Comparison of Nucleon-Nucleon Total Cross-Section Measurements at 3.00 GeV/c*

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A detailed comparison is made of two independent experiments to determine the total cross sections for 3.00-GeV/c protons on protons and deuterons. Part, but not all, of the discrepancy between the two measurements of the p-d cross section is explained. Best values for the two cross sections are given.

IN the last few years the statistical precision achieved in total cross-section experiments has reached levels of well less than 1%. Consequently the dominant errors arising in comparisons between experiments or in obtaining absolute values are systematic in nature rather than statistical. Two such experiments by the Cambridge-Rutherford (C-R) Group[1,2] at Nimrod and the Brookhaven (BNL) Group[3] at the alternating gradient synchrotron (AGS) have made independent measurements of the total cross sections for 3.00-GeV/c protons on protons and deuterons, by almost identical methods. The C-R group reported values of 44.47±0.04 and 83.45±0.05 mb, while the corresponding BNL values were 44.32±0.06 and 81.27±0.07 mb. Thus, while the values of $\sigma(p\text{-}p)$ are in good agreement, those of $\sigma(p\text{-}d)$ showed a 2.6% discrepancy, well outside the statistical error.

In view of the importance of the absolute value of the deuterium cross section in connection with neutron cross sections and Glauber theory, for example, a detailed investigation of possible causes of this discrepancy has been made. This note reports the results of this investigation and shows that some but not all of the difference can be understood in terms of small experimental differences between the two experiments.

In both experiments the standard good-geometry transmission technique was employed. This method is described in detail in Refs. 2 and 4. Briefly, the transmission of the incident beam through identically constructed targets containing liquid hydrogen, liquid deuterium, or a vacuum, is measured by a series of closely spaced circular counters, with their axes on the beam line and subtending various solid angles at the target. The partial cross sections as determined by the individual counters are then found from the ratios of the full-to-empty transmission rates. Finally, the cross section, which would be measured by a counter of vanishingly small size using a pencil beam, is obtained by fitting a quadratic in t (minus the square of the maximum momentum transfer to a scattered particle which would still strike the counter) to the partial cross sections and extrapolating to $t=0$.

The only significant differences between the two physical arrangements of counters were (i) the physical order of the transmission counters, and (ii) the range of maximum t values used. For the C-R experiment, the counters were arranged monotonically with the smallest nearest the target, while in the BNL setup the reverse order was adopted. The ranges of maximum t values used were (a) C-R, 0.0046–0.0222 (GeV/c)^2, and (b) BNL, 0.0077–0.0577 (GeV/c)^2. The first of these differences would cause a systematic effect if the neutrons and γ rays arising from interactions in the full targets are peaked sharply enough forward, since some of the neutrals convert to charged particles in the early transmission counters and thus reduce the cross section measured by the later ones. This effect has been investigated numerically and shown to give completely negligible corrections in the experiments under comparison.

The second physical difference, that of the range of t values used, can have important consequences if the elastic diffraction peak is very narrow. If the elastic scattering cross section is parametrized as $d\sigma/dt=\alpha\beta e^{-\beta t}$, the cross section for a diffraction scattered proton to strike a counter is approximately $\sigma'(t_m)=\alpha(1-e^{-\beta t_m})$, where t_m is the maximum value of t accepted by that counter. An error will thus arise if, over the range of t_m values used, a quadratic fit to this expression does not have a zero constant term.

Experimentally, $\alpha=17$ mb and $\beta=6$ (GeV/c)$^{-2}$ for p-p in the present momentum range,[5] while for p-d the corresponding values are[6] $\alpha=10.6$ mb and $\beta=37$ (GeV/c)$^{-2}$. Using these values, $\sigma'(t)$ has been fitted for the two full sets of counters used, yielding as extrapolated values

	$\sigma'(0)_{pp}$ (mb)	$\sigma'(0)_{pd}$ (mb)
C-R	0.00	0.08
BNL	0.01	0.51

Thus the C-R value for $\sigma(p\text{-}d)$ should be increased by

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TABLE I. Cross sections and corrections discussed in the text.[a]

	Experiment	Original σ (mb)	Diffraction correction (mb)	Density correction (mb)[b]	Corrected σ (mb)
p-p	C-R	44.47±0.04	···	···	44.47±0.04
	BNL	44.32±0.06	0.01	···	44.33±0.06
	Difference	0.15±0.07			0.14±0.07
p-d	C-R	83.45±0.05	···	−0.58	82.87±0.05
	BNL	81.27±0.07	0.51	···	81.78±0.07
	Difference	2.18±0.09			1.09±0.09

[a] Statistical errors only listed.
[b] See text for explanation of values used. The alternative choice leads to a difference between the values of $\sigma(p\text{-}d)$ of 0.85±0.09 mb.

0.08 mb and the BNL value obtained using all counters by 0.51 mb. Extrapolations of the BNL data omitting the largest two counters agree with this conclusion. This correction has been included both in the final values quoted in Ref. 3, and in the values given in Ref. 1.

A detailed study has also been made of the methods and corrections used in the two experiments for the analysis of the data obtained. In nearly all respects they are identical, with numerical values in good agreement with each other. The only major difference is in the way the density of the target liquid was obtained. In both experiments the conducting target vessels were surrounded by liquid-hydrogen jackets and, apart from connections to fill lines and pressure gauges or manometers, were sealed off. For the BNL target the hydrogen jackets were also connected to gauges. It would be expected that the temperatures of the target liquids would be the same as those of their jackets. For the hydrogen targets, the target and jacket temperatures as deduced from the observed vapor pressures were equal. Although the deuterium targets were identical in construction to the hydrogen ones, in both experiments the observed vapor pressures above the liquid deuterium indicated a temperature excess of the target liquid over that in the jacket. The differences were 0.53 and 0.66°K for the C-R and BNL experiments, respectively. Tapper's compilation[7] of other workers' measurements of vapor pressure and densities for hydrogen and deuterium were used and some checks made against the original measurements.[8] We are unable to resolve this difficulty without supposing that the tabulated values of deuterium vapor pressure are in serious error. Equally, we are unable to determine whether the vapor-pressure measurements or the jacket temperatures give a more reliable guide to the actual deuterium temperatures, and thus there is an over-all uncertainty in the absolute values of both measurements of $\sigma(p\text{-}d)$ of about 1.0%.

The C-R data were evaluated using the observed vapor pressures, while the BNL group assumed that the jackets gave the temperature of the target deuterium. Consequently, in a comparison of the two, the C-R data must be lowered relative to the BNL measurements. Using the vapor-pressure measurements leads to a raising of the BNL values of $\sigma(p\text{-}d)$ by 1.0% whereas using the jacket temperatures gives a reduction of the C-R value by 0.7%. For comparison purposes we arbitrarily assume the latter.

In conclusion, we list in Table I the cross sections and corrections discussed above. The estimated systematic error for the comparison of the two values of $\sigma(p\text{-}d)$ arising from those factors which are uncorrelated in the two experiments, such as target length and deuterium purity, is 0.3 mb. This error has been made to have as nearly as possible the meaning of a standard deviation. We thus conclude that there remains a discrepancy of 1.09 mb between the two values for $\sigma(p\text{-}d)$, which we are unable to reconcile with the known systematic errors.

We give as the best absolute values available for incident protons at 3.00 GeV/c: $\sigma(p\text{-}p)=44.42\pm0.03$ mb, and $\sigma(p\text{-}d)=82.3\pm0.6$ mb, with a possible further correction of $+0.7$ mb to $\sigma(p\text{-}d)$ as discussed earlier.

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[8] See listing given in Ref. 7.