Search for baryonia from a measurement of monochromatic π^0 mesons in antiproton-deuterium annihilation at rest

M. Chiba,[5] T. Fujitani,[4] J. Iwahori,[1,*] M. Kawaguti,[1,†] M. Kobayashi,[2] S. Kurokawa,[2] Y. Nagashima,[4] T. Omori,[4,‡] S. Sugimoto,[4,§] M. Takasaki,[2] F. Takeutchi,[3] Y. Yamaguchi,[4] and H. Yoshida[1,∥]

(Fukui-KEK-Kyoto Sangyo-Osaka-Tokyo Metropolitan Collaboration)

[1]*Faculty of Engineering, Fukui University, Fukui, Fukui 910-0017, Japan*
[2]*KEK, High Energy Accelerator Research Organization, Tsukuba 305-0801, Japan*
[3]*Faculty of Science, Kyoto Sangyo University, Kita, Kyoto 603-8555, Japan*
[4]*Physics Department, Osaka University, Toyonaka, Osaka 560-0043, Japan*
[5]*Physics Department, Tokyo Metropolitan University, Hachioji 192-0364, Japan*

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Using modularized NaI(Tl) detectors, we carried out a high-statistics measurement of inclusive π^0 spectra in antiproton annihilation at rest in a liquid D_2 target. At the statistical significance above 4σ, we did not see any narrow π^0 peaks due to the production of $B=$baryonium or similar narrow states in $\bar{p}d \to \pi^0 B N_s$ (N_s being a spectator nucleon) or $\bar{p}d \to \pi^0 B$. The 4σ upper limit for the yields (or branching ratios) per annihilation was 2×10^{-2}–2×10^{-3} for the baryonia with a mass (M_B) of 1700–1100 MeV/c^2 and a width smaller than 9 (at $M_B \sim 1700$ MeV/c^2) to 40 ($M_B \sim 1100$ MeV/c^2) MeV/c^2. [S0556-2813(99)06908-3]

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I. INTRODUCTION

The existence of baryonia below the threshold was once claimed with evidence of three discrete γ-ray lines in the inclusive γ-ray spectrum obtained in $\bar{p}p$ annihilation at rest in an experiment [1] at CERN-PS. This result was partially "confirmed" in an updated experiment [2] and a third experiment [3] with a liquid He target.

With a primary aim of checking the baryonium result obtained at CERN, we carried out an experiment on antiproton annihilation at rest in liquid H_2. We carried out a high-statistics measurement of γ rays by using an array of NaI(Tl) scintillator modules, and searched for both discrete γ-ray and discrete π^0 lines. We searched for π^0 lines also, because some theories suggested a possibility that the intensity of the strong interaction transition of antiproton-nucleon atom to baryonium (emitting π^0) may be larger than that of the electromagnetic one (for example, see [4]).

Based on the γ-ray result from liquid H_2, we rejected for the first time [5,6] the several discrete γ-ray lines which had been reported earlier (mentioned above). The same conclusion was also obtained by two LEAR experiments, one using BGO spectrometers [7] and the other using a magnetic pair spectrometer [8], with a similar statistics to ours. After the main result (the negative result on baryonia from a search for discrete γ-ray lines), we published a negative result on the π^0 lines in the inclusive π^0 spectra obtained in a liquid H_2 target [9]. Negative results have accumulated for baryonia below the $\bar{N}N$ threshold at a statistical significance larger than 4σ in $\bar{p}p$ annihilation experiments in liquid H_2. For more detailed reviews on the search for baryonia below threshold see [10], our previous results [5,6,9], and the references cited therein.

