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Observation of narrow structures in the p-p elastic analyzing power

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The momentum dependence of the analyzing power A_y in proton-proton elastic scattering has been measured in small steps using an internal target during polarized beam acceleration from 1 to 3 GeV/c. The momentum bin size ranges from 5 to 18 MeV/c. The relative uncertainty of A_y is typically less than 0.01 for each momentum bin. Narrow structures have been found in the two-proton invariant mass distribution of A_y.

In the past five years, narrow resonancelike structures have been observed in two baryon missing mass and invariant mass spectra[1-3] of few-body nuclear reactions. Because the widths are very narrow ($\Gamma \leq 20$ MeV) the observed enhancements are distinguished from the broad resonances in the $^1D_2$ and $^3F_3$ partial waves which have been deduced from nucleon-nucleon (N-N) phase shift analyses.[4] It is unlikely that these narrow structures can be explained in terms of a N-N interaction involving only hadronic degrees of freedom. Although an exotic six-quark state produced with hidden color degrees of freedom does not necessarily have a narrow width, a narrow resonance with baryon number 2, if it exists, would be a good candidate for an exotic state of six quarks. It is noteworthy, however, that such narrow enhancements, while seen in few-body reactions, have not been observed in previous N-N scattering experiments.

Evidence for these narrow enhancements would be seen in N-N scattering observables only if data of very good statistical precision are obtained in very fine energy steps over some region of incident beam energy. Since it is normally rather difficult to change incident beam energy in very fine steps, only a few published results which come close to meeting these requirements are available.[5-7] These energy-dependence measurements are, of the n-p total cross section,[5] made at LAMPF utilizing a "white" source of incident neutrons; of the p-p elastic differential cross section,[6] made at Laboratoire National Saturne, Centre d'Etudes Nucléaires de Saclay (LNS), with a hydrogen-gas-jet target intercepting the proton beam during its acceleration; and of the p-p elastic analyzing power,[7] also made at LNS but with the distribution of incident proton energies generated through energy loss of the primary beam traversing a thick target. (In this last experiment, however, the statistical accuracy was not very good.) In general, these experiments showed no statistically significant narrow structures.

If an exotic state exists with small probability in the N-N system, the corresponding resonance in the N-N observables would be difficult to see. It might be that the enhancements seen in few-nucleon reactions[1-3] suggest a stronger presence of such states in few-body systems. But if such states are present in the few-body systems at something like the 10% level, they should be observable in the N-N scattering channels as well, albeit at a very small level ($\sim 1\%$). Such resonances may be more evident in the spin observables than in the cross section, where they are buried under a large background. The spin observables are bilinear combinations of different amplitudes representing interference terms between them, while the cross section is merely a sum of the squares of amplitudes. The resonance structure may be enhanced by the interference effects; some amplitudes are more sensitive to a resonance in a particular partial wave than others.

The experiment was performed in the beam tunnel of the National Laboratory for High Energy Physics (KEK) proton synchrotron (PS) using an internal target. The number of circulating polarized protons in the PS ring was typically 1×10^9. A very thin polyethylene thread (30 μm in diameter) was used as the internal target since the effective beam intensity was very high; multiple traversals of the beam through the target and a lower limit to the beam intensity, dictated by the need to maintain acceleration, accounted for the high effective beam intensity. The average luminosity was calculated to be $\sim 150\ \mu b^{-1} s^{-1}$ for free p-p scattering. The target was flipped into the beam every acceleration cycle, while the beam momentum was increasing ("ramping"). A similar thread target made of carbon was also used, to measure background events which arose from carbon in the polyethylene target.

A left-right symmetric, four-arm detector system was installed in the PS ring to detect the left (right) forward-scattered proton in coincidence with the conjugate right (left) backward-recoil proton. A scintillator-hodoscope array was mounted on the forward arm and a small scintillator telescope was placed on the backward arm. Each hodoscope consisted of six adjacent vertical bars $(x_1, \ldots, x_6)$ in tandem with five adjacent horizontal bars $(y_1, \ldots, y_5)$ giving thirty (x_i, y_j) detector cells. Coincidences between each cell and the back angle telescope were scaled in 1 msec intervals which defined the momentum bin size, ranging from 5 to 18 MeV/c. The forward hodoscopes were placed so that the angular region conjugate to p-p elastic scatterings detected by the recoil telescopes mapped approximately onto the central y_3 cells (x_i, y_3) of these hodoscopes. The remaining cells were used to provide a supplementary measure of the deviations from conjugate angle and coplanarity and to give information on background due to quasifree scattering and many body reactions. The time-of-flight difference between the forward and backward counters was measured in each momentum bin with a time-to-digital-converter (TDC) in a sampling mode. The fraction of accidental coincidence events was found with the TDC data to be less than 2% up to 2 GeV/c and below 10% up to 3 GeV/c. After correction for the accidental coincidence events, all other background coincidence events were subtracted using information provided by the (x_i, y_1) and (x_i, y_5) cells together with the data taken with the carbon target.

