SEARCH FOR NARROW EXOTIC STATES IN $\bar{p}$ ANNIHILATIONS ON ${}^4\text{He}$

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ABSTRACT

After having found evidence for narrow exotic states in $\bar{p}p$ annihilation [1,2], the production of such states on a nuclear target was studied with similar techniques. The γ spectrum associated with $\bar{p}$ annihilation on ${}^4\text{He}$ at rest was measured. The spectrum shows two peaks, at energies of 161.9 and 203.0 MeV, corresponding to intermediate narrow states of masses which seem to be related to states found in $\bar{p}p$ annihilations. The confidence is better than 4σ .

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Several independent experiments on $\bar{p}p$ annihilation at rest have shown indications for monoenergetic γ -rays [1,2], which may be discussed in the context of exotic objects such as baryonium or glueballs. It is of great interest to know whether such objects, if existing, are also produced in $\bar{p}$ annihilations on nuclear targets. If so, also charged states could become observable through the γ -ray spectrum. We studied the reaction

$$\bar{p} \text{ } ^4\text{He} \rightarrow \gamma + X + \text{nucleons}$$

by measuring the γ spectrum associated with the $\bar{p}$ annihilation on an α particle.

The experimental method and the set-up are described in detail in ref. 2 and correspond to our 1979 run. The low-energy $\bar{p}$'s were stopped in liquid ^4He , contained in a target of 25 cm length and 12.5 cm diameter. A modular NaI(Tl) γ spectrometer [3] was used to measure the γ -ray spectrum. The experiment was performed at the separated beam k_{23} of the CERN PS.

In a run of 10 days about 10^7 $\bar{p}$'s were stopped. The resulting γ -ray spectrum is shown in fig. 1. As in the annihilation on hydrogen it consists of a large background produced by π^0 's from the annihilation, and exhibits a uniform shape very similar to that of $\bar{p}p$ annihilation at rest [2], with the exception, however, that it extends up to energies of 1150 MeV instead of 940 MeV and that it monotonically increases also below 70 MeV.

In order to reveal possible structures in this spectrum the background has to be understood quantitatively and eventually subtracted. For this purpose we adopt the hypothesis that the annihilation in ^4He occurs on a single nucleon, so that the background may be related quantitatively to the one produced by $\bar{p}p$ annihilation at rest. The latter has been explained quantitatively [2,4].

For normalization purposes we first estimate the number of γ 's per $\bar{p}$ annihilation on ^4He . In $\bar{p}p$ annihilation, on average, there are $1.7 \pi^0$, $1.7 \pi^+$, and $1.7 \pi^-$, and in $\bar{p}n$ annihilation, assuming only charge conservation, there are $1.7 \pi^0$, $0.7 \pi^+$, and $2.7 \pi^-$ per annihilation. Therefore the number of γ 's per $\bar{p}$ annihilation on ^4He is roughly the same as for $\bar{p}p$ annihilation.

Furthermore, assuming the same branching ratios of the multipionic final states in $\bar{p}n$ annihilation as in $\bar{p}p$ annihilation, the shape function found for the continuous background from $\bar{p}p$ annihilation at rest [4] may be applied to the $\bar{p}$ ${}^4\text{He}$ annihilation.

In addition to the continuous background there is a superposition of uniform γ -energy distributions from two-body final states where at least one of the particles decays into two γ 's as found in $\bar{p}p$ annihilation at rest [4]. The branching ratios found in ref. 4 or quoted therein were adapted to the mixed annihilations on neutrons and protons. The resulting branching ratios for $\bar{p}$ ${}^4\text{He}$ annihilation are listed in table 1.

The continuous background (taken from $\bar{p}p$ annihilation) and the two-body annihilations from table 1 lead to a γ spectrum in the $\bar{p}N$ rest frame. Owing to the Fermi motion of the nucleons in the α particle, however, the annihilation occurs on a system which is in motion, thus leading to a Doppler smearing of the γ energies. Moreover, the $\bar{p}$ in its atomic orbit, when annihilating, is localized at the nuclear surface. Hence, it has acquired kinetic energy in the Coulomb potential, which corresponds to a momentum in the lab. system of

$$k_{\bar{p}} \approx \sqrt{2M_{\bar{p}}^{\text{red}} \frac{\alpha Z}{R}} . \quad (1)$$

