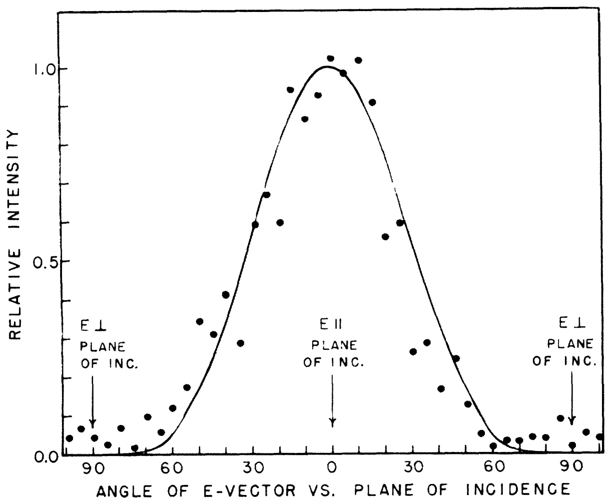

FIG. 2. Variation of second-harmonic light intensity with angle θ between the incident-light polarization vector and the plane of incidence. The theoretical $\cos^4\theta$ dependence (solid line) is included for comparison.

The comparison between the nonlinear susceptibility of conduction electrons and that of bound electrons in crystals such as quartz or potassium dihydrogen phosphate is clear. In both cases second-harmonic effects are enhanced when the system resonates at a frequency near 2ω. In the case of silver irradiated with ruby light, the plasma resonance is close to 2ω, making it a favorable material for initial experimentation. It will be of interest to study second-harmonic light produced in a variety of metals under uniform surface conditions in order to test the applicability of resonance theory to the case of harmonic generation by plasma oscillations.

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PION-PROTON TOTAL CROSS SECTIONS: 400 TO 2000 MeV

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We have measured the total cross section for the scattering of positive and negative pions on protons in the energy range of 400 MeV to 2 GeV with a statistical uncertainty of about 1% (0.3 to 0.5 mb). Known systematic uncertainties are of the same order or less except at energies below 750 MeV for π^--p where they vary from 2 to 10%.

The primary aim of this work was to resolve the systematic 3- to 4-mb difference between the Saclay[1] and Berkeley[2] measurements of the π^+-p total cross sections over most of this energy range. There was also some need to resolve differences in the measurements of the π^--p cross sections, especially at the peaks and valleys in the vicinity of the second and third "resonances." We also sought detailed measurements in the vicinity of the 830-MeV shoulder in the π^+-p cross section, and in the region of 1.5 to 2.0 GeV where a comparison with the Brookhaven measurements[3] was possible.

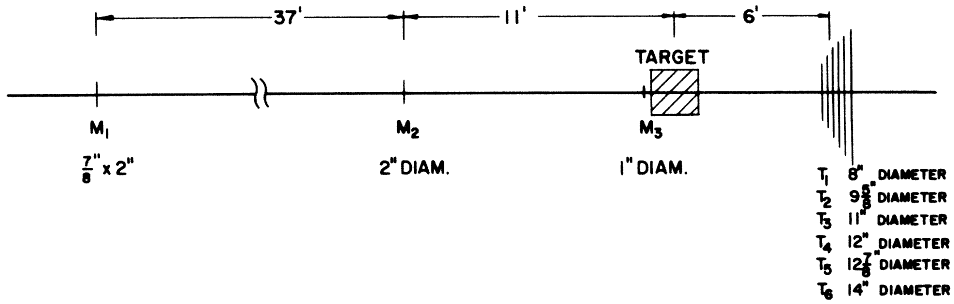

FIG. 1. Schematic diagram of experimental geometry. The vertical scale is greatly exaggerated. All scintillators are $\frac{1}{4}$ inch thick.

The pions were obtained from the Princeton-Pennsylvania Accelerator at an angle of 13° from the circulating proton beam. The beam transport system was 100 ft long, and was brought to a spatial and energy focus at the position of the transmission counters. The momentum distribution of the beam had a full width at half-maximum of 2%. The central momentum was determined by "wire orbits" to an accuracy of better than 1%, and it was corrected for the small energy loss in counters and the hydrogen target. Measurements of the pion-proton time-of-flight difference in the positive beam were consistent with the wire measurements.