After the measurement [5,6,9] in a liquid H_2 target, we extended it to a liquid D_2 target. In a liquid H_2 target, the Stark mixing makes it difficult to bring in a nonzero orbital angular momentum (l) to the $\bar{N}N$ system. But the nucleon spectator can take out a nonzero angular momentum, thereby allowing us to observe states with $l\neq0$. The centrifugal force should be essential to keep antidiquark ($\overline{qq}$) and diquark (qq) (or $\bar{N}$ and N) apart to make the lifetime of the baryonium long (see the discussions in [11,12]). In a previous paper [11], we described a search for narrow γ-ray lines in inclusive γ-ray spectra obtained in antiproton annihilation at rest in liquid D_2. The physics aim was the search for $B=(\overline{qq}qq)$ baryonia or ($\bar{N}N$) bound states in $\bar{p}N \to \gamma B$ ($N=p$ or n in deuterium), and $B=(\overline{qq}qqq)$ or ($\bar{N}NN$) bound states in $\bar{p}d \to \gamma B$. The result was negative: the 4σ upper limits for the baryonium (or similar narrow states mentioned above) production per annihilation were between 10^{-2} and 10^{-4} depending on the baryonium mass (between 1700 and 600 MeV/c^2) and the charge multiplicity in the decay of the baryonium.

In the same experiment [11], we also measured inclusive π^0 spectra with a high statistics in order to search for monochromatic π^0 peaks due to the production of $B=(\overline{qq}qq)$ baryonia or ($\bar{N}N$) bound states in the $\bar{p}d \to \pi^0 B N_s$ reaction with a spectator nucleon N_s and the production of $B=(\overline{qq}qqq)$ or ($\bar{N}NN$) bound states in the $\bar{p}d \to \pi^0 B$ reac-

*Present address: Kochi Medical School, Nankoku 783-8505, Japan.

†Deceased.

‡Present address: KEK, High Energy Accelerator Research Organization, Tsukuba 305-0801, Japan.

§Present address: KEK (Tanashi Branch), High Energy Accelerator Research Organization, Tanashi 188-8501, Japan.

∥Present address: Naruto University of Education, Naruto 772-0051, Japan.

tion. The existence of rather narrow $\bar{N}NN$ quasinuclear states has been predicted [13] in a potential model. This paper presents the result of these studies. In this experiment we also measured low-energy neutrons using a precision time-of-flight (TOF) spectrometer. Baryonia with a mass close to the $\bar{N}N$ threshold were searched for in the high-statistics inclusive neutron spectra and the result was recently published in a separate paper [12]. Although we also accumulated coincidence events between the neutron and π^0, the statistics was not enough to study the $\bar{p}d \to \pi^0 BN_s$ reaction with a spectator neutron or even with a nonspectator neutron.

A few more studies have also been carried out in the same experiment. The results of some unusual channels of $\bar{p}d$ annihilation into one meson and one nucleon, called Pontecorvo reactions [14], $\bar{p}d \to \pi^0 n$, ηn, $\pi^0\Delta(1232)$, and $\eta\Delta(1232)$, were also published recently in another paper [15]. The yields (or branching ratios) of $\bar{p}p$ and $\bar{p}n$ annihilations in liquid D_2 into two mesons with one of them being π^0 (or η) were also measured [16] from the obtained $\pi^0(\eta)$ peaks in the inclusive $\pi^0(\eta)$ spectra.

II. EXPERIMENT AND DATA REDUCTION

The experimental setup was described in [6,11,16]. Antiprotons at 580 MeV/c, produced in the KEK 12 GeV Proton Synchrotron, were degraded in a graphite slab and stopped in a liquid D_2 target of 14 cm in diameter and 23 cm in length. The charged particles coming out of the target were detected with a set of scintillator hodoscopes for triggering and tracked with cylindrical and planar multiwire proportional chambers, whose total coverage was 93% of 4π sr. The energy and position of each γ ray were measured with a calorimeter consisting of an array of 96 NaI(Tl) modules and the surrounding 48 scintillating glass modules assembled into a half barrel. The NaI covered a solid angle of 22% of 4π sr.

The triggering condition [6] was the detection of one or two neutral clusters on the NaI. The annihilation vertex was determined from the tracks of charged particles. For all-neutral events, we also used the range of the incoming antiproton calculated from the energy loss in a 3-mm-thick Si SSD. The vertex reconstruction was successful for $N_v = 6.93\times10^6$ events out of 1.82×10^7 triggered events after the following cuts: (i) the rms distance from the vertex to the charged tracks should be smaller than 3 cm, and (ii) the vertex should be inside the extended target volume by 2 cm radially and 1.5 cm longitudinally from the target walls. The γ rays were identified by applying a cluster-finding logics [6] on the signals of the calorimeter modules. Removing the γ rays whose shower leakage from the NaI to scintillating glass exceeded 10% of the γ-ray energy, we obtained $N_\gamma = 6.34\times10^6$ γ rays above 10 MeV.

