ACCURATE PROTON-PROTON DIFFERENTIAL CROSS SECTIONS NEAR 10 MeV *

Nelson Jarmie, Ronald E. Brown,† R. L. Hutson, and J. L. Detch, Jr.
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico 87544
(Received 1 December 1969)

In order to resolve inconsistencies in existing data, differential cross sections for the scattering of protons by protons have been measured at 9.690 and 9.918 MeV with accuracies near 0.4% relative and 0.6% absolute. Sources of error are given and the data are compared with previous experiments and theory.

Even though phenomenological reduction of proton-proton scattering in the elastic energy region has reached a sophisticated state,[1] there still exist some unresolved discrepancies. In particular, differential cross sections measured at 9.69 MeV by Johnston and Young[2] (the "Minnesota" data) are in disagreement with the 9.918-MeV data taken by Slobodrian et al.[3] (the "Berkeley" data).

In a paper by Sher, Signell, and Heller[4] it is shown that the central phase parameter, $9\Delta_C = \delta_{10} + 3\delta_{11} + 5\delta_{12}$, where the δ_{LJ}'s are the P-wave phases, extracted from the Berkeley and from the Minnesota data disagree by several standard deviations of error. In addition, MacGregor, Arndt, and Wright,[5] using an energy-dependent phase-shift analysis, have shown the Berkeley 9.918-MeV data to be inconsistent with the Berkeley data at 6.141 and 8.097 MeV and with other data at nearby energies.

To help resolve these inconsistencies, we have measured differential cross sections at 9.690 and 9.918 MeV with accuracies near 0.4% relative and 0.6% absolute. A summary of the method and errors will be given here.

The proton beam from the Los Alamos tandem Van de Graaff accelerator passed through a gas target with thin Havar foil windows, and the scattered protons were detected by a single E-ΔE detector arrangement using solid-state detectors. Amplified pulses gated by the E-ΔE coincidence were digitized and sent to an on-line computer for mass analysis and storage. The resulting spectra were later analyzed for the yield. Good resolution allowed easy subtraction of the background, which was caused mainly by slit-edge scattering. In a typical case the background was determined to be $(0.7 \pm 0.07)\%$. Electronic dead-time corrections were determined to an accuracy of 0.07%. The pressure was measured to 0.1% by an electronic pressure transducer.[6] The absolute temperature was measured to an accuracy of 0.1% by a thermocouple embedded in the target body. The gas purity was measured to an accuracy of 0.2% by observation of contaminant scattering peaks and by mass spectrographic analysis. The geometry factor was determined to an accuracy of 0.27%, the principal error being in the measurement of the slit widths. Data were taken both left and right of the beam and averaged, giving an accuracy for the stated angle of 0.03°. The lab full width at half-maximum (FWHM) of the angular acceptance varied from 0.4° at low angles to 0.7° at high angles, the variation being due to multiple scattering in the target foils. Beam integration was determined to be accurate to 0.2%.

A variety of calculations and experimental tests gave corrections which were either negligible or had negligible error ($\leq 0.1\%$). These include nuclear scattering in the target gas and foils; local heating of the target gas by the beam; deviations from the perfect gas law; and the effect on beam integration of secondary electrons, delta rays, and multiple scattering in the target foils. Also considered were the purity and monoenergeticity of the beam; switching errors in the scalers; effect on the geometry factor of finite beam size and slit sizes; accidental coincidences, pileup, and various possible losses in the electronic equipment, ADC's, interface, and computer; separation of contaminant peaks; the compensation of particles lost and gained in the detector because of multiple scattering in the exit foil of the target; and nuclear reactions in the detectors. In particular, the question of multiple-scattering compensation in the target foils is subtle and difficult. Both extensive calculations and experimental tests showed that excellent compensation takes place at this energy and with the geometry used.

Statistical counting errors contributed the largest errors, typically being about 0.6% for an individual run on one side. After combining these errors with other angle-dependent errors, the left and right data were combined and a total relative error was calculated. The final results, the cross sections with relative and absolute standard deviations, are shown in Table I. The

Table I. Differential cross sections for $p+p$ elastic scattering.

