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PROTON-PROTON ELASTIC SCATTERING AT 90° AND STRUCTURE WITHIN THE PROTON*

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This paper will report a recent series of measurements of the p-p elastic differential cross section for 90° center-of-mass scattering angle. This experiment was performed for a range of incident proton momenta from 5.0 to 13.4 GeV/c in steps of 200 MeV/c or less.

The experiment was performed on the slow extracted beam of the zero-gradient synchrotron (ZGS) at Argonne National Laboratory. With a "front porch" on the ZGS magnetic field, the internal beam of $(1\text{-}1.5)\times10^{12}$ protons per pulse was accelerated up to the appropriate momentum and a fraction of the beam was extracted. The rest was accelerated up to full energy for other experiments. The extraction efficiency was about 25%, and the beam was collimated to an angular divergence of ±3 mrad horizontally by ±1 mrad vertically. This yielded an incident beam of $(1\text{-}2)\times10^{11}$ protons per pulse on a one-square-inch polyethylene target. The momentum spread of the beam was about ±5 MeV/c and the spill time was about 150 msec.

The flux of incident protons was measured by radiochemical analysis of the CH_2 targets which were either 1 or 2 cm thick. A different target was used at each energy and after irradiation the Be^{7*} content was assayed by counting the characteristic 0.48-MeV gamma from the Be^{7*} decay. The excited Be^7 nuclei were produced by the process $p+C \to Be^{7*}+X$. The gamma activity was measured to 1% statistical accuracy with a standard NaI gamma-ray spectrometer. The absolute normalization[1] was obtained from Au and Al foils taped on the CH_2 targets during calibration runs. The results of this radiochemical analysis were consistent to better than 2%. There was an overall error in the normalization of about 5%.

The detection system was a double spectrometer arranged symmetrically on either side of the incident beam direction. Each of the two scattered protons was bent by a C magnet and passed through a beam port, as shown in Fig. 1. Each proton was then momentum analyzed by a 9° deflection in a 72-in. bending magnet and detected by a telescope of three scintillation counters.

The C magnets solved a problem caused by the Lorentz transformation from the center of mass to the lab. For 5.0-GeV/c incident-proton momentum the laboratory proton angle was 29°, while at 13.4 GeV/c the laboratory angle was 20°. Without the C magnet it would be necessary to move the bending magnet more than 10 ft in changing from 5.0 to 13.4 GeV/c. The spectrometer was designed so that at 9.4 GeV/c, when the protons were scattered at 23°, the C magnets were turned off. At 5.0 GeV/c the protons were bent in 6°, and at 13.4 GeV/c the protons were bent out 3°. At the two extremes the scattered protons emerged only 8 in. apart and easily fit through the aperture of the B magnet. The current in the B magnet was adjusted so that the protons always went through the L_3 or R_3 counter.

The value of this technique was twofold. It eliminated both costly moves of heavy magnets and the possibility of systematic errors due to misalignment at different data points. Changing energies only required varying the currents in the magnets. Note that the scintillation counters did not move and the timing between the L and R telescopes did not change, since the spectrometers were of equal length and the two protons had equal velocities. For these reasons we believe that there was essentially no point-to-point systematic error.

Whenever a proton passed through all three left counters, an L coincidence was generated. Similarly, a proton through all three right counters generated a R coincidence. The elastic scattering rate plus a small contamination of accidentals was determined by the coincidence of L and R called LR. The accidental rate was determined by triggering a time-to-amplitude converter with the LR signal. The time-to-amplitude converter was connected to a pulse-height analyzer so that the time-of-flight spectrum of the L_3 and R_3 counters could be measured and displayed. With this system the elastic events appeared as a large peak, 1.6 nsec wide, on top of a flat region, 30 nsec wide, caused by accidentals. From these spectra the accidentals could be subtracted from the elastic peak, a correction which varied from 0 to 5%.