We estimated the number of stopped antiprotons, $N_{\bar{p}}$, in two different ways: (i) dividing the total number of γ rays (N_γ) by the detection efficiency (0.49) and (ii) dividing the number of events after the vertex reconstruction (N_v) by the efficiency (0.54) of the trigger logics (one or two γ rays falling on the NaI). The efficiencies were calculated by a Monte Carlo method. Both ways gave consistently $N_{\bar{p}} = 1.25\times10^7$ for the final states with the charge multiplicity $N_{\rm ch} \geqslant 1$ within an ambiguity of $\pm5\%$. $N_{\bar{p}}$ for all-neutral events ($N_{\rm ch}=0$) was by 31% larger due to the looser vertex reconstruction. The antiproton momentum at the entrance of the liquid D_2 vessel spread between zero and 360 MeV/c with the peak at 280 MeV/c [16]. The fraction of the in-flight annihilation of antiproton in the total annihilation was estimated to be 19% [16].

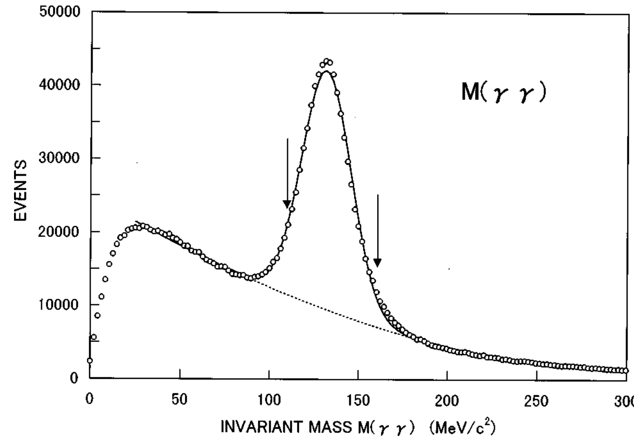

FIG. 1. The $\gamma\gamma$ invariant mass spectra summed for the charge multiplicities in the final state. The solid curve gives a fit of the π^0 peak with a Gaussian shape superimposed on a polynomial background. The arrows indicate the $\pm2\sigma$ cut with $\sigma = 13$ MeV/c^2 for π^0. The bin width is 2.08 MeV/c^2.

About 21% (1.48×10^6 events) of the reconstructed events had two or more γ rays on the NaI, giving 3.18×10^6 γ rays (above 10 MeV) in total. For these events, we calculated the $\gamma\gamma$ invariant mass $M(\gamma\gamma)$ [9,16] for all $\gamma\gamma$ combinations and obtained 1.92×10^6 $\gamma\gamma$ combinations in total. The $M(\gamma\gamma)$ spectrum is given in Fig. 1; corresponding spectra separately for each charge multiplicity ($N_{\rm ch}$) in the final state are given in Ref. [16]. The π^0 peak in the $M(\gamma\gamma)$ spectra was fitted with a Gaussian shape superimposed on a polynomial background. The obtained width (1σ) of about 13.9 MeV/c^2 for the π^0 peak was similar to 13.0 MeV/c^2 for π^0 [9] obtained in a liquid H_2 target. The Gaussian peak occupied 68% of the π^0 region (within the π^0 rest mass ±30 MeV/c^2) $\sim5.48\times10^5$ π^0's.

The π^0 spectrum, obtained after the above-mentioned cut on the invariant mass, is given in Fig. 2 for the total events; corresponding spectra separately for each charge multiplicity $N_{\rm ch}$ are given in Ref. [16]. The number of π^0, including the background $\gamma\gamma$ combinations, was 38 032 for $N_{\rm ch}=0$, 113 369 for 1, 286 897 for 2, 219 110 for 3, 117 399 for 4, 28 382 for 5, and 6460 for $\geqslant6$ with 809 649 in total. To search for narrow π^0 peaks, we fitted each spectrum with Gaussian peaks superimposed on a polynomial background by employing the minimization routine MINUIT [17]. The degree of the polynomial background, which gave a good fit, was between 2 and 4, depending on the spectra and the energy region to be fitted.

