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THE DIFFERENTIAL CROSS SECTION FOR PROTON-PROTON ELASTIC SCATTERING AT 90° c.m. BETWEEN 300 AND 500 MeV

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Abstract

The absolute differential cross section for proton-proton elastic scattering has been measured at 90° c.m. for 300, 350, 400, 450 and 500 MeV. The statistical uncertainty of the measurements is 0.5% with an additional systematic normalization uncertainty of 1.8%. The results are compared to phase shift analyses.

NUCLEAR REACTION: $pp \rightarrow pp$ elastic scattering; $\theta_{c.m.} = 90°$, T_p = 300, 350, 400, 450 and 500 MeV. Measured $d\sigma/d\Omega$ with 0.5% statistical precision.

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The motivation for the experimental measurement of the p-p elastic cross section reported here stemmed from the need to use it as a calibration in another proton induced reaction. Measurements of the differential cross section of the $^1H(p,\pi)^2H$ reaction[1] were facilitated by simultaneously measuring the protons elastically scattered at 90° from the target protons. By this means, the $^1H(p,\pi)^2H$ cross-section was measured relative to the p-p elastic cross section. Prior to the $^1H(p,\pi)^2H$ measurements, consideration of the elastic data available in the energy range of 300 to 500 MeV[2] revealed both lack of precision of the relevant data (5 or 10%) and inconsistency of the existing data with some of the phase shift fits to similar levels. This was much larger than the accuracy desired (1%). Clearly the precise knowledge of the p-p elastic cross section was required to provide an adequate constraint for the phase shift analyses of nucleon-nucleon scattering. These are, in turn, useful for predicting cross sections in other energy regions as well as other observables.

For these reasons the p-p elastic cross section was measured at 90° for 5 energies from 300 MeV to 500 MeV to a precision of approximately 1.8%. The experiment was performed using variable energy unpolarized beam at the T1 target position on the 4B external proton beam at TRIUMF. The experimental set-up is shown in fig. 1. The protons resulting from the p-p elastic scattering were detected in coincidence by the two-arm system shown. The 90°(c.m.) scattering angle was chosen because the 90° analyzing power is zero providing optimal reference data even for experiments using polarized beam. The rear detectors of the telescopes ($5\times2\times0.64$ cm^3 at 71.9 cm) defined the solid angle. The logic for each event was (PL1•PL2)•PR1+(PR1•PR2)•PL1, or left arm events plus right arm events. The percentage of events counted twice by this logic never exceeded 10%. Monte Carlo calculations at each energy defined the energy dependence of the solid angle. The experimental targets used were two small CH_2 targets ($5\times5\times 0.163$ cm^3 and $5\times5\times0.511$ cm^3) together with one (background) C target ($5\times5\times 0.196$ cm^3).

Proton beam intensities were monitored by three independent devices. A double three-arm polarimeter located 2.7 m upstream normally used for polarized beam experiments, monitored p-p elastic scattering from an independent target. The beam passed through a secondary emission monitor located 21 m downstream of the target before being stopped in a Faraday cup which provided a measure of the total beam charge transmitted.

Beam intensities were varied from 0.01 nA to 2.5 nA to test for rate effects on all the counters. The accidental rates in the p-p elastic telescopes ranged from 0.2% to 4% (the higher value came from the thick target, high current runs). Although the results were all consistent when corrected properly for these accidental rates, the nominal currents throughout the experiment were kept to 0.1 nA. In addition, tests of other systematics were made by deliberately steering the beam by amounts varying up to 1.5 cm to the left and right of target center. No measurable effect on the total p-p elastic telescope counting rate was observed.

All singles and coincidence rates for the scintillation detector system were recorded along with number of cyclotron RF timing pulses. Due to the high counting rates involved the contents of all the CAMAC scalers were recorded by a PDP11/34 on magnetic tape every 2.5 s, thus providing a running log of the experiment.

The cross sections reported here were normalized to the Faraday cup beam charge measurement. Of all four beam monitors, the polarimeter, the p-p elastics, the S.E.M. and the Faraday cup, it was found that the ratio of the p-p elastic telescope events and the Faraday cup charge was the most consistent over time, the consistency being within 0.5%. A detailed analysis of correlations and ratios between each of the beam monitors showed that the other two beam monitors, the polarimeter and the S.E.M., drifted and could not be trusted to less than 2%. Relating such drifts to changes in experimental data taking such as beam current, targets, etc. was not successful.

The Faraday cup and the p-p elastic telescope demonstrated reliable consistency over a wide range of beam current rates, target thickness variations and beam tunes. For the results presented here, it was assumed that all the beam charge was detected by the Faraday cup.