Here $M_{\bar{p}}^{\text{red}}$ is the reduced $\bar{p}$ mass, α is the fine structure constant, $Z = 2$, and $R = 1.676$ fm is the r.m.s. radius of the α particle [5]. This yields $k_{\bar{p}} = 51$ MeV/c. The α particle carries the opposite momentum. In evaluating the energy smearing, the Fermi-momentum distribution of the nucleons in ${}^4\text{He}$ is given by the Fourier transform of the nuclear density distribution, resulting in the momentum density

$$\rho(\vec{k}_F) = \exp [-(\vec{k}_F/k_0)^2] / (\pi\sqrt{\pi} k_0^3) , \quad (2)$$

where k_F is the nucleon's momentum relative to the α particle and $k_0 = 126.3$ MeV/c [6]. Because only one of the four nucleons of the α particle interacts with the $\bar{p}$, the total momentum of the annihilating $\bar{p}N$ system is in the lab. system

$$\vec{p}_{\bar{p}N} = \vec{k}_F + \frac{3}{4} \vec{k}_{\bar{p}}$$

and the unnormalized momentum density distribution is

$$\rho(\vec{p}_{\bar{p}N}) = \exp \left[- \frac{\left| \vec{p}_{\bar{p}N} - \frac{3}{4} \vec{k}_{\bar{p}} \right|^2}{k_0} \right]. \quad (3)$$

Monoenergetic γ -rays of energy E_Y^{cm} , isotropically emitted from the $\bar{p}N$ rest frame, experience a Lorentz boost when emitted from a moving system of momentum $p_{\bar{p}N}$ and energy E , and hence result in the normalized uniform distribution

$$B(p_{\bar{p}N}) = \frac{M_{\bar{p}N}}{2E_Y^{\text{cm}} p_{\bar{p}N}} \quad \text{for} \quad \frac{E - p_{\bar{p}N}}{M_{\bar{p}N}} \leq \frac{E_Y^{\text{lab}}}{E_Y^{\text{cm}}} \leq \frac{E + p_{\bar{p}N}}{M_{\bar{p}N}}, \quad (4)$$

$$= 0 \text{ otherwise,}$$

where $M_{\bar{p}N}$ is the effective mass of the annihilating system and E_Y^{lab} is the γ energy observed in the laboratory system. Note that since the nucleons are bound, $M_{\bar{p}N}$ becomes smaller with increasing $p_{\bar{p}N}$.

Since the γ background in the rest frame is continuous, integration over all available γ energies E_Y^{cm} has to be performed. Furthermore, integration has to be done over all available momenta. Hence the shape function $F_{\bar{p}\alpha}$ for the γ background from $\bar{p}$ ^4He in the lab. system is

$$F_{\bar{p}\alpha}(E_Y^{\text{lab}}) = \int_0^{938 \text{ MeV}} dE_Y^{\text{cm}} F_{\bar{p}\bar{p}}(E_Y^{\text{cm}}) \cdot N \int d^3 p_{\bar{p}N} \rho(\vec{p}_{\bar{p}N}) B(|p_{\bar{p}N}|), \quad (5)$$

where $F_{\bar{p}\bar{p}}$ is the shape function of ref. 4 for $p\bar{p}$ annihilation at rest, and N is a normalization constant. Integration over the angles may be performed by assuming that the momenta of the $\bar{p}$ and the nucleon are randomly oriented with respect to each other.

In order to reconstruct the background consistently a similar procedure has to be applied for the uniform distributions of table 1. In a procedure identical to that applied in ref. 4 the spectral shape function [eq. (5)] and the uniform

contributions were folded with the detector resolution and scaled to the experimental spectrum, where the scaling factor (the number of $\bar{p}$ annihilations) and the total height of the uniform distributions were varied in the fitting procedure. The spectrum corresponds to $N_{\bar{p}p} = 144000 \pm 1240$ annihilating $\bar{p}$'s giving a trigger in the γ spectrometer. The solid line in fig. 1 represents the fit. It is worth while noting, that with only one non-trivial parameter (the total height of the uniform distributions), the $\bar{p}$ ^4He γ spectrum could be related to the $\bar{p}p$ spectrum in an energy range from 200 to 1150 MeV.

A fine-tune on the two-body annihilation channels of table 1 yields the branching ratios in the third column of table 1. The yields do not differ drastically from the scaled ones. The errors are statistical ones only. There is an additional systematic error of 10%, coming from uncertainties in the normalization.