According to a numerical simulation, the instrumental energy resolution for π^0 depends weakly on the energy partition between the two decay γ rays and is better than that

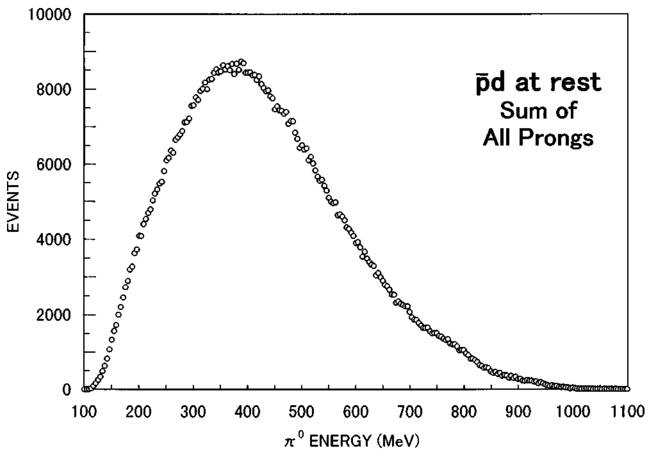

FIG. 2. Inclusive π^0 spectrum summed over the charge multiplicity in the final state. The bin width is 4.16 MeV.

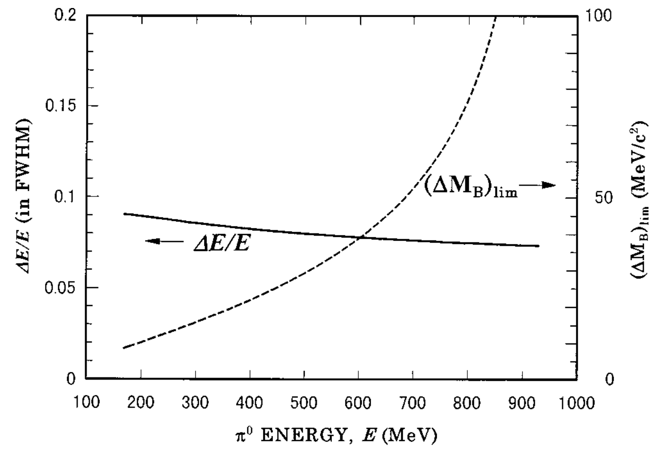

FIG. 3. The solid curve gives the modified energy resolution of the NaI calorimeter given by Eq. (1). The dotted curve gives the upper limit of the mass width [see Eq. (3)] of baryonia (or similar narrow states) which was searched for in the present experiment.

for single γ rays having the same energy by a factor of 0.89 on the average. We calculated in Ref. [11] the correction for the Doppler effect due to the Fermi motion for γ rays emitted from $\bar{p}d$ annihilation at rest. For π^0, the correction is reduced by a factor of the π^0 velocity (pc/E), and we obtained the energy resolution for π^0 as follows (see Fig. 3):

$$\Delta E/E(\text{in FWHM}) = [\{0.055/(E/\text{GeV})^{1/4}\}^2 + (0.0478pc/E)^2]^{1/2}. \qquad (1)$$

III. SEARCH FOR BARYONIA IN THE π^0 SPECTRA

Fitting of the π^0 spectra was carried out in three energy windows (140–350, 200–620, and 500–1000 MeV). We constrained the Gaussian width between 1.0 and 0.8 times the instrumental one. This is because (1) we searched for baryonia (or similar narrow states) with intrinsic widths much smaller than the instrumental one and (2) the instrumental width [Eq. (1)] was taken for safety on the larger side within its ambiguity. Since the baryonium mass (M_B) is related to the π^0 energy (E) as

$$M_B = (4M_N^2 - 4M_N E/c^2 + M_\pi^2)^{1/2}, \qquad (2)$$

where M_N and M_π denote the nucleon and π^0 rest masses, respectively, the instrumental width ΔE of Eq. (1) corresponds to the baryonium mass width [ΔM_B in the full width