The solid angle was determined by the L_3

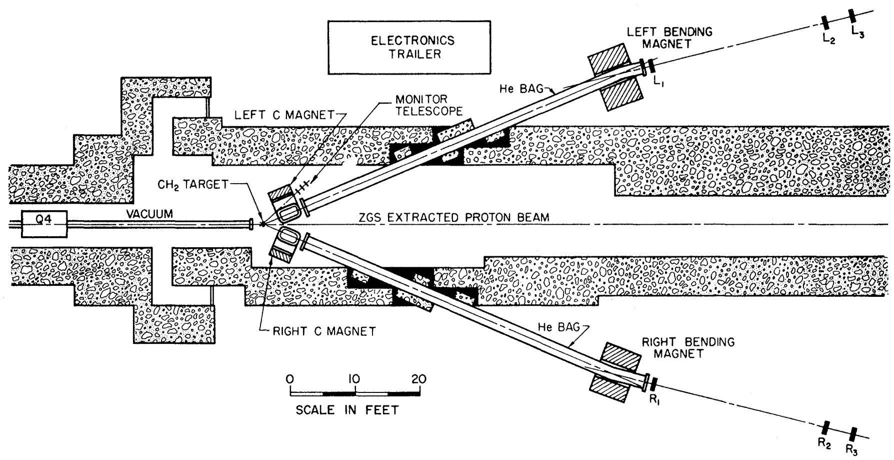

FIG. 1. Layout of experiment. The incident protons come down the extracted beam and strike the target. The scattered protons pass out through the magnets and scintillation counters.

counter which was 7 in. by 5 in. and about 100 ft from the target, covering approximately 2×10^{-4} sr in the center of mass. The momentum bite was about $\Delta P/P=\pm10\%$. The R_3 counter was sufficiently overmatched to allow for the angular divergence and momentum spread of the beam, the multiple scattering in the target, air, and early scintillators, a 1% error in all magnetic fields, and the target-spot size. This overmatching made in-scattering equal out-scattering and eliminated the need for correcting the raw data. The L_1, L_2, R_1, and R_2 counters were also overmatched. The horizontal overmatch was tested by running a curve of the elastic coincidence rate as a function of the current in the right B magnet. This curve had a flat top ±5% wide and dropped by a factor of 100 when detuned 15%. The overmatching was also checked by several runs with the defining counter reduced by a factor of 2 in area. These runs yielded identical cross sections showing that no events had been lost by lack of overmatching.

The carbon background was determined by running with a carbon target in place of the polyethylene. For an equivalent run with CH_2 of 1500 events, one event was recorded with carbon. At all energies the carbon runs gave less than 1%. No subtraction was made.

These carbon runs also gave firm evidence that we were not sensitive to inelastic events, the most serious being

$$p+p\rightarrow p+p+\pi^0. \quad (1)$$

We note that the π^0 production smears the p-p kinematics much more than the Fermi momentum of the proton in a carbon nucleus. Thus, if the Fermi momentum is sufficient to knock quasielastic events out of our detection system, then the π^0 production surely is. We set an upper limit of $\frac{1}{2}\%$ on inelastic production at all energies, and no subtraction was made.

The reason for the small background lies in the small solid angles (2×10^{-4} sr), the tight momentum constraints (±10%), and the overdetermination of the two-body kinematics. This strongly discreiminated against any reactions other than proton-proton elastic scattering.

The cross section was calculated from the formula

$$\frac{d\sigma}{d\Omega}=\frac{\text{Events}}{I_0\Delta\Omega N_0\rho t}. \quad (2)$$

Here I_0 is the incident proton beam as measured by Be^7 decays, $\Delta\Omega$ is the c.m. solid angle, N_0 is Avogadro's number, t is the target thickness, and ρ is the density of hydrogen in CH_2 which was measured to be 0.131. The event rate was corrected by 1.14 ± 0.02 for the 1-cm-thick target and 1.16 ± 0.02 for the 2-cm-thick target. This correction compensated for nuclear interactions of both scattered protons in the target, the air, the He, and the early scintillators. This correction should not change from point to point.

The proton-proton elastic scattering cross section is plotted in Fig. 2 along with other pp data.[2-4] The errors shown are statistical and range from 2 to 5%. We believe that the point-to-point systematic errors are smaller than 3%. There is a 7% normalization uncertainty which comes primarily from the uncertainty in the Be^7 cross section as well as a ±10-MeV/c uncertainty in the beam momentum. The final results, which will appear in a later paper, may differ by a few percent from these preliminary values.

There are four interesting conclusions that can be drawn from this experiment.

