What can be learned about the P-wave $N\bar{N}$ interaction from a study of the x-ray spectrum of protonium?

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New indications of the existence of near-threshold P-wave states of quasinuclear baryonium have been found from a theoretical analysis of the x-ray spectrum of protonium measured by the ASTERIX group at CERN.

Attempts to observe x-ray transitions to the ground state of the $p\bar{p}$ atom[1,2] have recently met success[3] thanks to the startup of the low-energy antiproton ring (LEAR) at CERN. It had been stated previously in many places that measurements of the nuclear shift and width of the $1s$ level and of the width of the $2p$ level of protonium would be of major interest for the theory of the low-energy $N\bar{N}$ interaction and, in particular, for the physics of baryonium (see Ref. 4 and the bibliography there). From this standpoint, we have a comment regarding the results obtained by the ASTERIX group on the x-ray spectrum of protonium.

The annihilation width of the $2p$ level, Γ^a_{2p}, can be extracted from data on the intensities of the x-ray lines of the L series and of the $K\alpha$ line through the use of balance equations for the population (p_{2p}) of the $2p$ level of protonium in gaseous hydrogen:

$$p_{2p} = \sum_{n\geqslant 3} Y_{nd\rightarrow 2p} , \tag{1a}$$

$$Y_{2p\rightarrow 1s} = p_{2p}\Gamma^{\gamma}_{2p} / (\Gamma^{a}_{2p} + \Gamma^{\gamma}_{2p}) . \tag{1b}$$

Here $Y_{nl\rightarrow n'l'}$ are the intensities of the radiative transitions $nl\rightarrow n'l'$, and $\Gamma^{\gamma}_{2p} =$

3.8×10^{-4} eV is the radiative width of the $2p$ level. Equations (1) are written under the assumption that the $2p$–$2s$ Stark mixing is negligible and that the $2p$ level is populated primarily through radiative transitions. These assumptions are clearly valid at a hydrogen density $N \lesssim 5\times 10^{-2} N_0$ (where N_0 is the density of liquid hydrogen) and, in particular, for gaseous hydrogen under standard conditions.[5]

From (1) we find

$$Y_{2p\to 1s} / \sum_{n\geqslant 3} Y_{nd\to 2p} = (1+\eta)^{-1} ,$$

where $\eta = \Gamma^{a}_{2p}/\Gamma^{\gamma}_{2p}$ is the ratio of the annihilation and radiative widths of the $2p$ level.

The radiative and annihilation widths of the $2p$ level are given by

$$\Gamma^{\gamma}_{2p} = (2/3)^8 M\alpha^5 ,$$

$$\Gamma^{a}_{2p} = 3M^4\alpha^5 \,\mathrm{Im}\,A/8 ,$$

where $M = m_p/2$ is the reduced mass of the $\bar{p}p$ atom, $\alpha = 1/137$, and $A = \lim_{k\to 0}[t_1(k)k^{-2}]$ is the so-called P-wave scattering volume, which is determined by the behavior of the P-wave amplitude $[t_1(k)]$ for proton-antiproton scattering at a small relative momentum k. For the width ratio η we have the expression

$$\eta^{\mathrm{theo}} = (3^9/2^{14})\, m_p^3 \,\mathrm{Im}\,A . \tag{2}$$

Since the annihilation radius $r_a \sim 1/2m_p = 0.1$ fm is small in comparison with the range of nuclear forces, $R\sim 1$ fm, we can use the following factorization relation for the imaginary part of the P-wave scattering volume[4,6]:

$$\mathrm{Im}\,A = |f_1(0)|^{-2}\,\mathrm{Im}\,\bar{A} \equiv g_1(0)\,\mathrm{Im}\,\bar{A} . \tag{3}$$

Here $\mathrm{Im}\bar{A}\sim r_a^3$ is a quantity determined by annihilation processes proper, and $f_1(k)$ is the P-wave Jost function for the nuclear potential. The quantity $g_1(k) = |f_1(k)|^{-2}$, the "gain," is a measure of the intensity of the nuclear interaction in the $N\bar{N}$ system.[4]

Using factorization relation (3), we can write (2) as

$$\eta^{\mathrm{theo}} = (3^9/2^{17})\ g_1(0) = 0{,}15\, g_1(0) .$$

The ratio of the annihilation and radiative widths of the $2p$ level of protonium is thus a measure of the intensity of the $\bar{p}p$ nuclear interaction in the limit $k\to 0$. The ASTERIX experiment[3] yielded the following value for the ratio of the intensity of the $K\alpha$ line to the overall intensity of the lines of the L series:

$$Y_{2p\to 1s} / \sum_{n\geqslant 3} Y_{nd\to 2p} = (2{,}5 \pm 1{,}5)\times 10^{-2} .$$

We then find $\eta^{\mathrm{expt}} \cong 0.4\times 10^2$ and $\Gamma^{a}_{2p}\sim 10^{-2}$ eV, which corresponds to $g_1(0)\sim 10^2$. This large value of the gain indicates an intense nuclear attraction between the p and the $\bar{p}$ in the P wave.

In an effort to carry out a quantitative study of the role of nuclear attraction, Dal'karov *et al.*[7] calculated the partial ($l = 0, 1, 2$) annihilation cross sections $\sigma_a^{(l)}$ with the help of a realistic potential for the one-boson interaction. They also calculated the annihilation cross sections $\bar{\sigma}_a^{(l)}$ with the nuclear interaction "turned off." The calculations describe a sharp increase in the P-wave gain $g_1(k)=\sigma_a^{(l)}/\bar{\sigma}_a^{(l)}$ toward the $N\bar{N}$ threshold because of a rich family of quasinuclear P levels near the threshold. The value of $g_1(0)$ can be varied over the range 10–10^2 by varying the parameters of the model (the positions of the levels of quasinuclear baryonium).

We can conclude from these calculations that the large annihilation width found in the experiment of Ref. 3 for the $2p$ level of protonium finds a natural explanation in a quasinuclear approach to the $N\bar{N}$ system. This large width is a further indication for the existence of near-threshold states of quasinuclear baryonium with an orbital angular momentum $l=1$.

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