TABLE I. Fitted results on narrow peaks in the inclusive π^0 spectra, excluding those which can be assigned to known mesons. Peak position, yield per $\bar{p}N$ annihilation [actually multiplied by $B(N_{ch})$], statistical significance, and width are given. The peaks were fitted to a Gaussian shape whose width was bound within the instrumental width +0%, −20% (see text); U and L denote the upper and lower limits, respectively. For the case of U (or L), the error in the width given in parentheses is meaningful only with a minus (or plus) sign. Notes give the weight-averaged peak position (in MeV) and the mass of a baryonium B (in MeV/c^2) produced in the assumed reaction $\bar{p}N \to \pi^0 B$ ($N=p$ or n). No narrow peaks were seen for $N_{ch}=1$, 3, and 4.

	Charge multiplicity (N_{ch})					
	N_{ch}= all	0	2	5	$\geqslant 6$	Notes
Position (MeV)	201.1±5.5		197.5±2.9	200.3±3.7	189.9±2.0	194.2±4.8
Yield (10^{-3})	11.0±5.34		4.76±2.42	3.04±1.20	1.94±0.62	M_B=1676±2
Significance	2.1σ		2.0σ	2.5σ	3.1σ	
Width σ (MeV)	7.2(1.4, U)		5.7(1.4 L)	7.2(1.4, U)	5.7(1.1, L)	
Position (MeV)		347.8±6.1				347.8±6.1
Yield (10^{-3})		2.39±0.72				M_B=1495±8
Significance		3.3σ				
Width σ (MeV)		12.1(1.9 L)				
Position (MeV)		472.4±4.9				472.4±4.9
Yield (10^{-3})		1.02±0.44				M_B=1329±7
Significance		2.3σ				
Width σ (MeV)		12.6(2.5 L)				

