the large and small scattering chambers, the scattering camera, and the Faraday cup.

zero. Correction could thus be made for protons which had penetrated the slit edges, or had scattered directly from several metal surfaces.

The Faraday cup apparatus was constructed with all of the usual precautions to ensure proper collection of proton current: magnetic fields of several hundred gauss at the entrance foil and at the rear of the insulated collecting cup; rounded, polished surfaces of the cup itself; a vacuum better than 10^{-5} mm of mercury; high leakage resistance. The current from the cup was integrated with a 0.01-μf Fast polystyrene condenser and a UCRL Model II electrometer located in the cyclotron control room. This current integrator was calibrated to 0.3% using a current-time method which is described in detail elsewhere.[3]

The proton energy was measured by determining the mean range of the beam in aluminum, using apparatus originally constructed to measure relative energy losses in thin foils.[4]

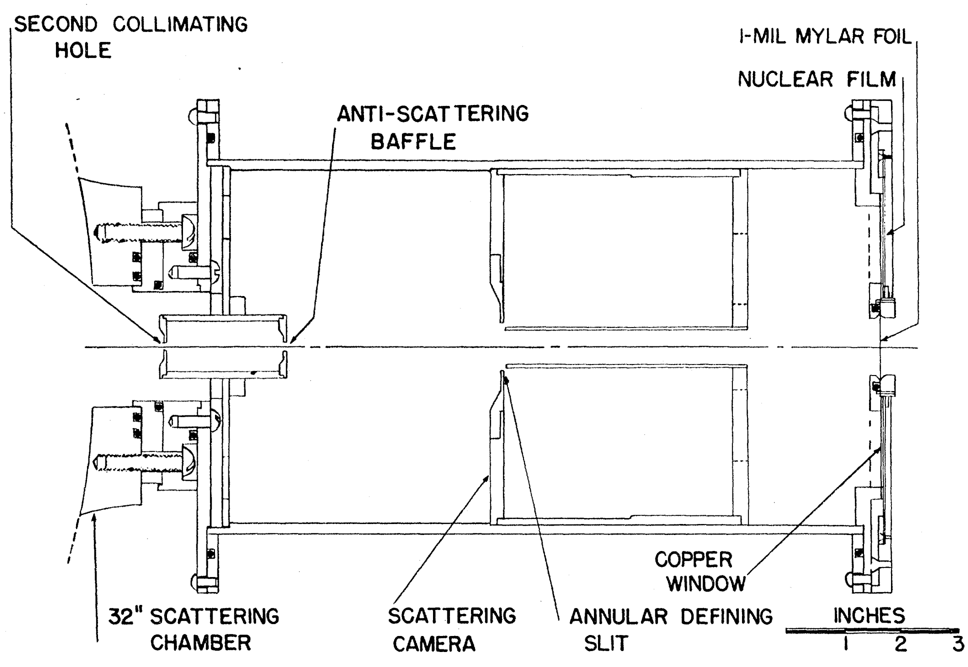

FIG. 2. Details of the scattering camera and nuclear film positioning arrangement.

[3] H. N. Royden and D. O. Caldwell, Rev. Sci. Instr. 27, 91 (1956).
[4] C. P. Sonett and K. R. MacKenzie, Phys. Rev. 100, 734 (1955).

TABLE I. Evaluation of sources of error in $\sigma(\theta)$.

Quantity	Sources of uncertainty in quantity	Contribution to uncertainty in $\sigma(\theta)$
Y	Counting statistics	2.5% (typical)
	Observer variation	0.4%
g	Uncertainties in measured lengths	0.46%
N	Uncertainty in hydrogen temperature	0.01%
	Uncertainty in hydrogen-atmosphere pressure differential	0.01%
	Uncertainty in atmospheric pressure	0.02%
n	Secondary electrons	0.05%
	Ionization current	0.05%
	Leakage current	0.05%
	Low-energy beam component	0.21%
	Calibration of current integrator	0.3%

TABLE II. Experimental data. Mean proton energy = 19.84 ±0.03 Mev; energy spread = ±0.13 Mev; maximum possible fluctuation in mean energy = ±0.01 Mev.

Lab angle (degrees)	C.m. angle (degrees)	C.m. cross section (mb/sterad)	Relative standard deviation: Statistical error (%)	Relative standard deviation: Over-all error (%)
9.0	18.0	31.7	2.2	3.0
11.1	22.2	23.7	2.6	2.7
12.2	24.4	23.4	2.6	2.6
13.1	26.1	23.8	2.6	2.7
14.9	29.8	23.0	2.6	2.7
16.0	32.1	23.2	2.7	2.8
17.6	35.1	24.2	2.8	2.9

RESULTS AND DISCUSSION

The formula used to calculate the differential cross section from the results of this experiment is the following:

$$\sigma(\theta)=Y/4\pi nNg, \tag{1}$$

where Y is the measured yield of protons scattered at average angle θ into the element of solid angle $\Delta\Omega$, n is the total number of incident protons, N is the number of target protons per unit volume, and g is a geometrical factor resulting from integration over solid angle. The factor g is a slowly varying function of θ.

Table I lists the assignments of relative errors in $\sigma(\theta)$ due to uncertainties in each of the quantities appearing in Eq. (1).

Quadratic combination of the errors listed yields a typical net uncertainty of 2.7% in $\sigma(\theta)$. The mean energy of the proton beam in the scattering volume was determined to be 19.84±0.03 Mev, with an energy spread of ±0.13 Mev. The maximum possible range of fluctuations in cyclotron parameters was investigated and found to be ±0.01 Mev.

The results of the experiment are tabulated in Table II. They are in agreement with those of the concurrent experiment of Burkig, Schrank, and Richardson,[5] which used a scintillation counter as detector, over the range of angles in which the two experiments overlap. The combined results are shown in Fig. 3.

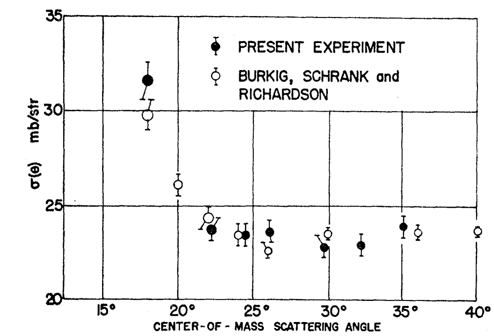

FIG. 3. A plot of the results obtained in this experiment, together with those presented in the preceding paper.

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[5] Burkig, Richardson, and Schrank, Phys. Rev. **113**, 290 (1959), preceding paper.