Annihilation of nonrelativistic protons

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The cross sections for annihilation $\bar{p}p(\sigma_a)$, $\bar{p}p$ elastic scattering (σ_e), and $\bar{p}p\to\bar{n}n$ charge exchange (σ_c) are calculated with realistic one-boson-exchange potentials. The level spectrum of quasinuclear baryonium is also calculated. It is the strong nuclear attraction between the nucleon N and the antinucleon $\bar{N}$ which gives rise to both the large observed annihilation cross section and the rich spectrum of comparatively narrow quasinuclear states (their widths range from a few MeV to several tens of MeV).

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Estimates[1,2] show that the large annihilation cross section of low-energy antiprotons is consistent with the possible existence of narrow levels of quasinuclear baryonium (levels with widths of 1–100 MeV, depending on the orbital angular momentum l). In the present letter we will demonstrate the reliability of these estimates, which are based on the circumstance that the linear dimensions of the annihilation region ($r_a \sim 1/2m \approx 0.1$ fm, where m is the mass of the nucleon) are small in comparison with the effective range of the nuclear forces ($R \approx 1$ fm).

As a model for the annihilation we adopt a nonrelativistic model of two coupled channels: and $N\bar{N}$ channel and a two-particle boson (annihilation) channel.[3–4] The $N\bar{N}$ nuclear interaction is described by a realistic one-boson–exchange (OBE) potential,[5] while transitions between channels are described by a local Yukawa "potential,"

$$W(r) = \lambda_l \exp\left(-r/r_a\right)/r$$

with a radius $r_a = 0.11$ fm. Here λ_l is a dimensionless adjustable parameter, which depends on only the orbital angular momentum l. The OBE-potential models which have been developed contain singular terms $(\sim r^{-3})$ due to spin-spin and spin-orbit interactions. The OBE potential must accordingly be regularized; the usual approach is to truncate

$$U(r<r_c) = 0.$$

Clearly, the truncation radius r_c may depend on the quantum numbers. In the present letter we use the following values of $r_c(^{2s+1}l_j)$ (s is the spin, and j is the total angular momentum):

$$r_c(^1S_0) = r_c(^3S_1) = 0.55\,\text{fm};\quad r_c(^3P_1) = 0.57\,\text{fm};$$

$$r_c(^1P_1) = r_c(^3P_0) = r_c(^3P_2) = 0.65\,\text{fm};$$

$$r_c(^3D_1) = 0.63\,\text{fm};\quad r_c(^1D_2) = r_c(^3D_2) = r_c(^3D_3) = 0.68\,\text{fm}.$$

To simplify the calculations, we have discarded the tensor forces which mix the triplet

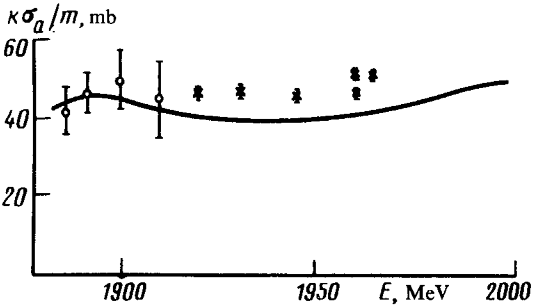

FIG. 1. The annihilation cross section σ_a or, more precisely, the quantity $k\sigma_a/m$, as a function of the total energy E. Circles—Experimental data from Ref. 9; crosses—experimental data from Ref. 10.

states with $l = j \pm 1$. The calculations are carried out by the phase-function method[6] in the approach described in Ref. 7.