Contamination of the pion beams by muons and electrons was determined with the aid of a SF_6 gas Cherenkov counter. The sum of electrons and muons in the negative beam ranged from 30% to 1% as a function of energy. Positrons and muons in the positive beam varied from 11% to 1%. These values were used to correct the cross section calculations. The magnitude and uncertainty of these corrections were the main sources of systematic error below 700 MeV. Protons in the positive beam were rejected by the method of time of flight over a 47-ft distance.

The counter geometry is shown in Fig. 1. With this geometry the multiple Coulomb scattering correction was negligible at all but the lowest energies. The transmission counters subtended solid angles ranging from 10 to 30 msr in order to allow a straight-line extrapolation to zero solid angle. The hydrogen target was 24 in. long and 5 in. in diameter.

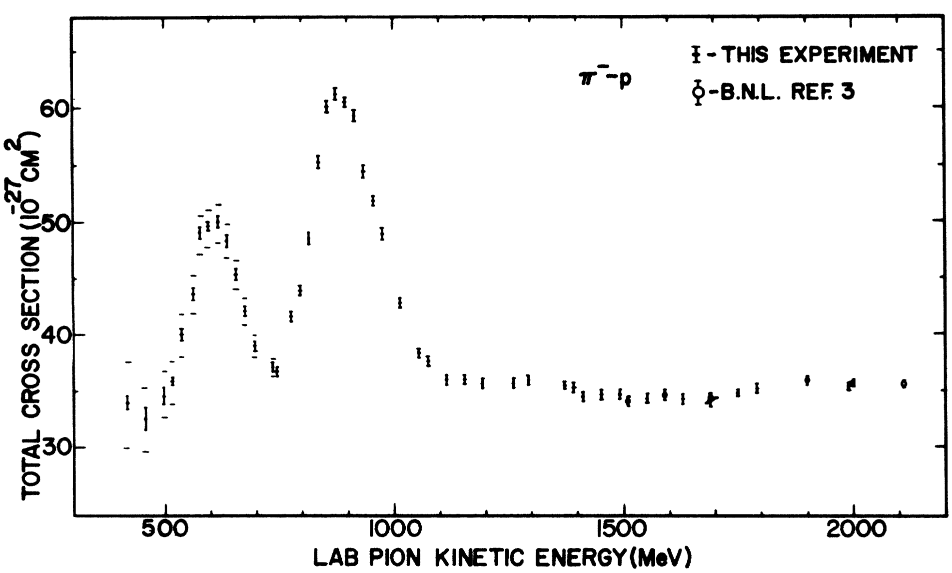

FIG. 2. Total cross section for negative pions on protons as a function of the kinetic energy of the pion in the laboratory system. Errors shown are statistical. The extra error bars shown on the low-energy pionts are the significant systematic uncertainties.

The discriminators and coincidence circuits used in the fast electronic logic were made by Chronetics. Corrections due to electronics accidentals and due to "bunching" (2 particles in one rf burst) were held below 3% by careful control of the incident beam flux.

The data are presented in Figs. 2 and 3 and Table I. The table gives known systematic uncertainties arising from muon and electron contamination in the region where they are significantly larger than statistical uncertainties. Some of the Brookhaven data[3] are also shown on the graphs. The agreement between the two experiments in the overlapping region is within the statistical uncertainties.

Comparison with the earlier π^+-p data shows our measurements to be systematically higher than the Saclay work[1] by 2 to 3 mb. While individual points generally favor the Berkeley measurements,[2] our points are systematically about 1 mb lower. The π^--p cross sections are generally in fair agreement with previous work with the major exception of the cross sections in the 600-MeV region, which we find to be about 4 mb higher than earlier measurements. The measurements at 750 and 900 MeV generally favor the Saclay work over that of Berkeley.

Our data are in good agreement with some recent work at Saclay[4] between 800 and 1600 MeV.

