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Evidence for the Existence of a Narrow $\bar{p}n$ Bound State*

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(Received 15 March 1971)

A method of search for an $\bar{N}N$ bound state is pointed out and evidence is presented for the existence of a $\bar{p}n$ bound state. It is produced in $\bar{p}d$ annihilations at rest and has been observed decaying into four and six pions. The binding energy is 83.3± 1.4 MeV and the width ≤8 MeV at the 95% confidence level.

We report here an investigation carried out with part of our data for $\bar{p}d$ at rest. This has been done in order to see whether $\bar{p}n$ bound states exist or equivalently whether resonances are formed in the "unphysical" region of the direct $\bar{p}n$ channel ($s<4m^2$). Although several experiments have been performed[1] studying nucleon-antinucleon resonance formation in the physical region ($s>4m^2$), there is no similar work covering the "unphysical" region with the exception of an experiment[2] similar to ours but of limited statistical significance. In order to do such a study we have looked for annihilation mechanisms of the type

$$\bar{p}+d\to p+(\bar{p}n)\to N_\pi+p, \qquad (1)$$

where $(\bar{p}n)$ symbolizes the formation of an intermediate $\bar{p}n$ bound state and N_π its pionic decay products. The observation[3] of the reaction $\bar{p}+d\to p+\pi^-$ is suggestive of the existence of mechanisms indicated by (1), if the pion is thought of as a $\bar{p}n$ bound state. The mass $M_{\bar{p}n}$ of the $\bar{p}n$ for annihilations at rest is uniquely determined from the proton energy ω: $M_{\bar{p}n}{}^2=(M_d+M_p)^2+M_p{}^2-2(M_d+M_p)\omega$. Consequently, any bias on proton identification or on its momentum measurement is critical to such investigations.

The present data come from the analysis of $\bar{p}d$ annihilations observed in the Brookhaven National Laboratory 30-in. deuterium bubble chamber. Details of the data acquisition procedures are given by Gray and Haggerty.[4] The scanning for all processes indicated by (1) has been done by physicists. When the proton has a momentum ≲100 MeV/c, it is not visible, and this results in an odd number of prongs. The protons are easily recognized up to ~800 MeV/c. We have found 4696, 4239, 16 617, 1315, 6878, 4580, 116, and 78 one- to eight-pronged events, respectively. We also found 1747 annihilations which had a proton and at least one kaon. These events have been measured unless one or more of the pions had a projected length < 5 cm in any of the three views. Remeasurements were performed on the failed events until ~95% of all the events accepted for measurement passed reconstruction. We completed 10 522, 8507, 3786, and 2205 three- to six-pronged events representing, respectively, 63, 65, 55, and 48% of the events found in scanning. The Berkeley FOG-CLOUDY reconstruction-kinematics programs were used. Knowledge of resolution functions etc. has been checked with $K_0\to\pi^++\pi^-$, $\bar{p}+d\to\pi^++\pi^-+n_s$, $\bar{p}+d\to K^-+K_1+p_s$. The range-energy relation has been tested with μ^+ coming from stopping-π^+ decays. On the basis of χ^2 and missing-mass-squared criteria, the events have been classified into the following groups: $2\pi^-+\pi^++p$, $2\pi^-+\pi^++p+\pi^0$, $2\pi^-+\pi^++p+>1\pi^0$, $3\pi^-+2\pi^++p$, $3\pi^-+2\pi^++p+\pi^0$, and $3\pi^-+2\pi^++p+>1\pi^0$ which is essentially $3\pi^-+2\pi^++p+2\pi^0$ because of the rarity of higher multiplicities. The selection criteria[4] are such that in the four-constraint (4C) fits a contamination of ~2% is present while for 1C fits it is ~10%, and it is mainly due to in-flight events. It may be of interest to point out that the branching ratios—which are sensitive to all aspects of the data processing—for reactions $\bar{p}+d\to 2\pi^-+\pi^++p$ and $\bar{p}+d\to\varphi+\pi^-+p$ have been in agreement with those obtained independently by our collaborators from Rome.[5,6]

The proton momentum spectra above 150 MeV/c are presented in Fig. 1. The momentum is the measured (in contrast to the fitted) one. The Fourier transform of the Hulthen deuteron wave function fits the spectra below 150 MeV/c well but fails to account for most of the events observed above 200 MeV/c; this is illustrated in Fig. 1 for the case of the $2\pi^-+\pi^++\pi^0+p$ final state. The interpretation of the excess of these events will be

