Measurement of the $\bar{p}p$ Charge-Exchange Cross Section below 1 GeV/c*

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No definite evidence for structure is found in the $\bar{p}p \to \bar{n}n$ cross section between 276 and 963 MeV/c. From these results limits are deduced on properties of the narrow enhancement reported in the $\bar{p}p$ total cross section at 475 MeV/c.

There have been many claims[1] for narrow boson resonances near $\bar{N}N$ threshold, a mass region where structure, called the S meson, was first reported[2] some nine years ago, but never confirmed.[3] The clearest of the recent evidence comes from the formation experiment of Carroll *et al.*[1] where an 18-mb bump was observed in the $\bar{p}p$ total cross section of 1932 MeV (475 MeV/c lab momentum) with a width of 9 MeV. Since then, a narrow effect at this mass has been reported in a bubble-chamber study of $\bar{p}d$ reactions.[4] In addition, two other bubble-chamber experiments indicate substantial, albeit conflicting, structure in the backward $\bar{p}p$ elastic differential cross section over the momentum range from 400 to 650 MeV/c.[5,6] From the theoretical side, calculations[7] based upon one-boson-exchange potentials derived from the NN interaction and suitably modified for $\bar{N}N$ suggest that there should be many (about twenty) bound states and resonances in the vicinity of threshold; further theoretical interpretation of the enhancement found in the $\bar{p}p$ total cross section in terms of such an $\bar{N}N$ resonance has recently been advanced.[8]

Here we report the results of a counter experiment done in the low-energy separated beam of the Brookhaven National Laboratory alternating-gradient synchrotron (AGS), in which the partial cross section for $\bar{p}p$ charge exchange was measured at 22 momenta from 276 to 963 MeV/c with a typical statistical precision of about 1%. The apparatus, originally designed to study $K^-p \to \bar{K}^0n$ and modified for $\bar{p}p \to \bar{n}n$, is shown in Fig. 1. The incident beam was defined by scintillation counters M and S_2. Background mesons in the beam were rejected by time of flight between M and a counter S_1 placed at the mass slit 5 m in front of M, by a threshold Cherenkov counter $\check{C}$, and by pulse height in M. Contamination of the $\bar{p}$ signal was always less than 0.5%. A veto box consisting of counters $A_1, \ldots, A_5$ detected all reactions except those yielding neutral final states,

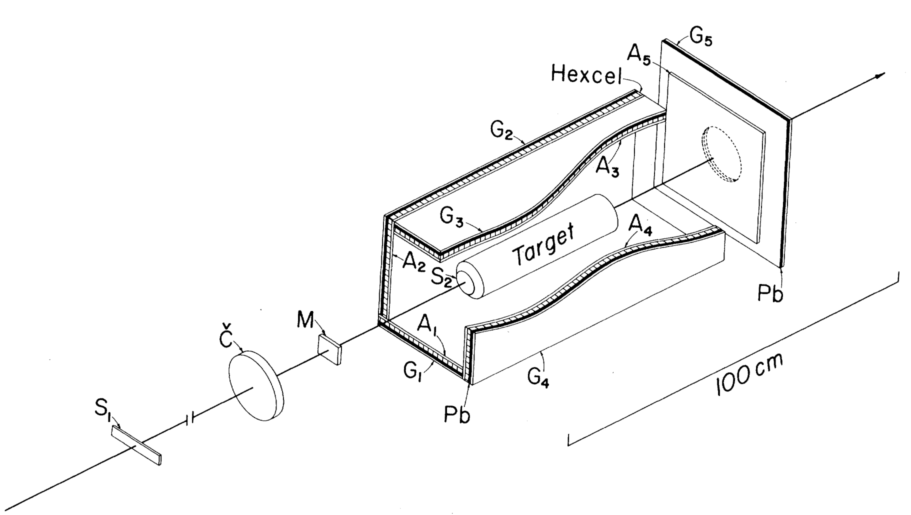

FIG. 1. Isometric projection of the apparatus. G_5 and its lead converter have 5-in.-diam holes through which the beam passes.

while counters $G_1, \ldots, G_5$ detected γ rays converted by approximately 1 radiation length of lead placed between the A and G counters. The signature for a charge-exchange reaction was an incident antiproton, $\varphi = S_1 M S_2 \overline{C}$, with no signal in either the A or G counters, $\varphi \overline{A} \overline{G}$. Empty-target rates, typically 5% of full rates, were measured at each momentum and subtracted.