The background shape [eq. (5)] accounts only for energies above ~ 200 MeV. As in the case of $\bar{p}p$ annihilation [2] the background at low energies requires an additional correction. For energies below 200 MeV an arbitrary smooth function had therefore to be added. After subtraction of the continuous background and the uniform distributions of table 1, the residual spectrum is obtained (see fig. 2). Between 100 MeV and 300 MeV the spectrum exhibits clearly two peaks. They are broader than expected from the resolution, which was taken to be $5\%/\sqrt{E(\text{GeV})}$ (c.f. ref. 4). Assuming that narrow structures coming from the process

$$\bar{p}N \rightarrow \gamma + X ,$$

are smeared by the Fermi motion, analogously to eq. (5) and folded with the detector resolution, the two peaks were fitted with only the peak positions and the peak intensities as free parameters. A third but narrower peak was found at a lower energy. Fits were also done where the width of each peak was a free parameter. The results are listed in table 2. The statistical errors are for fixed line shape. For the case where also the line widths were varied the errors are obtained by adding the fit systematic errors in quadrature to the statistical ones. There are additional systematic errors for calibration and normalization (c.f. ref. 4). The fitted line

widths tend to be somewhat larger than expected from the Fermi-motion induced line shape. The yields are on the level of 1% per annihilation, thus more than three times higher than those of the peaks from $\bar{p}p$ annihilation [2].

The two peaks are compatible with narrow states X. Assuming the same origin as in $\bar{p}p$ annihilation, i.e. $\bar{p}N \rightarrow X + \gamma$, two possible reactions have to be considered:

In the first reaction the annihilating $\bar{p}N$ system is at least 28.3 MeV (binding energy of the α particle) below threshold; in the case of tritium or ^3He being in the final state, the system is at least 19.8 and 20.6 MeV, respectively, below threshold. Carrying out the correct kinematical calculations we expect the "160 MeV" peak to be shifted with respect to $\bar{p}p$ by 28.8 MeV and 22.3 MeV for reactions (6a) and (6b), respectively. For the "200 MeV" peak the corresponding shifts are 31.9 MeV and 25.5 MeV, respectively. Since the absolute calibration might be wrong by about $\pm 5\%$, as indicated in table 2, we prefer not to discuss absolute energies for the moment, but instead compare the measured energy difference of the two peaks with the energy differences expected in $\bar{p} \text{ } ^4\text{He}$, assuming the intermediate states X of reactions (6) to be the same as in $\bar{p}p$ [2]. In the case where both states are produced by reaction (6a) the expected energy difference is 50.6 ± 3.7 MeV (case A); for reaction (6b) it is 50.5 ± 3.7 MeV (case B), and in the case where the "160 MeV" state is related to reaction (6b) whereas the "200 MeV" state is related to reaction (6a), the energy difference is 44.1 ± 3.7 MeV (Case C). The error of 3.7 MeV is deduced from the last column of table 2. The measured energy difference of $41.1^{+6.6}_{-5.0}$ MeV is fully compatible with case C and overlaps within 1 σ with cases A and B. The measured energy difference hence is compatible with expectation. The absolute energies of the two peaks become consistent with cases B and C if an energy shift of -5% (as possible from the systematic calibration errors) is applied.

Case A is not compatible with our measurement. The masses after applying this correction to the energies of table 2 are listed in table 3. For the "200 MeV" peak two masses are given since we cannot distinguish between cases B and C. The significance is on the level of 4σ . Comparison with the masses found from $\bar{p}p$ annihilation [2] shows good agreement.

The peak at 47.8 MeV cannot originate through the same processes as the others, since it is too narrow. It shows up on a confidence level of 2.7σ and therefore is not significant enough to exclude it as being due to a statistical fluctuation.

Two obvious questions have to be discussed: why are the yields of the peaks so high in ${}^4\text{He}$ as compared to hydrogen, and why are the peaks corresponding to 100 and 550 MeV in hydrogen [2] not observed?

One difference between annihilation of $\bar{p}$'s in liquid hydrogen and liquid He is the initial atomic state from which the annihilation occurs. For hydrogen it is most likely an s state, whereas for helium it is almost certainly an $\ell \neq 0$ state [7]. Hence we expect for peripheral reactions and sufficiently high relative momenta some enhancement of p state annihilation. States which can only be reached from p states of a $\bar{p}p$ system such as 1^{-+} , 2^{-+} (via dipole-radiation) or 0^{+-} , 2^{+-} (via quadrupole-radiation), would thus be strengthened in helium.

