ANTIPROTONIUM LEVEL SHIFTS FOR LARGE ORBITAL ANGULAR MOMENTA

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Level shifts due to a single-meson interaction are calculated for the proton-antiproton system.

STRONG interactions of particles in states with large orbital angular momentum l are determined by the exchange of the smallest possible number of mesons. An estimate of the two-meson nucleon-nucleon scattering phase shifts[1] showed that for energies of $E \lesssim 20$ Mev the interactions in states with $l \geq 1$ are quite accurately described by the single-meson interaction.* Similar estimations should be valid for the interaction between a nucleon and an antinucleon. This permits the use of the single-meson approximation for the calculation of the level shifts of the proton-antiproton system (antiprotonium) with $l \geq 1$, which are due to the nuclear interaction.

In the single-meson approximation, the peripheral interaction between the proton and antiproton coincides with the proton-proton interaction, and is described well by the tensor potential $U^{(1)}$. In the calculation of the shifts, one can use the main terms of the expansion of Coulomb functions at the origin of the coordinate system, which ensures an accuracy of $\sim me^2/\mu$ (m and μ are the masses of the nucleon and π meson, $e^2 = 1/137$, $\hbar = c = 1$). For the singlet levels and the "unmixed" triplet levels (states with $J = l$, and also $^3P_0$) we obtain

$$\Delta E_l = -\frac{1}{2}\mu f^2 \frac{(n+l)!\,(me^2/\mu)^{2l+3}}{(2l+1)!\,(n-l-1)!\,n^{2l+4}},$$

$$\Delta E_l^l = -\frac{l+1}{l}\Delta E_l, \quad \Delta E_1^0 = 3\Delta E_1,$$

where $f^2 = 0.08$ is the square of the renormalization constant of the interaction between the nucleon (antinucleon) and the π meson and n is the principal quantum number. For the "mixed" triplet levels we have

$$\Delta E_{J-1}^J = -\mu f^2 \frac{(n+J-1)!\,(me^2/\mu)^{2J+2}}{(4J^2-1)\,(2J-1)!(n-J)!\,n^{2J+2}} \quad \text{for } J \geqslant 2,$$

$$\Delta E_{J+1}^J = \frac{1}{4}\mu f^2 \frac{(4J^2-1)\,(n+J+1)!\,(me^2/\mu)^{2J+4}}{(2J+2)!\,(n-J-2)!\,n^{2J+6}} \quad \text{for } J \geqslant 1.$$

The largest of the calculated shifts is $E_1^0 = -0.08$ ev (for $n = 2$), and the ratio $\Delta E_1^0/E_1$ is equal to 2.5×10^{-5}.

The contribution to the level shifts from the next approximation in "degree of peripherality" (two-meson approximation) has an additional smallness of 4^{-l-1}. However, owing to the anomalous smallness of the matrix element

$$\langle J, J-1 \,|\, U^{(1)} \,|\, J, J-1 \rangle \sim (me^2/\mu)^{2J+2}$$

(additional power of me^2/μ) the shifts $\Delta E_{J\mp1}^J$ have an anomalous dependence on the parameter me^2/μ (ΔE_{J-1}^J is anomalously small and ΔE_{J+1}^J is anomalously large). For this reason, the two-meson approximation gives a correction to these shifts of $\sim \mu/4^{l+1}me^2$.

We shall compare the obtained shifts with the broadening due to annihilation. Since the annihilation occurs at distances $\lesssim \alpha/m$ ($1 \lesssim \alpha \leq 3$), the nuclear widths should have a smallness $(\alpha\mu/m)^{2l}$ in comparison with the nuclear shifts. This simple estimate is in agreement with the results obtained by Desai for the S- and P-level widths.[2] Thus, for comparatively small l, the widths should already be less than the shifts.

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[1] Galanin, Grashin, Ioffe, and Pomeranchuk, JETP 37, 1663 (1959), Soviet Phys. JETP 10, 1179 (1960), JETP 38, 475 (1960), Soviet Phys. JETP 11, 347 (1960).

[2] B. R. Desai, Phys. Rev. 119, 1385 (1960).

*An exception are states with a total angular momentum $J = l + 1$, for which the single-meson phase shifts have an anomalous energy dependence for small momenta $\sim p^{2l+3}$ and cannot make a basic contribution.

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