Several important corrections were made to the data: (1) The attenuation of the $\bar{p}$ beam through the 16-in. liquid-hydrogen target was calculated using a program which took into account the interaction cross section for $\bar{p}$'s as well as the spread in beam momentum and the energy loss in the target. Antinucleon cross sections used here and in the calculations discussed below were obtained from the measured $\bar{p}p$ and $\bar{p}d$ cross sections over this momentum region.[1] These corrections varied with momentum from 1.10 to 1.18. (2) The interactions of $\bar{n}$ and n in the hydrogen target or in the AG veto box surrounding the target were calculated with a Monte Carlo program. This required a knowledge of the absorption cross sections for $\bar{n}$ in carbon and lead. Since these have not been measured, extrapolations based on the optical model were made using data at higher momenta.[9] A visibility factor f_v, as introduced by Bricman *et al.*[10] to represent the fraction of interactions producing a detectable signal in a counter, was assigned to the $\bar{n}$ and n interactions in lead and scintillator: For $\bar{n}$ interactions in lead and scintillator, and for n interactions in scintillator, we used $f_v = 1$; for n interactions in lead we adopted the parametrization of Bricman.[11] These interaction corrections, approximately 20% coming from the target and 80% from the veto box, were due principally (about 75%) to $\bar{n}$'s because of their greater visibility and larger cross sections. They ranged from 1.24 and 1.56 at the highest and lowest momenta, respectively.

The angular distributions of $\bar{p}p \to \bar{n}n$ required for the Monte Carlo calculations were obtained from bubble-chamber experiments at ten momenta from 285 to 760 MeV/c.[12] These angular distributions show no significant momentum-dependent structure beyond that anticipated by the potential-model calculations of Bryan and Phillips.[13] It should also be noted that the configuration of the apparatus is such that over 90% of the solid angle the absorption correction is insensitive to changes in the angular distribution. Only in the forward direction ($\cos\theta_{\text{c.m.}} > 0.9$), where $\bar{n}$ penetrate no lead (see Fig. 1), and in the backward direction ($\cos\theta_{\text{c.m.}} < -0.9$), where low-momentum $\bar{n}$ interact strongly, is there any substantial angular dependence to these corrections. Thus comparing two very different angular distributions, for example strong forward peaking versus isotropy, one finds less than a 3% difference in the cross section.

The beam momentum was established at a series of momenta by p and $\bar{p}$ times of flight over a 6.25-m path beyond the apparatus, by proton range curves, and, during the experiment itself, by $\bar{p}$ stopping in the target at low momentum. These all agree within ± 0.5%.

The corrected charge-exchange cross section is displayed in Fig. 2 as a function of mean laboratory interaction momentum and is listed in Table I. Errors shown are statistical only. We estimate the systematic uncertainty in overall normalization, coming primarily from absorption corrections, to be ± 5% at high momenta and ± 10% at the low-momentum end. There is additional correlated uncertainty at the lowest three mo-

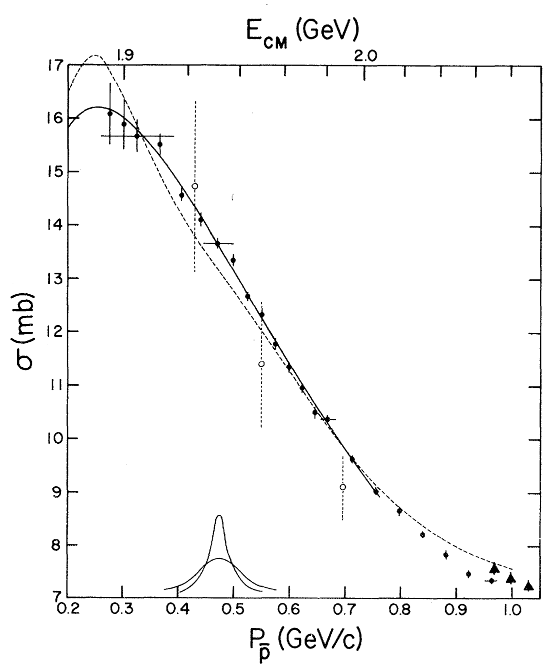

FIG. 2. Cross section for the reaction $\bar{p}p \to \bar{n}n$ versus lab momentum. The closed circles are from this experiment. The triangles are from Ref. 14 and the open circles are bubble-chamber points of Refs. 15 and 16. The dashed curve is a theoretical calculation of Bryan and Phillips (Refs. 13 and 14) while the solid curve is a three-parameter fit to the data below 760 MeV/c. The resonance curve at 475 MeV/c shown at the bottom of the figure is calculated from the total-cross-section results of Ref. 1 assuming $J = 4$, and is shown with and without our resolution folded in.