A second difference is the additional annihilation on neutrons in helium, which implies formation of negative states ($I \neq 0$). Reactions of the type $\bar{p}n \rightarrow X^- + \gamma$ are not subject to restrictions imposed by C-parity. The relevant symmetry instead is G-parity, which, however, is only restrictive in the frame of vector dominance. This is the reason why states such as 0^{+-} or 2^{+-} , which cannot be reached from s-states in hydrogen, can be reached from the 3S_1 state of the $\bar{p}n$ system. The consequence is that the yields of such states are stronger in helium than in hydrogen. A further enhancement of yields due to $\bar{p}n$ annihilations concerns 1^{+-} states, which in hydrogen are formed from initial 1S_0 atomic states only, whereas in $\bar{p}n$ annihilation both 1S_0 and 3S_1 states contribute.

Assuming dominant s-wave annihilation also in helium we therefore may conclude that the states observed in helium are also due to $\bar{p}n$ annihilations and thus have $I \geq 1$. The somewhat larger width, as discussed above, could be an indication of a charge splitting. Such charged states have previously not been observed [8].

The non-observation of the lines corresponding to 100 MeV and 550 MeV in hydrogen could indicate that they are related to $I = 0$ particles. The consequence would be that their yields in ${}^4\text{He}$ are two times lower than in hydrogen ($< 0.3\%$ [2]). The additional Fermi-motion induced broadening would render them unobservable with the present statistics.

A more detailed study of the phenomenon, e.g. an experiment on deuterium, is required before giving a conclusive answer to the above questions.

This experiment has provided evidence that exotic states associated with $\bar{p}$ annihilation may also be produced in nuclei, with yields larger than in hydrogen. Moreover, by these observations the confidence in the states of mass 1693 MeV and 1638 MeV which have been observed in three independent measurements on hydrogen [1,2], has further been strengthened. We also conclude that nuclear targets are complementary to hydrogen in the sense that, by comparing yields of reactions in hydrogen ($\bar{p}p \rightarrow X + \gamma$ or π) with yields from the nuclear target ($\bar{p}n \rightarrow X + \gamma$ or π), quantum numbers for the states X may be deduced. Therefore nuclear targets may be successfully used in the search for exotic states in the $\bar{p}N$ system.

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Table 1

Branching ratios for the relevant two-body final states for $\bar{p}$ ^4He annihilation as a percentage of all annihilations.

Channel	Scaled from ref. 4	Fitted
$\pi^0 \rho^0 + \pi^0 \rho^-$	1.2	$2.08 \pm 0.19^{*)}$
$\pi^0 \omega$	1.2	
$\pi^0 \pi^0 + \pi^0 \pi^-$	0.195	0.144 ± 0.037
$\pi^0 \gamma + \pi^- \gamma$	0.011	0.011
$\pi^0 \eta + \pi^- \eta$	0.41	0.39 ± 0.09

*) The two channels cannot be disentangled when fitting.

Table 2

Energies and intensities of the γ peaks. Intensities are given as a percentage of all annihilations. For comparison the γ energies found in hydrogen are listed as well (1979 run of ref. 2).

E (MeV)	Error (MeV)			Yield (%)	Error			Width (FWHM) (MeV)	E from $\bar{p}p$ (MeV)
	Stat.	Fit	Calibr.		Stat.	Fit	Norm.		
47.5	± 1.4	-	$\pm 5\%$	0.38	± 0.14	-	$\pm 10\%$	6.80 ± 2.5	-
161.9	± 3.3	$+2.1$ -3.0		0.93	± 0.16	$+0.48$ -0.00		30^{+10}_{-7}	170.4 ± 2.9
203.0	± 3.6	$+5.5$ -3.4		0.89	± 0.17	$+0.47$ -0.10		34 ± 12	224.1 ± 2.3

Table 3

Masses of the particles X. For comparison the masses found in hydrogen [2] are listed in column 2

M (MeV)	Error (MeV)	Final state	M from $\bar{p}p$ (MeV)
1687.1	+5.0 -4.3	t or ^3He	1693.5 ± 2.0
1644.0	+5.6 -7.3	t or ^3He	1637.8 ± 2.5
or 1637.1		$3N$	

Figure captions

Fig. 1 : The γ spectrum from $\bar{p}$ annihilation on ${}^4\text{He}$ at rest. The solid line represents the background fit.

Fig. 2 : The residual spectrum after subtraction of the background. Note that the peak at 135 MeV formerly seen in $\bar{p}p$ annihilation [1,2], which is due to the secondary reaction $\pi^- p \rightarrow n\gamma$, is not visible as expected.

Fig. 1

Fig. 2