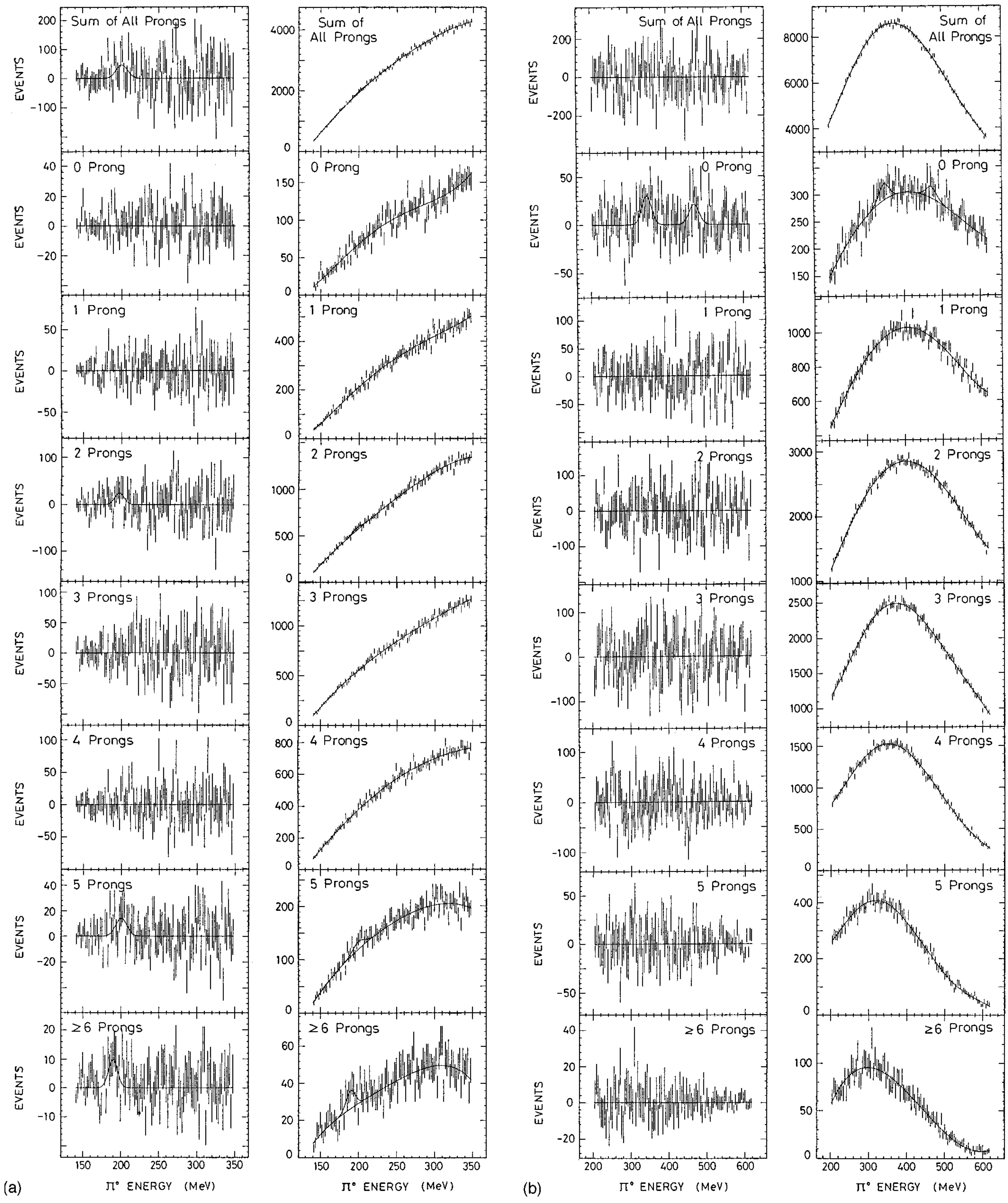

FIG. 4. Inclusive π^0 spectra for each charge multiplicity ($N_{\rm ch}$) as well as for their sum are given on the right. The residue after subtraction of the polynomial background is given on the left. (a) Between 140 and 350 MeV and (b) between 200 and 620 MeV. Solid curves give the fit (see text and Table I). The bin width is 4.16 MeV.

at half maximum (FWHM)] of $(2M_N/M_B)\Delta E/c^2$. The above-mentioned assumption (1) means that ΔM_B should be as small as or smaller than half of the above quantity,

$$\Delta M_B \leqslant (\Delta M_B)_{\mathrm{lim}} = (M_N/M_B)\Delta E/c^2. \tag{3}$$

This upper limit $(\Delta M_B)_{\mathrm{lim}}$ increases from 9 MeV/c^2 at $M_B \sim 1700$ MeV/c^2 ($E\sim 170$ MeV) to 40 MeV/c^2 at $M_B \sim 1100$ MeV/c^2 ($E\sim 600$ MeV); see Fig. 3.

The obtained fit is summarized in Table I and shown in Fig. 4 with solid curves. Except the two-meson annihilation peaks seen above 700 MeV (see [16]), no narrow peaks were seen at statistical significance above 4σ. At $(2–3)\sigma$ levels, three narrow peaks were seen at 194 MeV (for $N_{\mathrm{ch}}=2$, 5, $\geqslant 6$ and for the sum of all prongs) 348 MeV ($N_{\mathrm{ch}}=0$), and 472 MeV ($N_{\mathrm{ch}}=0$).

The yield (i.e., branching ratio) of the $\bar{p}N\rightarrow\pi^0 B$ ($N=p$ or n) reaction per $\bar{p}N$ annihilation is related to the π^0 peak area A above the background in the N_{ch}-pronged π^0 spectrum as

$$\alpha N_{\bar{p}} \times \mathrm{yield} \times \varepsilon_B(N_{\mathrm{ch}}) \times B(N_{\mathrm{ch}}) = A, \tag{4}$$

