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A new state of baryonium

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Abstract

The recent discovery of a narrow resonance in the decay $J/\psi \rightarrow \gamma p \bar{p}$ is described as a zero baryon number, deuteron-like singlet 1S_0 state. The difference in binding energy of the deuteron (-2.225 MeV) and of the new state (-17.5 MeV) can be accounted for in a simple potential model with a $\lambda \cdot \lambda$ confining interaction.

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1. Introduction

There has been a recent observation of a near-threshold narrow enhancement in the $P\bar{P}$ invariant mass spectrum from the radiative decays $J/\psi \rightarrow \gamma P\bar{P}$ by the BES Collaboration [1] who also report seeing nothing similar in the decay $J/\psi \rightarrow \pi^0 P\bar{P}$. The enhancement can be fit with either an S- or P-wave Breit–Wigner resonance function. In the case of the S-wave fit, the peak mass is below $2m_P$ at $M = 1859_{-10}^{+3}(\text{stat})_{-25}^{+5}(\text{sys})$ MeV/ c^2 with a total width $\Gamma < 30$ MeV/ c^2 at the 90% percent confidence level. The structure has properties consistent with either a $J^{PC} = 0^{-+}$ or $J^{PC} = 0^{++}$ quantum number assignment. The mass and width values are not consistent with any known meson resonance near this mass. Recently Belle has reported also observations of the decays $B^+ \rightarrow K^+ P\bar{P}$ [2] and $\bar{B}^0 \rightarrow D^0 P\bar{P}$ [3], also showing enhancements in the $P\bar{P}$ invariant mass dis-

tributions near $2m_P$. In addition to this probable spin zero state, there is also the report [4] of a narrow, S-wave triplet $P\bar{P}$ resonance at a mass of 1870 MeV/ c^2 with a width of 10 MeV/ c^2 and $J^{PC} = 1^{--}$.

There have been some signs of an anomalous behavior in the proton–antiproton system at a mass of $2m_P$ and since the 1960s there have been suggestions of states of nucleon–antinucleon, sometimes called baryonium. The name has also been invoked for states containing two quarks and two antiquarks. An example is the MIT bag model by Jaffe [5] which postulates the existence of baryonium for states made up of two quarks and two antiquarks. For a historical review see [6]. In fact, the recent observations of an unexpectedly light narrow resonance in $D_s^+ \pi^0$ with a mass of 2317 MeV by the BaBar Collaboration [7], together with a possible second narrow resonance in $D_s \pi^0 \gamma$ with a mass 2460 MeV/ c^2 have led, among other explanations [8,9], to a multi-quark–antiquark model [10]. The mass difference between the $D_s^*(2317)$ and the well established lightest charm–strange meson, D_s , is $\Delta M = 350$ MeV/ c^2 . This is less than the kaon mass, thus kinematically forbidding the

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decay $D_s^*(2317) \rightarrow D_{u,d} + K$. The possible resonance at $2460 \text{ MeV}/c^2$ also has such a mass difference when taken with the lighter D^* state; while this may be an artifact of a “feed-up” or “feed-down” mechanism [11] it is quite likely that both states may exist independently.

2. Nucleon–nucleon and nucleon–antinucleon interactions

For over fifty years there has been a general understanding of the nucleon–nucleon interaction as one in which there is, in potential model terms, a strong repulsive short distance core together with a longer range weaker attraction. Also, there have been many indications that in the nucleon–antinucleon system, there should be a strong attractive $N\bar{N}$ bound state near threshold [12,13]. This understanding evolved to attribute the long force to be that of pion exchanges and the repulsive short-range interaction to that of ω exchange [14]. In a nuclear physics approach this idea of meson exchange has evolved into an accurate phenomenological way to describe experiments.

Later potential models, such as the Bonn potential [15], were based on quantum chromodynamics (QCD). However, the Bonn potential model ended up as a ten parameter model [16] and its connection with concepts such as one-gluon exchange are tenuous. Many of these models were based on the non-relativistic quark model or on the MIT bag model [17,18]. The modern view is that there is a color interaction of a $\lambda \cdot \lambda$ type between pairs of quarks. The nucleon–nucleon or nucleon–antinucleon effective potential then arises from the residual color forces. However, to establish the connection between the effective potential and the color forces in practice requires somewhat ad hoc assumptions involving either resonating-group methods [19], variational techniques [20] or quark Born perturbative methods [21].

In nuclear physics models the potential for $N\bar{N}$ is more attractive than that for NN ; this is usually considered due to strong omega-exchange which is repulsive for NN and attractive in $N\bar{N}$. However, the idea of ω exchange should not be taken literally [21] since there is a mismatch of the ranges involved; $1/m_\omega \approx 0.2 \text{ fm}$ whereas the nucleon radius is about 1 fm . In the early String/Regge approach to $N\bar{N}$

[22,23] there are narrow $N\bar{N}$ states based on selection rules. For example, there is a large baryon–antibaryon effect near threshold. In all of these approaches there is a trade-off between ranges—the annihilation radius is short-range of about $1/2M_N \approx 0.1 \text{ fm}$, while the long range potentials are dominated by meson exchanges.