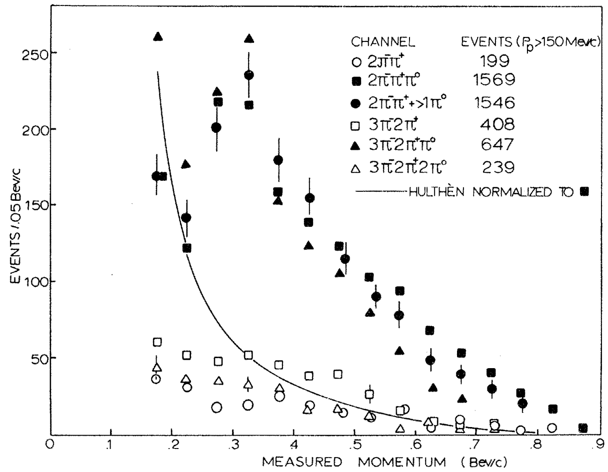

FIG. 1. The $3\pi^- + 2\pi^+ + \pi^0$ spectrum is normalized to the $2\pi^- + \pi^+ + \pi^0$. The Hulthén curve is normalized to *all* (including three-prong) $2\pi^- + \pi^+ + \pi^0$ events.

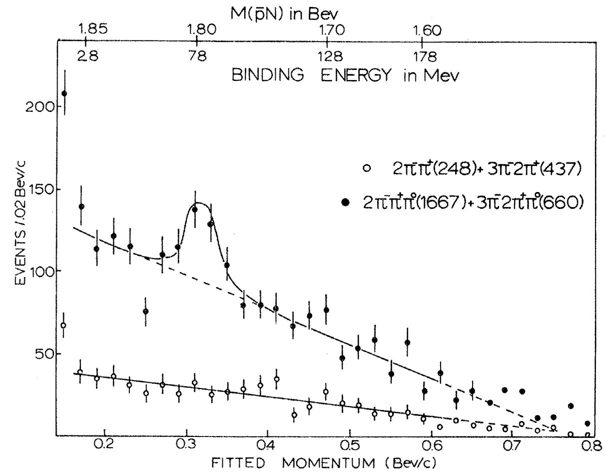

FIG. 2. Fitted momentum spectra for the 4C and 1C events. The curves are least-squares fits by second-order polynomials and a Breit-Wigner form of variable mass and width.

presented in a forthcoming publication. It may be relevant to point out here that this tail is not due to πp final-state interactions (see also Ref. 2). The phenomenon which is of interest to us here is the peak at ~300 MeV/c present in the reactions $2\pi^- + \pi^+ + \pi^0 + p$, $2\pi^- + \pi^+ + p + {>}1\pi^0$, and $3\pi^- + 2\pi^+ + \pi^0 + p$ but absent in $2\pi^- + \pi^+ + p$, $3\pi^- + 2\pi^+ + p$, and $3\pi^- + 2\pi^+ + p + 2\pi^0$. No other statistically significant structure is observed among these final states from 150- to 800-MeV/c proton momentum, which corresponds to a $\bar{p}n$ mass of ~$2M_N$ to 1350 MeV. We shall now explore possibilities of this peak being a consequence of some bias.

Identification biases.—Contamination of the spectra because of misidentifications is certainly present to some extent. The most likely and certain misidentification comes from taking a K^+ as a proton. A K^+ with momentum $\lesssim 500$ MeV/c (ionization $\gtrsim 2\times$ min) would certainly be taken as a proton unless it decayed or a K^- or K^0 was seen associated with the event. This contamination is easily discounted as the source of the 300-MeV/c peak: (i) Kaon events do not fit reaction (1); (ii) K^+ momentum spectra are much wider than the observed peak; (iii) K^+ rates are rare to account for the size of the peak. For example, using the rates[7] for $\bar{p} + p \to K^+ + K_1^0 + 2\pi^- + \pi^+$, $\bar{p} + p \to K^+ + K^- + \pi^+ + \pi^- + \pi^0$ we estimate that only 28 events of this type will be produced among our four-prong sample.

Measurement biases.—The analysis procedure implies that the biases are independent of the prong multiplicity except for those which depend on the rejection of events due to the short track cut. The very indirect way that this bias (or any other scanning bias) enters into the proton spectrum and the narrowness and the systematics of the peak preclude such biases as sources of the observed bumps. The systematics of the bump, however, do not preclude a direct measuring bias on the proton momentum. The difference in sensitivity between 4C and 1C fits can reproduce qualitatively the systematics. An event which is a true 4C but has a biased proton momentum may be rejected by the 4C fit, but a 1C may not be rejected. Consequently the peak should be more prominent in the unfitted events, less in 1C, and even less (absent) in 4C. This is the case in our data except for the unfitted six-prong events. This exception, however, may be discounted on the basis of its weak statistical significance. There is also another contradiction: The kinematical fitting tends to change the measured momenta towards the true ones, and therefore it is expected that a bump due to a measuring bias will be broader when plotted in fitted variables. This is contrary to our observation (see Fig. 2).