TABLE I. Cross sections versus $\bar{p}$ lab momentum.

$\bar{p}$ Momentum (MeV/c)		Cross section (mb)	
Mean	RMS Resol.	Charge exchange	Neutral annihil.
276	59	16.09±0.58	---
301	65	15.89±0.48	---
325	68	15.67±0.31	---
366	50	15.51±0.19	5.32±0.19
406	38	14.57±0.13	4.54±0.13
439	32	14.10±0.13	4.38±0.12
470	28	13.65±0.10	3.89±0.09
498	24	13.33±0.11	3.65±0.11
525	22	12.66±0.09	3.59±0.08
550	20	12.32±0.12	3.09±0.10
575	19	11.77±0.11	3.27±0.09
599	18	11.34±0.11	3.07±0.09
623	17	10.95±0.09	2.89±0.08
645	16	10.49±0.11	2.88±0.09
668	15	10.37±0.08	2.68±0.07
712	14	9.62±0.07	2.63±0.07
755	13	9.02±0.07	2.54±0.06
798	13	8.64±0.09	2.35±0.08
840	13	8.21±0.06	2.38±0.05
881	12	7.83±0.08	2.44±0.08
922	12	7.47±0.07	2.14±0.07
963	12	7.35±0.05	2.26±0.05

menta (where $\bar{p}$'s stop in the target) due to the 0.5% uncertainty in beam momentum. This uncertainty increases from ± 2% at 325 MeV/c to ± 5% at 276 MeV/c. At the highest momentum our value agrees within 5% with the State University of New York at Stony Brook–University of Wisconsin counter experiment[15] and at lower momenta with less precise bubble-chamber results[16,17] as shown in Fig. 2. The general shape of the momentum dependence of our results is in reasonable agreement with the calculations of Bryan and Phillips, and a reevaluation[14] of their cross section using a slightly higher value of $g_{\pi N}^2 = 13.5$ for the pion-nucleon coupling constant fits our absolute value as well (see Fig. 2).

Within the momentum resolution of our experiment, which is indicated at several momenta in Fig. 2, there is no evidence for narrow structure. In particular, there is no enhancement at 475 MeV/c where Carroll *et al.*[1] have reported an (18^{+6}_{-3})-mb bump in the $\bar{p}p$ total cross section with a width of 9^{-3}_{+4} MeV. If it is assumed that their observed structure arises from a resonance in a pure spin and isospin state, then

$$\Delta\sigma_T = \pi\lambda\!\!\!^{-2}(2J+1)x/2, \tag{1}$$

where $x = \Gamma_{\bar{N}N}/\Gamma_T$ is the elasticity of the resonance $(0 \leq x \leq 1)$, and J is the spin. With $\Delta\sigma_T = 18$ mb, this yields $x(2J+1) = 1.56$. $J = 0$ is thus excluded by unitarity. For charge exchange, on the assumption that there is no background in the same J^{PC} state, the corresponding expression for the cross-section enhancement is

$$\Delta\sigma_c = \pi\lambda\!\!\!^{-2}(2J+1)(x/2)^2. \tag{2}$$

A good fit to our data below 760 MeV/c can be achieved without a resonance by use of a three-parameter expansion (suggested by the S-wave scattering-length approximation, although higher waves are clearly present). Thus the expression

$$\sigma = 18.15[1-(0.10/P)^2]^{1/2}/[1-0.49P+2.40P^2],$$

where P is in GeV/c, yields the fit shown by the solid line in Fig. 2 with a confidence level of 74%. If we add to this a resonance of mass and width given by Ref. 1 and readjust background parameters, then the best fit after unfolding our resolution gives an enhancement of $\Delta\sigma = 0.33 \pm 0.28$ mb. A combination of this with the total-cross-section results, using Eqs. (1) and (2), indicates for the resonance a small elasticity $x = 0.037$ and an improbably large spin $J = 21$. However, if we allow a 1.7-standard-deviation variation in the enhancements of both experiments, the value $J = 4$, as suggested by the Regge trajectory of $\rho(765)$, $A_2(1310)$, and $g(1680)$, would be acceptable.

The neutral annihilation cross section was measured simultaneously in this experiment by the signature $\varphi\bar{A} - \varphi\bar{A}\bar{G}$, and the corrected cross sections are tabulated in Table I.[18] We estimate the overall normalization uncertainty to be ± 20%. The sum of our charge-exchange and neutral annihilation cross sections agrees well with the topological zero-prong cross sections as measured in bubble-chamber experiments.[19] Again, no structure is apparent in regions where resonances have been reported.