The sign of the beam polarization was alternated every acceleration cycle. An "injection polarimeter," also located in the PS ring, was used to monitor the polarization of the beam. This polarimeter consisted of double-arm counter telescopes with conjugate backward counters. The relative beam polarization was continuously measured at 1 GeV/c, just before the start of acceleration, with the injection polarimeter target inserted into the beam in the PS ring. The data taken with the polarimeter gave a beam polarization at 1 GeV/c equal to 0.46. Beam momentum was automatically calibrated at two momenta where the sign of the beam polarization flipped in crossing the $\gamma G = \nu_z$ and $\gamma G = 7$ resonances.[8]

The analyzing power results are shown in Fig. 1, together with all data previously available[9–14] for the laboratory proton backward scattering angles of this experiment $(68° \pm 1.5°)$. The present results are in good overall agreement with the world's data. The special value of the present results is that all of the data were obtained in a single experiment, so that the problem of relative normalization between different data sets is avoided. (False indication of structure can easily occur if different data sets subject to normalization uncertainties are combined over incompletely overlapping energy intervals.) It is for this reason, and because of the high statistical accuracy and fine energy binning, that the present experiment affords a unique opportunity to detect structure if it exists.

In this momentum region three weak imperfection resonances capable of causing depolarization occur at $\gamma G = 3$, 4, and 5. The corresponding beam momenta are indicated with vertical dash-dotted lines in Fig. 1. The resonance

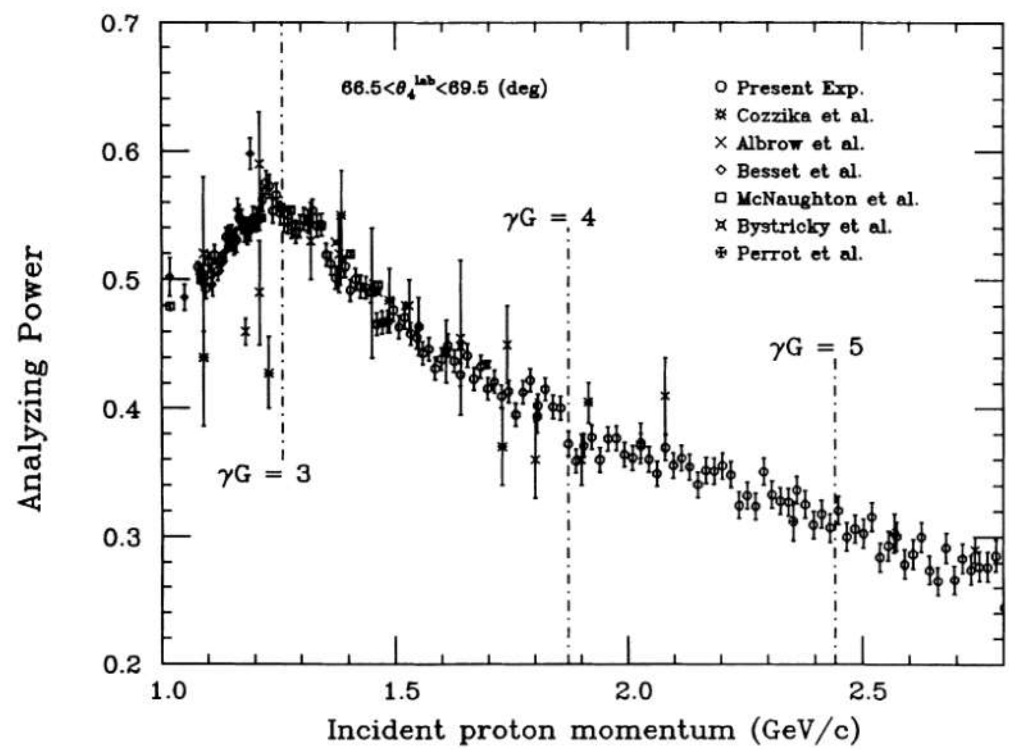

FIG. 1. The momentum dependence of A_y for p-p elastic scattering at the laboratory backward angle of 68°. No correction is made for the apparent depolarization of the beam at $\gamma G = 4$.

widths are calculated to be much less than one momentum bin. Thus the beam polarization and the measured asymmetry are expected to decrease like a step function at the momentum bin where depolarization occurs. No such step is seen in Fig. 1 at beam momenta corresponding to $\gamma G = 3$ and 5, but a small step is apparent at 1.87 GeV/c corresponding to $\gamma G = 4$. Similar evidence of depolarization at the same momentum was seen in the data taken with backward monitor counters placed at $\theta_{lab} = 75°$. The beam polarization was estimated to be 0.46 for beam momentum up to 1.87 GeV/c and 0.44 for the remaining range of beam momentum covered by the present data. No correction for this small change has been made since it does not affect the structures reported here.