The only bias we see which may result in a narrow peak would be flagging of *nonstopping protons.* This flag is used by the reconstruction in determining momenta by range. The dimensions of the chamber could then create a superfluous enhancement. This is illustrated in Fig. 3(a) where we show the $2\pi^- + \pi^+ + \pi^0 + p$ proton spectrum for the protons leaving the chamber and having momenta computed from measured length considered as range. As is seen, if for some reason outgoing tracks are being called stopping

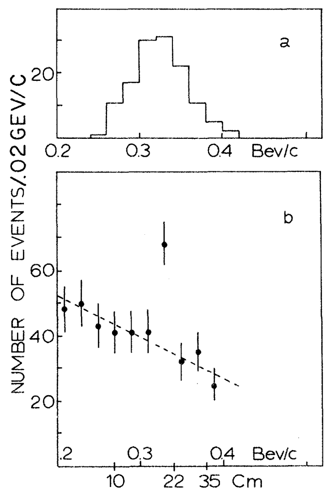

FIG. 3. (a) Spectrum of the protons leaving the chamber. Momenta are calculated using their measured length as their range. (b) Combined proton spectra of the stopping protons with potential path >35 cm of the two-, four-, and six-pronged events. Momenta have been evaluated from $0.275(0.1R)^{0.272}$ BeV/c, where R is their range in centimeters. The dashed line is a fit by eye.

and the reconstruction program does not reject them, they would create a peak at the right place with comparable width! (We point out that such biases should be carefully considered in other experiments as well, and to our knowledge no one has pointed out the danger of such biases.) We have made the following checks of this important point: (a) We have checked the protons for the $2\pi^- + \pi^+ + \pi^0 + p$ final state which had momenta greater than 200 MeV/c. We found that among the 98 events which were flagged as stopping, 94 of them were verified as stopping while 4 were close to the boundary of the chamber, and it is possible that they might have gone out. Thus we found no direct evidence of a stopping bias.
(b) We have examined all our measured events (two-prong included) with protons whose momenta had been evaluated by range. For each proton a potential length in the chamber (length before getting out) has been evaluated from the vertex coordinates, the proton direction, and the chamber's visible volume. The spectrum of the protons which had a stopping flag and a potential path >35 cm is shown in Fig. 3(b). A momentum of 380 MeV/c corresponds to 35 cm, while momenta between 300 and 350 MeV/c correspond to range lengths of 14-24 cm [see range scale in Fig. 3(b)]. Thus the region of interest is well away (>10 cm) from the chamber walls and no question on the reality of the stopping protons up to 380 MeV/c can be raised. Moreover, all protons have essentially equal efficiency of being measured by range up to 380 MeV/c. The result of this "controlled" spectrum is a ~5σ peak between 320 and 340 MeV/c over a linear background! The narrowness of this peak excludes also the possibility of protons which, although they do not leave the chamber, nevertheless are not stopping but interact with the deuteron and produce two invisible protons.

In-flight contamination.—The in-flight contamination cannot consistently explain the peak. If it reflects the dynamics of in-flight events it should then be present among the 4C and 1C groups. If on the other hand it is due to some kind of compensation for the incoming momentum the peak should only be present in the fitted variables.

We therefore have failed to account for the peak being a consequence of some bias and we shall therefore consider it as a genuine $\bar{p}n$ dynamical effect.