Figure 1 shows the quantity $k\sigma_a/m$ (k is the momentum of the $\bar{p}$ in the c.m. frame, and σ_a is the annihilation cross section) as a function of the total energy E over the interval[1)] from the $N\bar{N}$ threshold (1878 MeV) to 2000 MeV, where the annihilation constants are

$$\lambda_0 = \lambda_1 = 86, \qquad \lambda_2 = 100.$$

Curves 1 and 2 in Fig. 2 show the calculated cross sections for $\bar{p}p$ elastic scattering (σ_e) and for the charge exchange $\bar{p}p \to \bar{n}n$ (σ_c), respectively. We see that the experimental

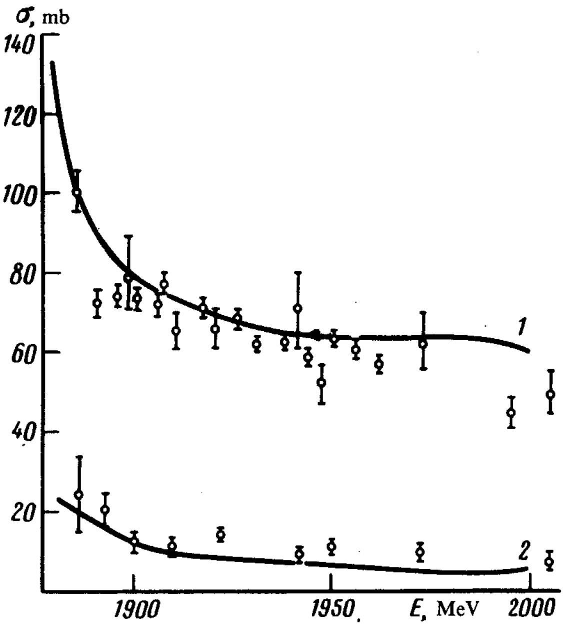

FIG. 2. Cross sections for $\bar{p}p$ elastic scattering (σ_e, curve 1) and the charge exchange $\bar{p}p \to \bar{n}n$ (σ_c, curve 2).

TABLE I. Spectrum of p and d levels of quasinuclear baryonium.

$^{2S+1}L_j$	$I^G(J^P)$	Mass MeV	Total width MeV	$\Gamma_{N\bar{N}}/\Gamma$
$^1P_1$	$1^+(1^+)$	1875	50	–
	$0^-(1^+)$	–	–	
$^3P_0$	$1^-(0^+)$	1842	65	–
	$0^+(0^+)$	1590	8	
$^3P_1$	$1^-(1^+)$	1756	55	–
	$0^+(1^+)$	1585	10	
$^3P_2$	$1^-(2^+)$	1885	50	0.35
	$0^+(2^+)$	1875	55	–
$^1D_2$	$1^-(2^-)$	1990	85	0.32
	$0^+(2^-)$	2050	130	0.15
$^3D_1$	$1^+(1^-)$	1935	37	0.27
	$0^-(1^-)$	1637[1]; 1815[2]	1[1]; 8[2]	–
$^3D_2$	$1^+(2^-)$	1975	80	0.38
	$0^-(2^-)$	1970	76	0.43
$^3D_3$	$1^+(3^-)$	2000	95	0.26
	$0^-(3^-)$	2000	96	0.25

[1]With a truncation radius $r_c = 0.63$ fm.
[2]With $r_c = 0.685$ fm.

data of Refs. 9 and 10 are described completely satisfactorily by the theory.

Table I shows the spectrum of the p and d levels of quasinuclear baryonium. The annihilation width of the subthreshold p levels is[2] 10–50 MeV, while that of the d levels is an order of magnitude smaller (1–10 MeV). The sharp decrease in the annihilation width of the levels with increasing orbital angular momentum stems from the centrifugal barrier, which prevents the N and $\bar{N}$ from closing to annihilation distances. The resonances above the threshold shown here are seen quite clearly in the corresponding partial cross sections and on the Argand diagrams. It can be seen from Figs.