θ_{lab} deg.	$\sigma(\theta)_{lab}$ mb/sr	$\theta_{c.m.}$ deg.	$\sigma(\theta)_{c.m.}$ mb/sr	Relative Error %	Absolute Error %
			9.918 MeV		
10.00	290.41	20.05	73.36	0.80	0.90
12.50	208.44	25.06	53.12	0.41	0.58
15.00	191.03	30.08	49.22	0.40	0.57
17.50	188.00	35.09	49.06	0.37	0.55
20.00	185.35	40.10	49.11	0.37	0.55
25.00	182.37	50.12	50.14	0.41	0.58
30.00	176.86	60.13	50.92	0.34	0.53
35.00	169.15	70.14	51.53	0.34	0.53
40.00	158.41	80.15	51.65	0.34	0.54
45.00	145.46	90.15	51.42	0.36	0.55
50.00	132.90	100.15	51.73	0.36	0.55
			9.690 MeV		
13.00	211.07	26.06	53.90	0.41	0.58
15.00	197.82	30.07	50.98	0.38	0.56
20.00	192.24	40.09	50.95	0.36	0.55
25.00	188.82	50.11	51.91	0.40	0.57
30.00	183.00	60.13	52.69	0.42	0.59

relative and absolute errors for the $\theta_{lab}=10°$ datum at 9.918 MeV have been increased from the values obtained from our standard treatment (0.55 and 0.68%) to their final values (0.8 and 0.9%) because of an additional systematic error arising from uncertainty in the method of making geometric corrections where the angle is small and the cross section is changing very rapidly. The beam energy is accurate to ±15 keV and has a width (FWHM) of 20 keV. An indication of a lack of systematic errors was given by a series of runs (for $p+{}^3$He elastic scattering) over several months for one given point (45°) with varying conditions; e.g., different detectors, target gases, electronic configurations. A statistical analysis of these runs showed no evidence of unknown fluctuations.

Comparisons with the Berkeley and Minnesota data are shown in Figs. 1 and 2. (We use the Berkeley "BGS" data; see pp. 1124-1125 of Ref. 3.) The data may be compared with respect to both absolute normalization and shape. The Minnesota data at 9.69 MeV are systematically 1.7% higher than ours. Since their absolute error is about 1.0%, the difference has significance. There is no significant normalization difference between our data at 9.918 MeV and the Berkeley data. In either case, by eye there is no significant shape difference, but this is hard to judge at low angles where the cross section is rapidly changing. An analysis by Signell, Holdeman, and Sher[7] finds that the shape-sensitive central P-wave parameter Δ_C extracted from our 9.918-MeV data agrees with their multienergy prediction and with the Minnesota data, but disagrees sharply with the Berkeley 9.918-MeV data. In this analysis our 10° (lab) datum was excluded because of a high contribution to the χ^2 value.

On the other hand, Signell, Holdeman, and Sher,[7] when extracting the S-wave phase ${}^1\delta_0$ from the data, find the Berkeley phase to be in agreement with us but to be in marked disagreement with the multienergy prediction and the phase extracted from the Minnesota data. This result is particularly disturbing because the multienergy prediction is tied to data at other energies and it is not easy to adjust the 10-MeV ${}^1\delta_0$ prediction.

MacGregor[8] has applied the Livermore energy-dependent program[5] to our data and finds also