All the counting rates were expressed as a mean number per beam burst and manipulated$^{3)}$ by Poisson statistics to correct for pulse pile-up and accidentals during individual proton beam "buckets". This careful correction procedure was done because the simplistic method of determining accidentals in the telescopes by delaying one arm with respect to the other by the rf period is only an order of magnitude estimate of the real accidental rate. In order to do these corrections all appropriate single, double and triple coincidence rates plus a simple model relating the geometry, rate and size of the telescope counters was utilized to give an appropriate correction. For example, a 4% effect as determined by simple delay line technique in the hardware logic actually corresponded to a 3% real accidental rate. This correction agreed with that required to establish consistency between the high rate runs and low rate runs.

Corrections to the data were also made for nuclear reaction losses in the target, scintillation counter and window materials. Protons that were absorbed before scattering did not present a problem as they were lost from both the elastic counters as well as from the Faraday cup. However, corrections were made for scattered protons that were subsequently absorbed in the target, the vacuum windows, the air or the front detectors of the telescopes. In addition, corrections were necessary to account for loss of beam before the Faraday cup due to the material of the secondary emission monitor. Consideration of such corrections increased the differential cross sections by 0.6 to 1.1% depending on the beam energy and the thickness of the target.

The differential cross section of p-p elastic scattering from a CH_2 target is

$$\frac{d\sigma}{d\Omega_{pp}} = \frac{1}{2}\left\{\frac{N_s}{N_p\ n_t\ 2\Delta\Omega} - \left.\frac{d\sigma}{d\Omega}\right|_c\right\} \qquad (1)$$

where $d\sigma/d\Omega|_c$ is a measure of events from proton-carbon scattering (discussed below), N_s is the total number of scattered protons detected both p-p elastic telescope arms each with c.m. solid angle $\Delta\Omega$, N_p is the number of incident protons determined by charge integration and n_t is the number of target molecules (CH_2) per cm^2. Both N_s and N_p have been corrected for nuclear absorption. The solid angle $\Delta\Omega$ was determined from a Monte Carlo program which included effects of beam profile and multiple scattering. The results of the p-p elastic cross section calculated via eq. (1) are shown in table 1.

The contribution of the carbon contained in the CH_2 target was deduced from measurements at each energy using a graphite target. The quantity $d\sigma/d\Omega|_c$ was defined by the equation

$$N_s = N_p n_t \left.\frac{d\sigma}{d\Omega}\right|_c \Delta\Omega \qquad (2)$$

where N_s, N_p, and n_t are similar quantities as in eq. (1) except being applied to the carbon target runs, and $\Delta\Omega$ is the same solid angle as in eq. (1). The differential cross sections from carbon obtained by this method are also given in table 1.

The values presented in table 1 were obtained from several independent runs (12 runs at 500 MeV, 4 to 6 runs at each of the other energies). The results from the individual runs were averaged to give the final values. The errors presented came from two sources, the counting statistics, and the fluctuations in the ratio of the p-p elastic events versus the Faraday cup charge. The latter source, the ratio, had a rms deviation of 0.5% averaged over all runs at all energies. For the CH_2 target runs the fluctuations in the ratio dominated the error whereas for the C target runs the counting statistics dominated the error.

In addition there is 1.8% systematic error due to the change in aperture between the front face and rear face of the solid angle defining counters due solely to the thickness of the counters. This was not an oversight in the design of the p-p elastic telescope as the telescope was originally intended as a beam current monitor which is not influenced by this uncertainty.

To check the reliability of the results, an independent measurement of the beam current was made at 500 MeV by reducing the primary beam current to a level where individual protons were detected with a 3 counter transmission telescope mounted directly downstream of the target chamber. It was necessary to reduce the normal minimum beam intensity by a factor of 1000 to keep the beam rate below 1 × 10^7 $\sec^{-1}$. This was accomplished by the installation of a 5 cm thick Cu collimator containing a 1 mm hole prior to two bending magnets situated 14 m upstream of the target.

Unfortunately, the collimated beam had a low energy tail which was the result of beam particles going through energy degradation in the collimator, then going through a larger bending angle in two subsequent downstream dipoles. Such effects were discovered by noticing anomalous behaviour of the in-beam telescope counters and subsequently verified by beam profiles produced on photographic film. It was decided that the geometry of this set up was bad in that a beam particle passing through the target could not be certain to pass through the beam counter and vice versa. However, since such effects were estimated to be on the order of 3% the measurement nevertheless would serve as a useful check on the Faraday cup data. The data point at 500 MeV with its statistical error, calculated from the beam counter data, is shown in fig. 2 which indicates the degree to which direct beam counting agreed with the Faraday cup results.

The experimental results of the differential cross section are plotted in fig. 2. Included also are the recent results of Chatelain et al. from 500 to 600 MeV.$^{3)}$ The two sets of data are in good agreement. The most significant contribution of the two experiments certainly is the precise knowledge of the energy dependence of the cross section in this energy region.

