NEW RESULTS IN THE SEARCH FOR NARROW STATES IN THE $p\bar{p}$ SYSTEM BELOW THRESHOLD

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More than five years ago, two experiments were carried out to look for discrete γ -rays from stopped antiprotons. One, performed by the Syracuse group [1] at BNL, gave only an upper limit of $\sim 3\%$ on the yield of monoenergetic gammas. The other, performed by the Basle-Karlsruhe-Stockholm Collaboration at CERN [2], claimed three monoenergetic gamma rays with a yield of a few per mille (fig. 1a), reflecting the existence of narrow states strongly related to the $p\bar{p}$ system.

Various theoretical ideas [3] based on nuclear physics arguments, quark models, and the dual typological unitarization led to the expectation of massive mesons, called baryonium, coupled strongly to the $p\bar{p}$ channel but weakly to ordinary mesons, thus resulting in a virtually high stability, particularly for states below the $p\bar{p}$ threshold. If there exist bound states of $N\bar{N}$, a highly characteristic way of revealing them would be by the observation of γ transitions between them or from the atomic $p\bar{p}$ state to bound states. A discrete spectrum would be a clear signature. With the experiment of the Basle-Karlsruhe-Stockholm Collaboration the search for discrete γ -rays had reached, at that time, just the region of relevant branching ratios.

We now report on a new experiment with higher statistics and a considerably improved γ detection system. The experiment (fig. 2) took place at the k_{23} low-momentum electrostatically separated beam of the CERN Proton Synchrotron (PS). We found the optimum conditions at 600 MeV/c, and with a momentum spread of $\pm 2\%$ we stopped about 250 $\bar{p}$'s per burst in our 2 g/cm² thick liquid-hydrogen target. A configuration of scintillation and Čerenkov counters, the so-called telescope, typical for stop experiments, identified the incoming particles. A time-of-flight (TOF) counter system worked parallel to the telescope so that we finally obtained a pure $\bar{p}$ trigger, the remaining contamination of $\sim 10^{-4}$ being only fast pions.

Gamma-rays in the energy range between 20 and 1000 MeV were detected in a modular NaI(Tl) detector [4] with good energy resolution and high efficiency for the rejection of background events (neutrons, double hits, charged particles, γ -rays entering from the side, etc.). The shape of the detector is a sector cut out of a hollow sphere and subtending a solid angle of $\sim 7\%$. It consists of

54 modules of polycrystalline pieces of NaI(Tl) shaped as truncated pyramids. Each of the 54 modules is 16 radiation lengths long and is equipped with its own photomultiplier, amplifier, and two ADCs allowing for two different dynamical ranges. The topology of the shower was reconstructed to achieve an energy-independent efficiency. Only events where the shower was safely located inside the detector were accepted, and the light output of the neighbouring modules was added. In this way a good energy resolution was achieved. This required an energy calibration of each module in the relevant energy region (few hundred MeV) with a precision of about 1%. For this purpose, pions of 200 MeV/c momentum, coming out of the same beam line, were stopped in the hydrogen target, giving rise to the reactions $\pi^- p \rightarrow n\gamma$ or $n\pi^0$. The monoenergetic γ line at 129.4 MeV was used as the calibration standard, and the relative calibration of each module was performed in an iterative procedure [4]. This calibration method for a modular high-energy gamma detector was never applied before, and has led to the (so far) best resolution of $\sim 4\%/\sqrt{E}$ (GeV) for a large NaI(Tl) system. As energy reference at high energies, the upper edge (774 MeV) of the uniform γ -distribution from the annihilation channel $p\bar{p} \rightarrow \pi^0\omega^0$ and the end point of the spectrum were used. The data-taking extended over periods of several months and required the stabilisation of the γ -detection system, which was achieved by using a Xe bulb light-pulser system. This resulted in a stability of better than 1% for the 129.4 MeV γ -line, which was regularly checked in short pion runs.

With this experimental set-up, two major runs were performed, one in 1979 and one in 1980, with 40×10^6 and 110×10^6 stopped antiprotons, respectively. Between these two runs, major components of the experiment were modified:

- a) Two targets, different in diameter and container material, were used.
- b) Positive photomultiplier high voltage was used in the second run, involving the replacement of photomultipliers and their electronics for the gamma spectrometer.

Hence these two running periods can be considered as two independent experiments. The resulting two sets of γ spectra show the same high background from annihilation

π^0 's, so that small structures can hardly be seen. In order to subtract this background, the γ spectra originating from all known annihilation channels were simulated by Monte Carlo and resulted in a spectrum with equivalent shape. Scaling the shape function with a proper factor and subtracting it from the data, we found a good agreement in the high-energy part (above 400 MeV) of the spectrum, only below 400 MeV some background remained. It corresponds to only 3% of the whole spectrum and is perhaps due to annihilation processes not being considered in the Monte Carlo calculations. The resulting spectra, after the subtraction of these backgrounds, show small but very similar structures (figs. 1b and 1c). A computer fit to the peaks yields the results of Table 1.