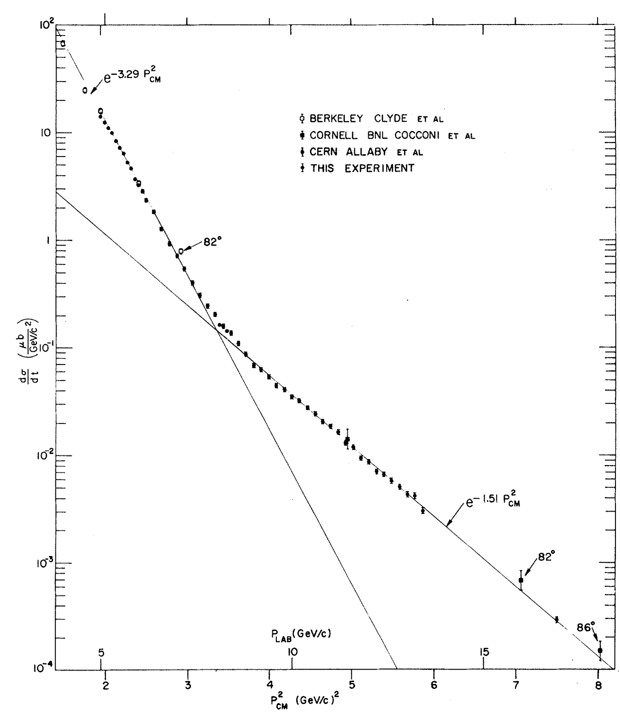

FIG. 2. Plot of $d\sigma/dt$ vs $P_{\text{c.m.}}^2$ for proton-proton elastic scattering at 90° in the center of mass. Other data[2-4] are also plotted. The lines drawn are straight line fits to the data.

First, notice that there are no bumps or valleys in this fixed-angle differential cross section. Any dibaryon resonances in the range 3300-5200 MeV would show themselves as bumps or valleys. We believe there are no fluctuations greater than a level of 5% at 5.0 GeV/c to 10% at 13.4 GeV/c. Since the resonant amplitude at 90° is given crudely by

$$f_R(90°) = (i\hbar c/P_{\text{c.m.}})(2l+1)P_l(90°)X_l[\exp(2i\delta_l)-1], \quad (3)$$

and assuming that there is a resonance so that $\exp(2i\delta_l)-1=-2$, we obtain an upper limit on the elasticity of any even-l dibaryon resonances with $S=0$ and $T=1$:

$$X_l < 0.005 \text{ at } 5.0 \text{ GeV}/c, \quad < 0.0005 \text{ at } 13.4 \text{ GeV}/c. \quad (4)$$

This smooth curve for the fixed-angle pp cross section is particularly striking, in view of the violent structure observed in the fixed-angle π^-p 180° cross section earlier this year.[5] These two experiments demonstrate clearly a difference between the π-nucleon and nucleon-nucleon systems.

Next we note that our data disagree violently with the statistical model prediction that at fixed angle $d\sigma/d\Omega$ goes as $\exp(-aP_{\text{c.m.}})$. On a plot of $\log d\sigma/d\Omega$ against $P_{\text{c.m.}}$ our data appear S shaped with at least 25 points missing the statistical-model[6] prediction of a straight line by ten or more standard deviations. This model does not appear to be useful in the momentum range 5.0-13.4 GeV/c.

Third, notice that while our data do not fit the curve $\exp(-P_{\text{c.m.}})$, they do appear to drop as $\exp(-P_{\text{c.m.}}^2)$. For proton-proton scattering the quantity S is given by

$$S = 4P_{\text{c.m.}}^2 + 4m^2. \quad (5)$$

Thus in our energy region the fixed-angle differential cross section appears to drop as e^{-S}. If this trend continues at asymptotic energies, it will violate the lower bound of Cerulus, Martin, and Kinoshita.[7] This would be an indication that the scattering amplitude is not analytic and bounded.

Finally, notice that there are two straight lines in Fig. 2 giving a sharp break in the cross section around $P_{\text{c.m.}}^2 = 3.4$ (GeV/c)^2. We believe that each of these lines is caused by an inner region of the proton. A Gaussian-shaped region whose opacity or interaction probability density is given by

$$P(R) = e^{-\frac{1}{2}R^2/A^2} \quad (6)$$

will give an elastic diffraction-scattering cross section of the form[8]

$$\frac{d\sigma}{dt} = \frac{d\sigma}{dt}\Big|_{P_{\text{c.m.}}=0}[\exp(-\tfrac{1}{2}A^2P_{\text{c.m.}}^2)]. \quad (7)$$

Thus from the slopes in Fig. 2 the sizes of the inner regions of the proton are 0.50 ± 0.02 F and 0.34 ± 0.02 F. The size of the outer region of the proton, which is seen in the familar diffraction peak at small angles, is about 0.92 F.

Thus our data seem to indicate that the proton looks[9] something like an onion with an outer pion cloud of radius 0.92 F, an inner heavy cloud of radius 0.50 F, and a core of radius 0.32 F. A model of this type was suggested several years ago.[10] It will be interesting to see if there are any more breaks at higher $P_{\text{c.m.}}^2$. A 31-GeV/c Cornell-Brookhaven[3] point suggests another break,[11] but the errors are very large.