We have made some attempt to establish the energies, widths, and spin assignments for states giving rise to the "shoulder" and peaks in the cross sections. We first calculated cross sections for the states of pure isotopic spin:

$$\sigma(I=\tfrac{3}{2})=\sigma(\pi^+\text{-}p),$$

and

$$\sigma(I=\tfrac{1}{2})=\tfrac{3}{2}\sigma(\pi^-\text{-}p)-\tfrac{1}{2}\sigma(\pi^+\text{-}p).$$

We then attempted to fit[5] the measured cross sections with several resonant shapes of the form

$$\sigma_r(E)=\frac{\sigma_0\Gamma^2/4}{(E-E_0)^2+\Gamma^2/4},$$

superimposed on a reasonable "nonresonant" background. E_0 was the total c.m. energy of the resonance, and the width Γ was taken to be

$$\Gamma=\Gamma_L \text{ for } E<E_0 \text{ (lower width)}$$

and

$$\Gamma=\Gamma_U \text{ for } E>E_0 \text{ (upper width).}$$

This choice of Γ was made to account for the obvious lack of symmetry in the various maxima. For the nonresonant background we assumed a smooth curve joining the measured values at low energies to the measured values

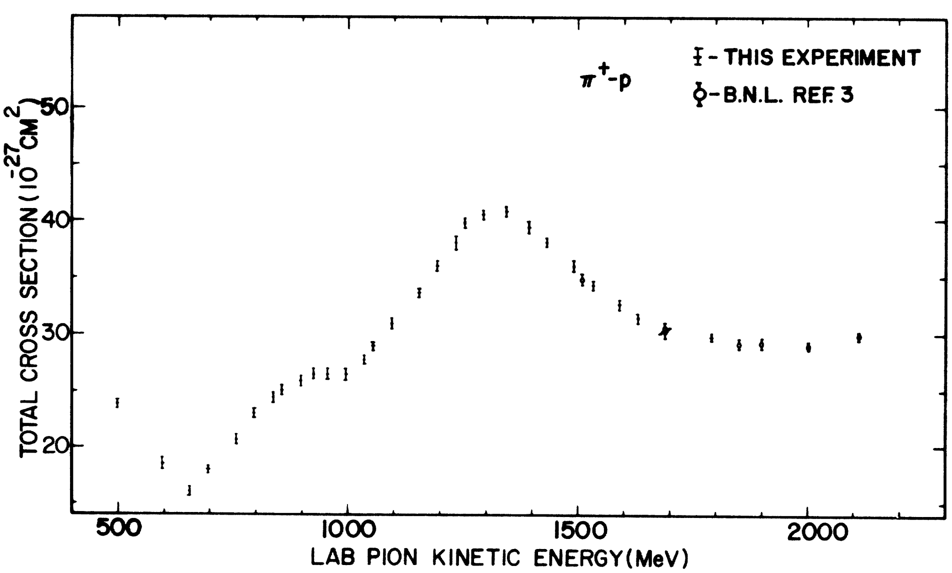

FIG. 3. Total cross section for positive pions on protons as a function of the kinetic energy of the pion in the laboratory system. Errors shown are statistical only.

Table I. Measured total cross sections.

Kinetic energy (MeV)	Total cross section (mb)	Uncertainties Stat. (mb)	Uncertainties Syst. (mb)	Kinetic energy (MeV)	Total cross section (mb)	Uncertainties Stat. (mb)	Uncertainties Syst. (mb)
	$\pi^- - p$				$\pi^- - p$		
418	34.0	0.6	4.0	1492	34.7	0.4	
457	32.6	1.0	3.0	1552	34.3	0.4	
497	34.6	0.7	2.2	1630	34.3	0.4	
516	35.9	0.3	2.0	1691	34.0	0.4	
537	40.0	0.5	1.9	1749	34.8	0.3	
563	43.6	0.5	1.8	1790	35.2	0.4	
577	49.0	0.5	1.8	1989	35.4	0.3	
596	49.6	0.3	1.8		$\pi^+ - p$		
617	50.0	0.5	1.8				
636	48.3	0.5	1.6	497	23.8	0.4	0.7
656	45.3	0.5	1.4	596	18.6	0.5	0.5
676	42.1	0.4	1.2	656	16.1	0.4	0.4
696	39.0	0.4	1.0	696	18.0	0.3	0.4
735	37.1	0.4	0.8	756	20.7	0.4	0.3
745	36.7	0.4	0.6	795	23.0	0.4	0.2
776	41.6	0.4	0.5	836	24.4	0.4	
795	43.9	0.4	0.5	855	25.1	0.4	
815	48.5	0.5	0.5	895	25.9	0.5	
836	55.2	0.5	0.5	924	26.5	0.4	
855	60.1	0.5	0.5	954	26.5	0.5	
875	61.2	0.5	0.5	994	26.5	0.5	
895	60.5	0.4	0.5	1034	27.8	0.4	
914	59.3	0.5	0.5	1054	29.0	0.4	
934	54.4	0.5	0.4	1094	31.0	0.5	
955	51.8	0.4	0.4	1154	33.7	0.4	
975	48.9	0.5	0.4	1193	36.1	0.4	
1014	42.8	0.4	0.3	1234	38.1	0.6	
1054	38.3	0.4		1253	39.9	0.4	
1074	37.6	0.4		1293	40.6	0.4	
1114	36.0	0.5		1343	40.9	0.4	
1154	36.0	0.4		1392	39.5	0.5	
1193	35.6	0.4		1432	38.2	0.4	
1260	35.7	0.4		1491	36.1	0.5	
1292	35.9	0.4		1532	34.4	0.4	
1372	35.5	0.3		1591	32.7	0.4	
1392	35.3	0.4		1631	31.5	0.4	
1412	34.5	0.4		1691	30.2	0.4	
1452	34.7	0.4		1790	29.9	0.3	