In comparison with the old spectrum (fig. 1a), we conclude that two of the previous lines (183, 216 MeV) reappear in the present spectra at the same energies within the limits of the energy error, whereas the evidence for the 420 MeV line has become weak. The confidence level for the structures at 175 and 220 MeV varies for each individual spectrum between 2.2 and 3.1 σ . In the present experiment the 220 MeV line shows a width slightly larger than the instrumental resolution (Table 1). With a similar confidence level, two more peaks appear in the spectra: structures around 102 MeV (3.3-3.6 σ) and around 550 MeV (2.4-3.9 σ). The appearance of these peaks does not contradict the old results because: i) the line at 102 MeV appeared also in the old spectrum (fig. 1a), but owing to the high background and the worse resolution of the 10" $\times$ 12" spectrometer at this energy, in connection with the adjacent 129.4 MeV line the evaluation was difficult and thus we hesitated at that time to present it as a peak; ii) the statistics at energies above 500 MeV were so marginal as to prevent the appearance of low intensity lines. The recent yields seem to be systematically lower as compared to the old experiment. However, we are more confident of our present results owing to the following fact:

- 1) The experimental energy resolution is improved by a factor of two.
- 2) The lateral size, the depth and the modularity of the new γ spectrometer allowed an energy-independent γ detection efficiency over the whole energy range of interest.

- 3) The exact studies of the Monte Carlo simulated annihilation reactions allowed, in the present experiment, a normalization which is rather independent of further assumptions. This was not possible in the old experiment.

More details will be given in a forthcoming paper.

Summarizing the results of the former experiment and the present one, it is concluded that three independent measurements have found tiny narrow structures with an individual significance of up to three standard deviations, and yields of several per mille per formed $p\bar{p}$ system are visible. Their simultaneous appearance in all three spectra at energies identical within the errors quoted and with similar yields seems to rule out any statistical fluctuation as their source. The above γ transitions correspond to states with masses of 1771 ± 1 MeV, 1694 ± 2 MeV, 1640 ± 3 MeV, and 1210 ± 5 MeV, assuming atomic states as initial states (Table 1).

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Table 1

Results of the two experimental runs (cols. 1, 4 and 5) in comparison with the results of ref. 2 (col. 3). Yields (cols. 1, 4 and 5) have an additional systematic error of 15%, γ -energies (cols. 4 and 5) have an additional systematic error of $\pm 5\%$.

(1)	(2)	(3)	(4)	(5)
Mass (MeV) Yield (%)		1976	1979	1980
1770.78 $\pm$ 1.06 1.8 $\pm$ 0.36	Position (MeV) Yield (%) Stat. significance Width (MeV)	$\sim$ 108 MeV	102.0 $\pm$ 1.9 2.7 $\pm$ 0.9 3.3 σ < 6.2	103.1 $\pm$ 1.2 1.6 $\pm$ 0.4 3.6 σ < 8.0
$\pi^- p \rightarrow \eta \gamma$	" " " "	132 $\pm$ 6 5.1 $\pm$ 2.7 1.9 σ < 16	129.4 $\pm$ 2.3 3.0 $\pm$ 1.0 2.9 σ < 7.5	125.0 $\pm$ 2.1 3.5 $\pm$ 0.8 4.5 σ 17.4 $\pm$ 4.3
1693.53 $\pm$ 1.99 1.6 $\pm$ 0.44	" " " "	183 $\pm$ 7 7.2 $\pm$ 1.7 3.0 σ < 19	170.4 $\pm$ 2.9 1.8 $\pm$ 1.0 2.2 σ < 9.3	176.2 $\pm$ 2.2 1.6 $\pm$ 0.5 3.1 σ < 12.0
1637.77 $\pm$ 2.52 3.0 $\pm$ 0.8	" " " "	216 $\pm$ 9 6.0 $\pm$ 1.9 2.6 σ < 21	224.1 $\pm$ 2.3 3.0 $\pm$ 1.2 2.6 σ 18.1 $\pm$ 7.8	222.0 $\pm$ 6.3 3.0 $\pm$ 1.1 2.7 σ 38.4 $\pm$ 18.6
	" " " "			294.2 $\pm$ 2.5 1.2 $\pm$ 0.5 3.0 σ < 18.2
	" " " "			336.0 $\pm$ 3.8 1.1 $\pm$ 0.5 2.3 σ 17.3 $\pm$ 10
1420.69 $\pm$ 6.08 0.64 $\pm$ 0.35	" " " "	420 $\pm$ 17	395.9 $\pm$ 9.0 0.8 $\pm$ 0.7 1.3 σ < 17.6	402.1 $\pm$ 5.4 0.6 $\pm$ 0.4 1.5 σ < 22.6
1383.21 $\pm$ 2.04 < 1.0	" " " "	8.5 $\pm$ 2.0 2.8 σ < 34	428.3 $\pm$ 11 1.0 $\pm$ 0.7 1.8 σ < 17.9	428.6 $\pm$ 1.5 0.1 $\pm$ 0.4 0.3 σ < 23.0
1209.81 $\pm$ 5.12 0.98 $\pm$ 0.26	" " " "	?	545.5 $\pm$ 7.1 1.2 $\pm$ 0.5 2.4 σ < 22.4	549.4 $\pm$ 3.7 0.9 $\pm$ 0.3 3.9 σ < 29.0

Figure captions

Fig. 1 : The spectrum of the first Basle-Karlsruhe-Stockholm experiment (1976) and the spectra of the 1979 (a) and 1980 (b) runs after subtraction of the background. Two point smoothing was applied in all three spectra.

Fig. 2 : The experimental set-up.

Fig. 1

THE TELESCOPE

THE SET-UP

Fig. 2