where α is a constant to be described below, $\varepsilon_B(N_{\mathrm{ch}})$ the overall detection efficiency for π^0 produced in the assumed reaction, and $B(N_{\mathrm{ch}})$ the decay branching ratio of B into N_{ch}-pronged states. The reaction $\bar{p}d\rightarrow\pi^0 B$ was treated in a similar way. The constant α is either α_N = fraction of $\bar{p}N$ ($N=p$ or n) annihilation in $\bar{p}d$ annihilation or unity for direct $\bar{p}d$ annihilation. The α_N should be either $\alpha_p=0.57$ [11] or $\alpha_n=1-\alpha_p$, corresponding to N_{ch} = even or odd. However, misidentification of the N_{ch} = even or odd can occur due to the $\gamma\rightarrow e^+e^-$ conversion (6% per γ ray) and the acceptance gap (7% per charged particle) of the present detector. We assumed $\alpha_N=\alpha_p=\alpha_n=0.5$ for simplicity. Since we could not tell between $\bar{p}N$ and $\bar{p}d$ annihilation, we used $\alpha=0.5$ also for the direct $\bar{p}d\rightarrow\pi^0 B$ reaction, allowing an overestimation of the yield by twice.

In the Monte Carlo calculation of the ε_B for the $\bar{p}p$ (or $\bar{p}n$) $\rightarrow\pi^0 B$ reaction, the decay modes of B, which are unknown, were assumed to be the same as the branching ratios of $\bar{p}p$ (or $\bar{p}n$) annihilation at rest. Using the branching ratios of $\bar{p}p$ annihilation [6], we calculated ε_B for the $\bar{p}p\rightarrow\pi^0 B$ reaction and gave it in Fig. 3 of Ref. [9]. Since the statistical models [18] give similar pion multiplicity for both $\bar{p}p$ and $\bar{p}n$ annihilations, the branching ratios of $\bar{p}n$ annihilation should be similar to those of $\bar{p}p$ annihilation except for a change due to the replacement of one π^0 by π^- in the annihilation products. The resultant change in ε_B was estimated by a Monte Carlo calculation to be an increase by $(0.07–0.1)\varepsilon_B$ roughly independently of the specific decay channels of B. Consequently, we took the $\varepsilon_B(N_{\mathrm{ch}})$ for $\bar{p}n\rightarrow\pi^0 B$ simply as 1.1 times the $\varepsilon_B(N_{\mathrm{ch}}-1)$ for $\bar{p}p\rightarrow\pi^0 B$. For $\bar{p}d\rightarrow\pi^0 B$, the decay mode of B is not known at all either. So we assumed the decay of the meson part of B to be the same as the $\bar{p}p$ or $\bar{p}n$ annihilation at rest. The baryon part of B, which is a proton or a neutron, should not give large effects on the ε_B. As a result, we simply assumed the ε_B for $\bar{p}d\rightarrow\pi^0 B$ to be the same as the ε_B for $\bar{p}p\rightarrow\pi^0 B$.