of the cross section above 2.5 BeV. The "best-fit" parameters are given in Table II.

Under the assumption that the resonances were in a single state of total angular momentum J and that the real part of the phase shift was 90°, we tested σ_0 for possible spin assignments consistent with unitarity, i.e.,

$$\sigma_0 = (2J+1)\pi\lambda^2(1+b),$$

where λ is the c.m. wavelength, and b is the inelasticity parameter with physical values between 0 and 1. These results are given in Table II.

It is characteristic of this treatment that a measured value of σ_0 less than the lower limit of the above formula for a given J cannot be considered evidence against that value of J. This arises from the fact that the real part of the phase shift need not be 90°. However, a value of σ_0 greater than the upper limit constitutes evidence against a single state with that value of J.

Table II. Parameters obtained by fitting resonant curves to the cross sections.

T Lab kinetic energy (MeV)	I Isotopic spin	E_0 Total c.m. energy (MeV)	$\frac{1}{2}\Gamma_L$ Lower half-width (MeV)	$\frac{1}{2}\Gamma_U$ Upper half-width (MeV)	σ_0 Height (mb)	J Spin	b Inelasticity parameter
611 ± 8	1/2	1519 ± 5	61 ± 5	52 ± 3	45 ± 5	3/2	0.90
						5/2	0.27
873 ± 10	1/2	1673 ± 6	43 ± 3	73 ± 3	54 ± 1	7/2	0.78
						9/2	0.42
						11/2	0.19
829 ± 20	3/2	1648 ± 12	51 ± 22	150 ± 71	9.3 ± 2.7	1/2	0.13
1305 ± 18	3/2	1900 ± 9	126 ± 31	130 ± 24	22.1 ± 4.6	5/2	0.52
						7/2	0.14

An assignment of $J=\frac{7}{2}$ for the $I=\frac{3}{2}$ state at 1305 MeV is consistent with evidence from the differential elastic cross sections of Helland et al.[6] The "shoulder" at 829 MeV appears to be well fitted by a resonant shape, but no value of J can be ruled out.

In the $I=\frac{1}{2}$ peak at 873 MeV, our data are consistent with a single state of spin $J=\frac{7}{2}$ or higher, and rule out the possibility of any single state with $J=\frac{5}{2}$ or lower. Helland, however, finds definite evidence against any major contribution from states of $J=\frac{7}{2}$ or higher at this energy, and he finds evidence that both $D_{5/2}$ and $F_{5/2}$ states are prominent. The charge-exchange angular distributions of Kenney et al.[7] also show these states to be prominent, and furthermore indicate that both are in the $I=\frac{1}{2}$ channel. Our results can be interpreted in a manner consistent with this.

For the 611-MeV peak in the $I=\frac{1}{2}$ state, the angular distributions[6] do not indicate the prominence of any particular angular-momentum state. Our result is consistent with any single state of angular momentum $J=\frac{3}{2}$ or higher, as well as any combination of states. No clear picture of the nature of this peak has emerged.

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