3. A simple toy model

Within the modern QCD approach, it is the $\lambda \cdot \lambda$ color interaction that plays an important role in trying to understand the few nucleon problem [20]. Nevertheless, the actual calculational details rely on other time-honored techniques as mentioned above. Here we wish to propose a model that has as its basis the 6-quark state making up the deuteron. It is known that in the triplet neutron–proton system there is only one bound state (the deuteron 3S_1) with a binding energy of -2.225 MeV . There is also a large singlet scattering state, the virtual 1S_0 , often called a virtual 1S_0 state, with an energy just above zero of 0.0382 MeV [24,25]. A simple phenomenological model of the deuteron consists of using a square well potential [24–26] with a depth sufficient to bind the isoscalar 3S_1 state but not quite deep enough to bind the 1S_0 state. Then the equation for a bound state is

$$\alpha \cot(\alpha a) = -\beta, \quad (1)$$

where

$$\alpha = \sqrt{2M(V - E)} \quad (2)$$

and $\beta = \sqrt{2ME}$, where V is the depth of the potential, E , the binding energy and a the size of the well. For the deuteron $a \approx 2 \text{ fm}$. For a binding energy $E = 2.225 \text{ MeV}$ the solution of Eq. (1) gives a well of depth $V = 36.5 \text{ MeV}$ (here $-E$ and $-V$ are the bound state energy and potential depth, respectively).

Our approach uses the fact the potential between two quarks due to the $\lambda \cdot \lambda$ color interaction gives an attraction factor of $-2/3$. In the case of $q\bar{q}$, the potential becomes even more attractive by a factor of two [20,27]. Whether this factor of two translates into a similar doubling of the phenomenological potential is not obvious. We will solve for the attractive force to fit the binding energy of the new $P\bar{P}$ state (17.5 MeV). It turns out from Eq. (1) the solution is $V = 64 \text{ MeV}$, surprisingly just a factor of 1.76, very close to two,

Table 1

Final states that are allowed or disallowed: here, I, C mean that the final states are disallowed by isospin or charge conjugation

Final state in $J/\psi \rightarrow \gamma P \bar{P}$	Isospin ($P \bar{P}$)	J^{PC}	Allowed
$\gamma + {}^1S_0$	0	0^{-+}	yes
$\gamma + {}^1S_0$	1	0^{-+}	no (I)
$\gamma + {}^3S_1$	0	1^{--}	no (C)
$\gamma + {}^3S_1$	1	1^{--}	no (C, I)
$\pi^0 + {}^1S_0$	0, 1	0^{-+}	no (C)
$\pi^0 + {}^3S_1$	0	1^{--}	no (I)
$\pi^0 + {}^3S_1$	1	1^{--}	yes (OZI suppressed)

deeper! Such a stronger attractive force, such as that expected from the color factor in the potential would seem to be consistent with the new 0^{-+} being a real 1S_0 bound state. In the case of the deuteron, we might assign the role of hyperfine interactions to raise the effective potential from that which binds the 3S_1 “deuteron” to a value which just fails to bind the virtual 1S_0 state. For $N\bar{N}$ baryonium we expect that the annihilation is a short-range phenomenon, which can modify the affect of the short-range hyperfine interactions making its role in the $P\bar{P}$ system unclear. Hence there is no simple way to predict the potential for the 3S_1 $P\bar{P}$ state. Also, while there is a clear distinction between the spin-one PN deuteron (3S_1) being isoscalar and the spin-zero 1S_0 being isovector, no similar distinction can be made for the nucleon–antinucleon state since both $I = 0$ and $I = 1$ states can exist with either spin-zero or spin-one [28].

However, this does not mean they should all be seen in the $J/\psi \rightarrow \gamma P \bar{P}$ as we show in Table 1.

4. Summary and conclusions

We have presented a simple model where we account for the new 0^{-+} state of $P\bar{P}$ being a bound state of baryonium comparable to the 1S_0 virtual bound state of the deuteron. This would imply that the “deuteron” equivalent 3S_1 state may also exist although we do not have any guidance on how to derive the size of the equivalent potential. The 1^{--} state at $1870 \text{ MeV}/c^2$ seen in the $e^+e^- \rightarrow P\bar{P}$ would appear to be a suitable candidate. It also would appear likely that similar types of baryonia should exist; for example, a calculation similar to that described above but with the Λ mass substituted for that of the proton predict another $\Lambda\bar{\Lambda}$ 0^{-+} state with a binding energy

of 31 MeV at a mass of $2200 \text{ MeV}/c^2$. Therefore, the idea that these resonances could be analogous to the “virtual bound state” in the $N-P$ system implies that further resonances should be expected. Rosner has also looked at baryon–antibaryon enhancements in B decays [29]. He also notes that there is a whole new interesting set of B decays possible involving exotic mesons and baryons.

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