We would like to thank the entire ZGS staff for their help and encouragement during the experiment, and Dr. E. Steinberg and Dr. A. Stehney for their aid and advice in the radiochemical analysis of the targets. We also thank Professor M. H. Ross for his helpful comments.

*Work supported by a research grant from the U. S. Atomic Energy Commission.

†Work supported by a summer grant from Argonne National Laboratory.

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LOW-MASS $K\bar{K}$ SYSTEMS PRODUCED IN π^-p INTERACTIONS BELOW 5 BeV/c*

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(Received 7 October 1966)

In a study of $K\bar{K}$ pairs produced in π^-p interactions from 1.5 to 4.2 BeV/c, we observe the $K_1^0K_1^0$ threshold enhancement at all beam momenta, and the φ meson at beam momenta below 2.3 BeV/c. There are no significant enhancements in the K^0K^- system near threshold.

Recent studies have suggested the existence of several low-mass $K\bar{K}$ enhancements: (a) a threshold effect in the $K_1^0K_1^0$ system attributed to a large $I=0$ scattering length[1,2]; (b) a $K_1^0K_1^0$ peak near $M=1060$ MeV with full width $\Gamma \simeq 80$ MeV interpreted as evidence for an $I=0$ resonant state[3,4]; and (c) a narrow peak in the $K_1^0K^\pm$ system at $M \simeq 1025$ MeV with $\Gamma \simeq 40$ MeV, interpreted as an $I=1$ resonance.[5,6] In addition, the low-mass $K_1^0K_2^0$ and K^+K^- final states exhibit peaks from decay of the well-established $I^GJ^P = 0^-1^-$ φ meson at 1020 MeV. In this Letter we discuss the behavior of the $K\bar{K}$ systems observed in the reaction $\pi^- + p \to K + \bar{K} + N$ below 5 BeV/c. Both the low-mass $K_1^0K_1^0$ threshold enhancement and the φ meson are observed in the $I=0$ final states; no significant deviations from phase space are apparent in the $I=1$ states at low effective mass.

The film was obtained using the Lawrence Radiation Laboratory's 72-inch hydrogen bubble chamber in the course of a systematic study of π^-p interactions within the interval 1.5 to 4.2 BeV/c. The experimental details have been discussed by Hess.[7] The observed numbers of events and corresponding cross sections are given in Table I.

(A) $K_1^0K_1^0$ threshold enhancement.—The $M(K_1^0K_1^0)$ distribution is shown in Fig. 1(a) for events with $\Delta^2(n) \le 0.5$ (BeV/c)^2. The $\Delta^2(n)$ distribution in Fig. 1(b) demonstrates that this selection includes most events with $M(K_1^0K_1^0) \le 1.075$ BeV. The strong concentration at low $\Delta^2(n)$ in this mass interval suggests production through pion exchange. In this case, the isospin is zero for the initial $\pi\pi$ system since C is +1 for the $K_1^0K_1^0$ system. A quantitative test of the isospin may be made with the charge-independence triangle inequality. For $I=1$ in the observed $K_1^0K_1^0$ system, we have

$$\{2\sigma(\pi^- + p \to (K\bar{K})^0 + n)\}^{1/2} \le \{\sigma(\pi^+ + p \to (K\bar{K})^+ + p)\}^{1/2} + \{\sigma(\pi^- + p \to (K\bar{K})^- + p)\}^{1/2}. \quad (1)$$

If we use the data of Lander et al.[8] for $\pi^+ + p \to (K\bar{K})^+ + p$ at 3.5 BeV/c and our data at 3.2 BeV/c, (1) becomes

$$(60 \pm 20)^{1/2} \le (6.0 \pm 6.0)^{1/2} + (1.4 \pm 1.4)^{1/2}, \quad (2)$$

where the values are given in microbarns. Since the inequality is poorly satisfied, we conclude that $I=0$ for the low-mass $K_1^0K_1^0$ system. The distributions in decay angle and Treiman-Yang angle are shown in Figs. 1(c) and 1(d) for all events with $M(K_1^0K_1^0) \le 1.075$ BeV; they are consistent with the isotropic distributions expected for a $J^P = 0^+$ state.

In experiments above 5 BeV/c,[3,4] the same reaction yields a peak in the $K_1^0K_1^0$ mass distribution near 1060 MeV, with $\Gamma \approx 80$ MeV, suggesting a resonant state. The dashed curve in Fig. 1(a), representing phase space multi-