In conclusion, we have measured the $\bar{p}p \to \bar{n}n$ cross section below 1 GeV/c with high statistical precision. These data are consistent with a smoothly varying cross section without resonant structure. However if a narrow structure is imposed at 475 MeV/c, then our data are compatible with the results of Ref. 1 for a resonance of high spin, $J \geq 4$. This experiment *per se* establishes an upper limit $x^2(2J+1) < 0.058 \pm 0.049$ for a pure resonant state at a mass of 1932 MeV.

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[1]A. S. Carroll *et al.*, Phys. Rev. Lett. 32, 247 (1974), and references therein.

[2]G. Chikovani *et al.*, Phys. Lett. 22, 233 (1966).

[3]D. Bowen *et al.*, Phys. Rev. Lett. 30, 332 (1973).

[4]T. E. Kalogeropoulos and G. S. Tzanakos, Phys. Rev. Lett. 34, 1047 (1975).

[5]D. Cline *et al.*, Phys. Rev. Lett. 21, 1268 (1968).

[6]Ch. d'Andlau *et al.*, in *Proceedings of a Symposium on Antinucleon-Nucleon Interactions, Liblice-Prague, Czechoslovakia, 1974*, edited by L. Montanet (CERN, Geneva, Switzerland, 1974).

[7]L. N. Bogdanova *et al.*, Ann. Phys. (New York) 84, 261 (1974).

[8]D. Weingarten and S. Okubo, Phys. Rev. Lett. 34, 1201 (1975).

[9]R. T. Abrams *et al.*, Phys. Rev. D 4, 3235 (1971). We used for the $\bar{n}$-Pb cross section $\sigma = 10\pi[6.41 + (2.10 + 1.66/P)^{1/2}]^2$ where P is in GeV/c. The second term increases the effective radius of the lead nucleus as the $\bar{n}$-N cross section rises.

[10]C. Bricman *et al.*, Phys. Lett. 29B, 451 (1969), and 31B, 148 (1970); C. Bricman, thesis, Université de Paris-Sud Report No. A 971, 1972 (unpublished).

[11]$f_v = T_n + 1.11 T_n^2$ for $T_n < 0.6$ GeV; $f_v = 1$ for $T_n > 0.6$ GeV.

[12]V. R. Scherer, thesis, University of Wisconsin, 1974 (unpublished).

[13]R. A. Bryan and R. J. N. Phillips, Nucl. Phys. B41, 485 (1972).

[14]R. J. N. Phillips, private communication.

[15]D. Cutts *et al.*, to be published.

[16]R. Bizzarri *et al.*, Nuovo Cimento 54A, 456 (1968).

[17]H. Kohno *et al.*, Nucl. Phys. B41, 485 (1972).

[18]This reaction, its corrections, and further discussion of charge exchange are elaborated by R. Tripp *et al.*, in Proceedings of the Fourth International Nucleon-Antinucleon Symposium, Syracuse, New York, 1975 (to be published).

[19]U. Amaldi *et al.*, Nuovo Cimento 46A, 171 (1966).

Polarization of Colliding $e^+ e^-$ Beams at SPEAR II*

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We have studied the angular distribution for the reactions $e^+e^- \to e^+e^-$ and $e^+e^- \to \mu^+\mu^-$ at beam energies of 1.55, 3.1, and 3.7 GeV at SPEAR II. At a beam energy of 3.7 GeV a significant azimuthal asymmetry was observed indicating that the electron and positron beams are strongly polarized. The angular distribution of the μ pairs was found to be in good agreement with the predictions of quantum electrodynamics. The equilibrium value of the polarization and the polarization time constant are found to be $P_0 = 0.76 \pm 0.05$ and $\tau = 10_{-5}^{+20}$ min.

The transverse polarization that arises when electron and positron beams circulate in a storage ring is an interesting process permitting verification of the polarization dependence of e^+e^- reactions and is potentially a valuable experimental tool in the study of higher-order quantum-electrodynamic (QED) processes, weak interactions, and hadronic final states.

The polarization arises[1] through the emission of synchrotron radiation, which produces unequal transition rates between the two states of spin orientation with respect to the guide field. Positrons align their spins parallel to the guide field, while electrons acquire the opposite polarization.

The polarization at a time t after injection of the beam is given by

$$P(t) = P_0(1 - e^{-t/\tau}), \qquad (1)$$