We fitted the data of Fig. 2 in the region of 140-600 MeV/c (solid line) with a second-order polynomial in momentum and a Breit-Wigner resonance function with variable mass and width. The polynomials came to be straight lines $(1-p/M_p)$. The mass and width of the resonance are $M_R = 1794.5 \pm 1.4$ MeV and $\Gamma = 15 \pm 2$ MeV. The errors are statistical. The width is consistent with our estimate of the resolution function obtained from curvature measurements of the $\pi^+ + \pi^- + n_s$ and the $K^- + K_1 + p_s$, and it corresponds to a momentum measurement error of ±5%. Consequently Γ is less than 15 MeV. From the study of the collinears and the K_0 and Λ masses, we have concluded also that the systematic errors on M_R are not larger than the statistical ones. On the other hand, the selected sample of stopping protons [Fig. 3(b)] gives a mass of 1790 and a width <8 MeV at the 95% confidence level. We have reexamined the energy-versus-range relation from μ^+ measurements (the measured μ^+ range in our run is 0.975 ± 0.025 cm), and we have found that the momenta as determined in Fig. 3(a) have a systematic error of +10 MeV/c corresponding to a ~5-MeV shift in mass. Thus the mass as determined by range [Fig. 3(b)] agrees with the mass as obtained [Fig. 2] essentially by curvature plus fitting. In conclusion, the two almost independent methods of measurement give the consistent results: $B = 83.3 \pm 1.4$ MeV or $M_R = 1794.5 \pm 1.4$ MeV and $\Gamma < 8$ MeV at ~95% confidence level.

We estimate that the observed production-decay branching ratios defined by $(\bar{p} + d \to p^+ X^-)/(\bar{p}$

$+d$) are $(0.9\pm0.3)\times10^{-3}$, $(2.2\pm0.4)\times10^{-3}$, and $(0.9\pm0.3)\times10^{-3}$ for the X^- decaying into $2\pi^-+\pi^++\pi^0$, $2\pi^-+\pi^++>1\pi^0$, and $3\pi^-+2\pi^++\pi^0$, respectively. We also have searched for $X^-\to\pi^-\omega^0$ and we found that $(X^-\to\pi^-+\omega^0)/(X^-\to2\pi^-+\pi^++\pi^0)<0.07$ at the 95% confidence level.

The only certain quantum number coming from the production mechanism is the isospin which is unity. Under the assumption of a strong decay, which may be disputed because of the unknown but small width, $G=+1$. Moreover, using $G_{\bar{p}n}\equiv-(-1)^{L+S}$, $P_{\bar{p}n}=-(-1)^L$, where L is the $\bar{p}n$ orbital angular momentum, and $S=0$ or 1, we obtain the following possibilities for spin and parity: $J^P=1^-,2^-,3^-,\cdots;\ 1^+,3^+,\cdots$. Namely, all spin and parity assignments are allowed except $J=0$ and the even-even cases.

We have not found any known resonances[8] compatible in mass and width with the one reported here. Moreover, under the assumption of linear Regge trajectories this resonance is not a recurrence of the ρ trajectory.

*Work supported by the National Science Foundation.

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A_2^+ Mass Spectrum in π^+p Interactions at 3.7 GeV/c*

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(Received 24 March 1971)

A study of the A_2^+ mass spectrum in π^+p interactions at 3.7 GeV/c is presented. For a cut of $t'=0.1$-2.0 GeV^2 and on eliminating the Δ^{++} we find that the three-pion mass spectrum in the A_2^+ region is fitted by the dipole formula with a confidence level of 53% and a single Breit-Wigner formula with a confidence level of 11%. Our result thus favors A_2^+ splitting although a single Breit-Wigner fit cannot be ruled out. We also report the A_2^+ decay branching fractions measured over all t' values. They are 0.78 ± 0.05, 0.15 ± 0.04, 0.06 ± 0.03, and <0.02 for $\rho\pi$, $\eta\pi$, $K\bar{K}$, and $\eta'\pi$, respectively, in good agreement with other experiments.

The A_2 meson has been the subject of considerable experimental and theoretical investigation since the observation of the splitting of the A_2^- by the CERN missing mass spectrometer and CERN boson spectrometer experiments.[1] Much less was known about the positive A_2 meson. The Bonn-Durham-Nijmegen-Paris (E.P.)-Torino Collaboration reported[2] observing structure in the A_2^+ in 5-GeV/c π^+p interactions, but their statistics were rather limited. More recently Alston-Garnjost *et al.*[3] have reported on a high-statistics π^+p bubble-chamber experiment at 7 GeV/c, where they see no evidence for splitting. Furthermore a neutron missing-mass spectrometer experiment[4] has recently studied the A_2^0 in π^-p interactions at 3.16 GeV/c incident momentum and observed splitting.

In this Letter we report on the A_2^+ spectrum produced in π^+p interactions at 3.7 GeV/c with a sample of A_2^+ events intermediate in number between that of the 5- and 7-GeV/c experiments. The data come from a 180 000 picture exposure of the Lawrence Radiation Laboratory 72-in. hydrogen bubble chamber at the Bevatron. The experimental details have already been presented.[5,6] The exposure yielded the following numbers of