Also plotted in fig. 2 are the "Winter 1982" phase shift predictions of Arndt$^{2)}$ showing the energy dependence of the 0-1 GeV fit. Our data and the Chatelain data have been included in this nucleon-nucleon elastic scattering data base. For comparison the BASQUE phase shift predictions [4]) are also plotted. It is remarkable how similar the two analyses are considering that the BASQUE results predated the measurements of both Chatelain and ourselves.

It is interesting to compare the Arndt solutions before and after inclusion of the recent data. The Winter 1981 energy-dependent solution (which predates the data of Chatelain and ourselves) is also plotted in fig. 2. The two solutions agree in the 300 to 400 MeV range but differ by 9% at 500 MeV and 10% at 600 MeV. Some of this "time dependence" may result from the effects of data outside the range of concern.

A "single energy" solution at 450 MeV (based on data within a 50 MeV bin) was compared over this time frame. The cross-section prediction decreased by only 0.2% (from 3.623 to 3.615 mb/sr) although the errors assigned decreased from 1.6% to 1.1% from the earlier version to the later version.

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Table 1

The p-p elastic absolute differential cross section at 90° c.m. for proton energies E_p. Also included is the contribution due to carbon contained in the CH_2 target.

E_p (MeV)	Carbon $d\sigma/d\Omega$ (mb/sr)	p-p elastic $d\sigma/d\Omega$ 90° cm (mb/sr)
300	0.432 ± 0.007	3.769 ± 0.019
350	0.509 ± 0.009	3.759 ± 0.019
400	0.568 ± 0.010	3.742 ± 0.019
450	0.604 ± 0.010	3.682 ± 0.019
500	0.638 ± 0.011	3.471 ± 0.018

Figure Captions

Fig. 1. Schematic representation of the experimental set-up. The scattered protons were detected in the two-arm system. Proton intensities were measured with a secondary emission monitor and a Faraday cup downstream of the target and a polarimeter located upstream of the target. The scale shown applies only to the polarimeter and the p-p elastic telescope.

Fig. 2. Comparison of our experimental results (full circles) and those of Chatelain et al.[3]) (open circles) of the p-p elastic differential cross section (90° c.m.) with the phase shift predictions of SAID[2]) Winter 82 (solid line) SAID Winter 81 (dotted line) and BASQUE[4]) (dashed line). The triangular data point at 500 MeV is calculated from the beam counter data.

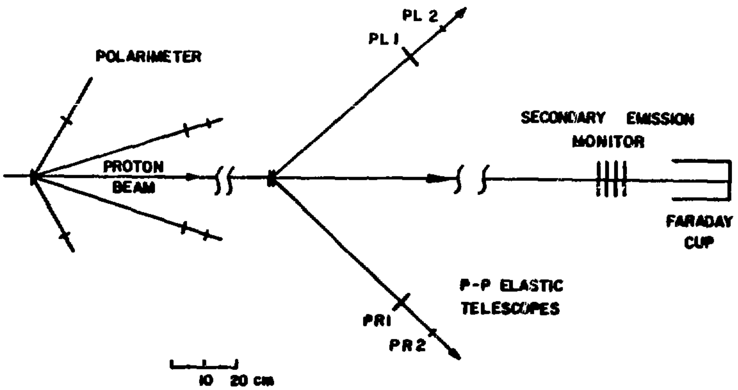
PL 2
PL 1
POLARIMETER
SECONDARY EMISSION
MONITOR
PROTON
BEAM
FARADAY
CUP
P-P ELASTIC
TELESCOPES
PR1
PR2
10 20 cm

Fig. 1

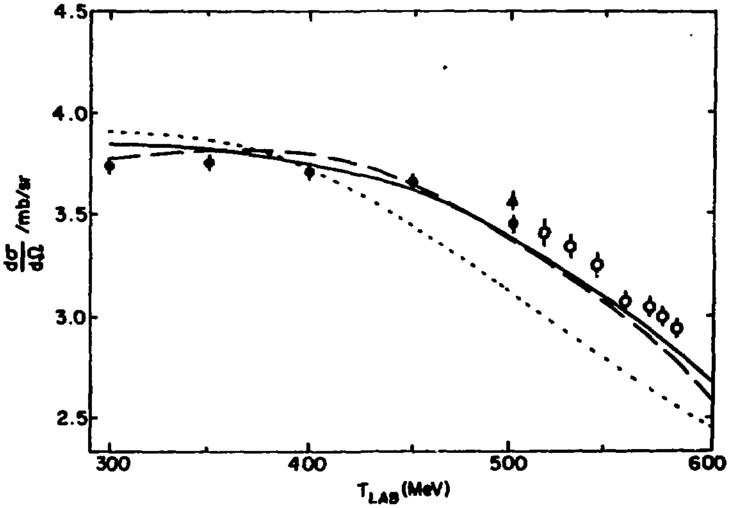
4.5
4.0
3.5
3.0
2.5
$\frac{d\sigma}{d\Omega}$ /mb/sr
300
400
500
600
T_{LAB} (MeV)

Fig. 2