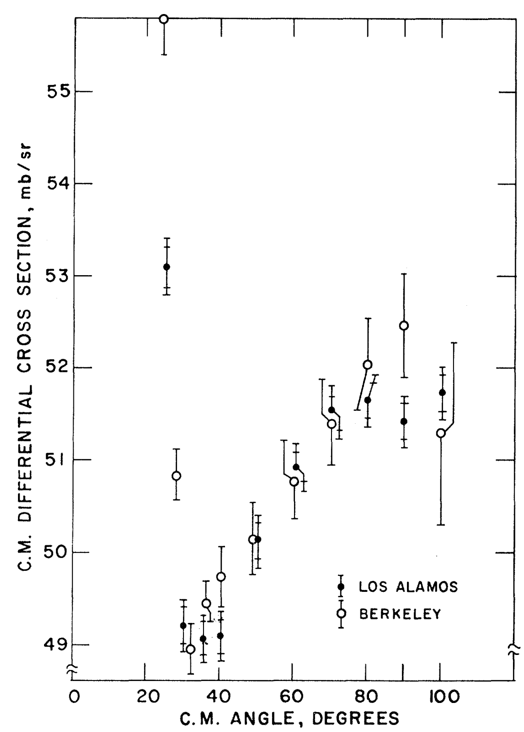

FIG. 1. Comparison of the Los Alamos and Berkeley (BGS) proton-proton elastic-scattering data at 9.918-MeV laboratory bombarding energy. The Los Alamos and Berkeley 20-deg cross sections are identical. The errors shown for the Los Alamos data are the relative and absolute errors. Systematic absolute errors for the Berkeley data were reported to be negligible so that the error bar on their data indicates an independent absolute error (relative and absolute errors equal).

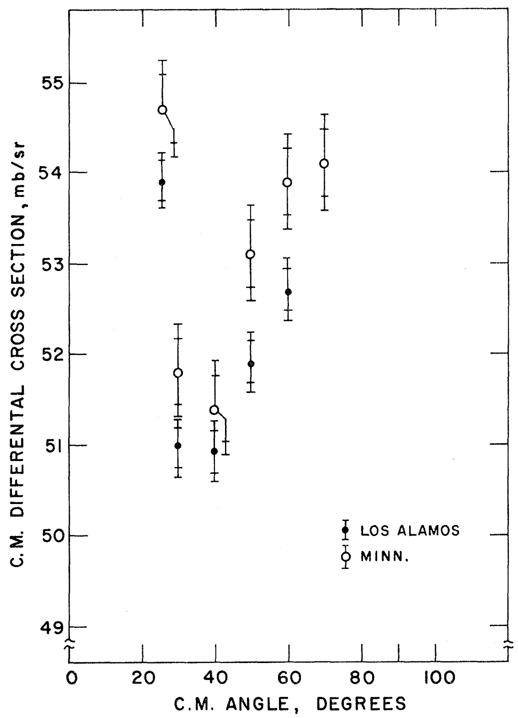

FIG. 2. Comparison of the Los Alamos and Minnesota proton-proton elastic-scattering data at 9.690-MeV laboratory bombarding energy. The error bars indicate both the relative and absolute errors.

that the $\theta_{\rm lab} = 10°$ datum does not fit well. G. Breit, J. Lucas, S. Mukherjee, and M. Tischler have made a preliminary comparison[9] of our data with the predictions of their energy-dependent program[10] $(\text{Y-IV})_{pp+np}$ and have found similar results. In particular, the 10° datum and absolute normalization of our 9.918-MeV data led to a poor fit. They have also applied $(\text{Y-IV})_{pp}$ to the energy range 0-40 MeV and have encountered so far no major difficulty in reconciling our data with other data used in $(\text{Y-IV})_{pp}$ and have observed an increased smoothness of the P-wave energy dependence.

The understanding of proton-proton elastic scattering at low energies is still not clear. We suggest two experimental studies that would help. First, a more sophisticated calculation of the geometrical corrections at low angles should be made, and possibly a remeasurement should be done of the low-angle data, to decide whether the Berkeley low-angle data and our 10° datum are in fact correct or contain a systematic error. Secondly, the absolute normalization of the data needs to be verified, preferably by an independent laboratory.

We wish to express our thanks to Peter Signell, Leon Heller, and John C. Hopkins for enlightening discussions, to David Waymire for his help with the experiment and the analysis, and to the staff of the accelerator and computer for their ceaseless toil.

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*Work performed under the auspices of the U. S. Atomic Energy Commission.

†Visiting Staff Member from the School of Physics and Astronomy, University of Minnesota, Minneapolis, Minn. 55455.

[1]See the references contained in R. J. Slobodrian, H. E. Conzett, E. Shield, and W. F. Tivol, Phys. Rev. 174, 1122 (1968), and M. H. MacGregor, R. A. Arndt, and R. M. Wright, Phys. Rev. 179, 1624 (1969).

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[3]Slobodrian, Conzett, Shield, and Tivol, Ref. 1.

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[5]MacGregor, Arndt, and Wright, Ref. 1.

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[9]G. A. Breit, private communication.

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