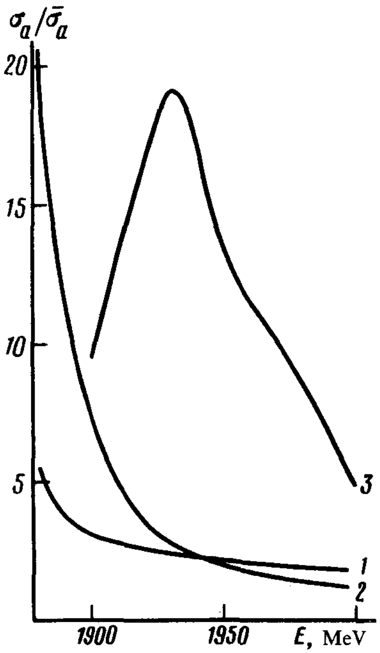

FIG. 3. Ratio of the partial annihilation cross sections with a given value of l with (σ_a) and without ($\bar{\sigma}_a$) the nuclear interaction. 1, 2, 3—$l = 0$, 1, 2, respectively.

1 and 2 that it is not a simple matter to experimentally distinguish the contribution of an individual resonance to the total cross sections. For this reason, a phase-shift analysis of experimental data with a good energy resolution is necessary for the reliable detection of above-threshold resonances of a quasinuclear natures.[3)]

The small parameter $r_a/R \approx 0.1$ leads to the factorization relation[1,2]

$$\sigma_a = \bar{\sigma}_a / |f(k)|^2.$$

Here $\bar{\sigma}_a \sim r_a^2$ is a cross section determined completely by the annihilation processes, while $f(k)$ is the Jost function for the $N\bar{N}$ nuclear potential. The strong nuclear attraction, which gives rise to levels near the threshold [the zeros of $f(k)$], causes a substantial increase in the annihilation cross section. For a quantitative determination of the role played by the realistic $N\bar{N}$ nuclear attraction, we also calculated the annihilation cross section with the nuclear interaction "turned off" ($U \equiv 0$). Figure 3 shows the ratio of the sums of the partial annihilation cross sections with $l = 0$, 1, 2 (curves 1, 2, 3, respectively) with and without the nuclear interaction. As expected, the strong nuclear attraction between N and $\bar{N}$ leads to a large increase (by an order of magnitude, on the average) in the annihilation cross section. The sharp increase in the p-wave enhancement toward the $N\bar{N}$ threshold is a consequence of the rich family of subthreshold p levels (see Table I). The particular energy dependence of the d-wave enhancement is a consequence of above-barrier quasinuclear d resonances.

Our results are strikingly different from those found previously in the optical model and by other methods.[14] The experimental data of the cross sections are reproduced equally well by all the models, but the annihilation widths of the baryonium levels are an order of magnitude smaller in the coupled-channel model. A discussion of the applicability of the methods used in Ref. 14 goes beyond the scope of the present letter (to some extent, this topic is discussed in Refs. 2 and 4).

It is important to note that these calculations have dealt with only the most important physical features of the $N\bar{N}$ annihilation (the strong nuclear attraction, combined with the short-range annihilation interaction proper). A genuinely systematic calculation (a calculation "from first principles") of the annihilation characteristics of the $N\bar{N}$ system cannot be carried out until we understand the relativistic dynamics of the $N\bar{N}$ system at short range, as has been stressed in several papers.[2,3] The results reported above should be regarded as a model-based demonstration that the qualitative calculations which underlie the quasinuclear approach to the theory of NN systems are reliable.

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[1)]Partial waves with $l \leqslant 2$ contribute to the cross sections in this interval. We are not considering energies $E > 2$ GeV, because there we would have to take into account the strong coupling with the $\bar{\Lambda}\Lambda$ and $\Sigma\bar{\Sigma}$ channels.[8] The effects of these channels will be studied in a separate paper.

[2)]Levels of this type should appear directly in electromagnetic transitions from the $\bar{p}p$ state of an atom (protonium) to quasinuclear states. The spectrum and relative intensities of the corresponding γ lines were predicted in Ref. 11, long before the appearance of experimental evidence of their existence.[12] The p-level widths found here are consistent with the line widths in the γ spectrum.[12]

[3)]It will now become possible to obtain the necessary information because the LEAR slow-antiproton storage ring is coming on line.[13]

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