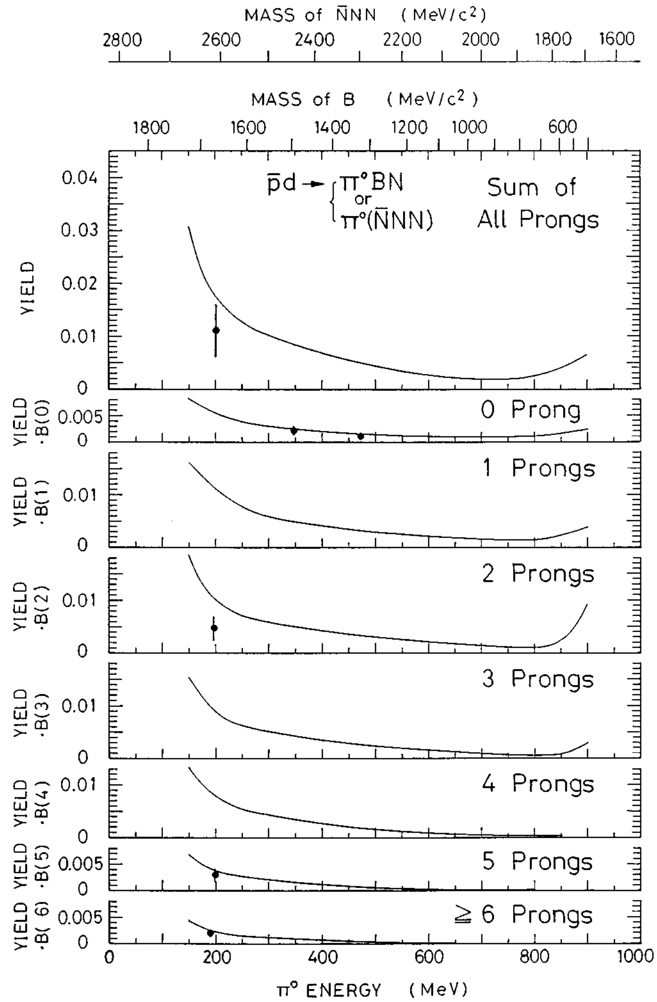

FIG. 5. The 4σ upper limit (see text) for the yield of narrow states per annihilation is plotted with solid curves. B indicates symbolically any baryonia or ($\bar{N}N$) bound states, while ($\bar{N}NN$) indicates ($\bar{q}qqqq$) exotics or ($\bar{N}NN$) bound states. Solid circles given the narrow peaks seen at $(2–3)\sigma$ statistical significance (see Table I). Bars on the data points give the fitting errors ($\pm 1\sigma$).

The obtained 4σ upper limit for the baryonium (or similar narrow state) production is given in Fig. 5 with solid curves. Based on a numerical simulation, we took for the 4σ upper limit 4 times the statistical fluctuation of the background π^0 lying in the energy region of twice the instrumental FWHM. The three peaks seen at $(2–3)\sigma$ levels are shown with solid circles.

IV. RESULTS AND DISCUSSION

The obtained results can be summarized as follows.

(1) In the inclusive π^0 spectra, we did not see, at the statistical significance above 4σ, any narrow peaks due to the production of B = baryonium (or similar narrow states) in $\bar{p}d\rightarrow\pi^0 BN_s$ (N_s being a spectator nucleon) or $\bar{p}d\rightarrow\pi^0 B$. The 4σ upper limit for the yields (or branching ratios) per annihilation was $2\times10^{-2}–2\times10^{-3}$ for the baryonia with a mass (M_B) of 1700–1100 MeV/c^2 and a width smaller than 9 (at $M_B\sim 1700$ MeV/c^2) to 40 ($M_B\sim 1100$ MeV/c^2)

MeV/c^2. The obtained result including the upper limit for each charge multiplicity separately is given in Fig. 5. The energy range where we searched for baryonia is essentially 130–600 MeV in π^0 energy, since the search becomes ineffective in the energy region higher than 600 MeV due to the existence of the π^0 peaks coming from the $\overline{p}N$ annihilations into two known mesons.

(2) At (2–3)σ levels, three narrow peaks were seen at the π^0 energies of 194 MeV ($M_B = 1676\,\mathrm{MeV}/c^2$ under an assumption of a baryonium for B; see Table I), 348 MeV ($M_B = 1495\,\mathrm{MeV}/c^2$), and 472 MeV ($M_B = 1329\,\mathrm{MeV}/c^2$). We cannot take these peaks to be significant because of the following estimation on the statistical fluctuations. We can calculate the number of statistically independent π^0 energy bins in units of 2σ of the instrumental energy width for π^0. Then the region of 130–600 MeV contains about 23 independent bins. Multiplying the probability (2.5%) that the statistical fluctuation of the π^0 events in a bin exceeds 2σ of the background in the larger direction, we can expect 0.6 peaks with 2σ or higher significance levels. Multiplying the number of spectra (for different charge multiplicities (0, 1, 2, 3, 4, 5, 6) of seven, roughly four $\geqq 2\sigma$ peaks are expected from pure statistical fluctuation of the spectra. This is consistent with the experimentally observed number of (2–3)σ peaks.

Negative results have accumulated for baryonia below the threshold with a branching ratio of order 10^{-3}–10^{-4} or larger. But some calculations [19] give the branching ratio of the electromagnetic transition to baryonium of order of 10^{-4}. The transition by a strong interaction has not been much measured yet. From the theory side, there are no clear reasons why baryonia should be absent. In the QCD, there is still much interest in exotics, including hybrids, glueballs, diquark-antidiquark states, etc. [20]. If a new *pp* (or *pd*) annihilation experiment could be carried out with orders of magnitudes higher statistics, it could give a clearer conclusion on baryonia.

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