Figure 2 shows the p-p elastic analyzing power as a function of the invariant mass of two protons. These are essentially the same data as those shown in the lower-momentum region of Fig. 1. The mass resolution is 2 MeV at 2.15 GeV and gradually increases to 5 MeV at 2.30 GeV. Two small, but narrow structures are observed in the figure. The solid curve shows the result of fitting the data with a sum of two Gaussians and a fourth-order polynomial function. The value of χ^2 for the fit is 46.1, with 51 degrees of freedom (d.f.), which corresponds to a confidence level of 67%. When the same data are fitted only with a fourth-order polynomial, the value of χ^2 increases to 79.8 (57 d.f.), which corresponds to a confidence level of only 2.5%. These two peaks in the data were also compared with a smooth background curve, given by another fourth-order polynomial fit, to a modified data set which excluded the six points in the vicinity of each peak. This fit is shown by the dotted line in Fig. 2. The statistical significance of the difference between the points in the peaks and the background curve under them was computed in the same manner as in Ref. 1, and amounts to 4.1 s.d. for the peak at 2.160 GeV, and 3.1 s.d. for the peak at 2.192 GeV. This procedure accounts for the number of points (6) in each of the peaks, which results in a net error smaller than the errors on the individual points by a factor $\sim 1/\sqrt{6}$. (No attempt was made to fit the hint of a small dip which is seen at 2.242 GeV.) Although the peaks are not necessarily a manifestation of resonances, it is useful to characterize each of these structures with a position and a width. These are listed in Table I. The positions coincide well with those of narrow enhancements observed in the missing-spectra of the ^{3}He$(p,d)X$ reaction,[1,3] which are also listed in Table I. The locations of these enhancements were compared (in Refs. 1 and 3) with the predictions of a rotational model.[15] In this model, rotational bandheads are assumed at the energies $E_0 = 2m_p + m_\pi$, $2m_p + 2m_\pi$, etc., and energy levels are given by $E = E_0 + 0.0206J(J+1)$, where $J = 0,1,2,\ldots$ These predictions are also included in Table I and shown in Fig. 2. If anything, comparison of the present data with the model predictions should be more straightforward for the elastic channel because the initial and final states of the reaction are simpler. Within the context of this model, however, it is difficult to explain the narrowness of the peaks.

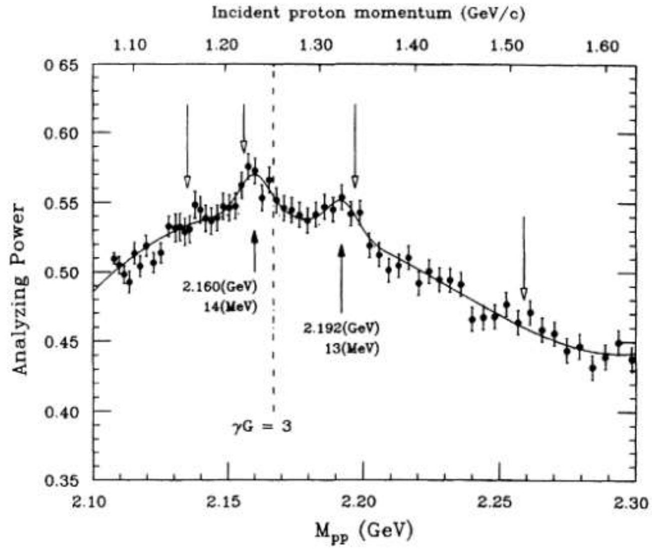

FIG. 2. The invariant mass distribution of A_y for p-p elastic scattering, for the momentum region below 1.63 GeV/c. The solid curve is fit to the data with a sum of two Gaussians and a fourth-order polynomial function. The background shown by the dotted line is explained in the text. The arrows above the curves show the positions of the resonances predicted by the model of Ref. 15.

These data are the first demonstration of narrow energy variations in the strong interaction domain through N-N

TABLE I. Positions and widths (in MeV) of the peaks observed in fits to the invariant mass distribution of A_y, compared with LNS and LAMPF results and a rotational model prediction.

Present results p-p elastic		LNS results[a] ^{3}He$(p,d)X$		LAMPF results[b] ^{3}He$(p,d)X$		Model prediction[c]		J
Position	FWHM[d]	Position	FWHM	Position	FWHM			
				2015 ± 5	34	2012	$pp\pi$	0
				2054 ± 4	11	2053	$pp\pi$	1
		2121 ± 3	25	2125 ± 3	6	2135	$pp\pi$	2
2160 ± 3	14	2155	?	2152 ± 4	20	2156	$pp\pi\pi$	0
2192 ± 3	13	2192 ± 3	25	2181 ± 5	20	2197	$pp\pi\pi$	1
2242	?	2240 ± 5	16			2259	$pp\pi$	3

[a]Reference 1.
[b]Reference 3.
[c]Reference 15.
[d]Full width at half maximum.

elastic scattering in an energy region which, up till now, has been thought to be devoid of structure. The large deviations from a smooth polynomial dependence on energy correspond to statistically significant N-N amplitude variations, which need to be incorporated into a partial wave analysis in order to establish whether they correspond to narrow resonances or not. This is the first observation of narrow peaks in the energy dependence of any observable for elastic scattering. Similar measurements need to be made at other angles, and in inelastic channels such as that of pion production in N-N scattering.

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