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Pseudospin Symmetry in Nuclei, Spin Symmetry in Hadrons

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Abstract. Ginocchio argued that chiral symmetry breaking in QCD is responsible for the relativistic pseudospin symmetry in the Dirac equation, explaining the observed approximate pseudospin symmetry in sizable nuclei. On a much smaller scale, it is known that spin-orbit splittings in hadrons are small. Specifically, new experimental data from CLEO indicate small splittings in *D*-mesons. For heavy-light mesons we identify a cousin of pseudospin symmetry that suppresses these splittings in the Dirac equation, known as spin symmetry. We suggest an experimental test of the implications of spin symmetry for wave functions in electron-positron annihilation. We investigate how QCD can give rise to two different dynamical symmetries on nuclear and hadronic scales.

Recently, Isgur [1] has re-emphasized the experimental fact that spin-orbit splittings in meson and baryon systems, which might be expected to originate from one-gluon-exchange (OGE) effects between quarks, are absent from the observed spectrum. He conjectures that this is due to a fairly precise, but accidental, cancellation between OGE and Thomas precession effects, each of which has "splittings of hundreds of MeV" [1]. Taking the point of view that precise cancellations reflect symmetries rather than accidents, we have examined what dynamical requirements would lead to such a result.

Below, we first elucidate the experimental evidence for small spin-orbit splittings. Then we identify the symmetry that suppresses these splittings. We show how this symmetry leads to a proposed experimental test in electron-positron annihilation. The existence of pseudospin symmetry in nuclei is also indicated. Finally, we investigate how QCD can give rise to two different dynamical symmetries on nuclear and hadronic scales.

We study systems made from one light quark and one heavy antiquark. Because the light quark is expected to move relativistically, and the heavy quark can be treated as stationary, we examine the relativistic Dirac Equation. The equation includes the possibility of the OGE and Thomas precession effects mentioned before.

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The dynamics are approximated as a light quark moving in a relativistic vector and scalar potential of a heavy antiquark.

In the limit where the antiquark is infinitely heavy, the angular momentum of the light quark, j , is separately conserved. The states can be labelled by l_j , where l is the orbital angular momentum of the light quark. In non-relativistic models of mesons the splitting between $l_{l+\frac{1}{2}}$ and $l_{l-\frac{1}{2}}$ levels, e.g. the $p_{\frac{3}{2}}$ and $p_{\frac{1}{2}}$ or $d_{\frac{5}{2}}$ and $d_{\frac{3}{2}}$ levels, can *only* arise from spin-orbit interactions [1]. In Fig. 1 it is seen that the $p_{\frac{1}{2}}$ level corresponds to two degenerate broad states with different total angular momenta $J = j \pm \frac{1}{2}$, where $\frac{1}{2}$ is the spin of the heavy antiquark. For example in the case of D -mesons the two states are called D_0^* and D_1' . There are also two degenerate narrow $p_{\frac{3}{2}}$ states D_1 and D_2^* . The degenerate states separate as one moves slightly away from the heavy antiquark limit.

For the D -mesons, the CLEO collaboration claims a broad $J^P = 1^+$ state at $2461^{+41}_{-34} \pm 10 \pm 32$ MeV [2], belonging to the $p_{\frac{1}{2}}$ level, in close vicinity to the D_2^* at 2459 ± 2 MeV, belonging to the $p_{\frac{3}{2}}$ level, indicating a remarkable $p_{\frac{3}{2}}-p_{\frac{1}{2}}$ spin-orbit degeneracy of -2 ± 50 MeV.

For the K -mesons, the $p_{\frac{1}{2}}$ level is at 1409 ± 5 MeV, with $p_{\frac{3}{2}}$ nearby at 1371 ± 3 MeV, corresponding to a $p_{\frac{3}{2}}-p_{\frac{1}{2}}$ splitting of -38 ± 6 MeV. The splitting between the higher-lying $d_{\frac{5}{2}}$ and $d_{\frac{3}{2}}$ levels is -4 ± 14 MeV or 41 ± 13 MeV, depending on how the states are paired into doublets. These results indicate a near spin-orbit degeneracy if the strange quark can be treated as heavy, although it has certainly not been established that such a treatment is valid.

For B -mesons, L3 has performed an analysis, using input from theoretical models and heavy quark effective theory, to determine that the $p_{\frac{3}{2}}-p_{\frac{1}{2}}$ splitting is 97 ± 11 MeV [3]. Note that this is *not* a model-independent experiment.

There is currently no agreement within either lattice QCD, or models, on the magnitude, and even sign, of the $p_{\frac{3}{2}}-p_{\frac{1}{2}}$ splitting in D , D_s , B and B_s -mesons [4].

In order to more quantitatively measure the spin-orbit splitting, define $r = (p_{\frac{3}{2}} - p_{\frac{1}{2}}) / ((4p_{\frac{3}{2}} + 2p_{\frac{1}{2}}) / 6 - s_{\frac{1}{2}})$, where all entries refer to masses. The experimental data on D , K and B mesons give respectively $r = 0.00 \pm 0.10$, -0.06 ± 0.00 and 0.23 ± 0.04 . For the Dirac equation with arbitrary vector and scalar Coulomb potentials, the only potential for which the relevant analytic solutions are known, $-0.7 \lesssim r \lesssim 0.6$. It is hence evident that the spin-orbit splittings extracted from experimental results are indeed small.

The Dirac hamiltonian describing the motion of the light quark is

$$H = \vec{\alpha} \cdot \vec{p} + \beta(m + V_S) + V_V + M, \quad (1)$$

where we have set $\hbar = c = 1$, $\vec{\alpha}$, β are the usual Dirac matrices, $\vec{p}$ is the momentum, and m and M are the masses of the light and heavy (anti)quarks respectively.

If the vector potential $V_V(r)$ is equal to the scalar potential plus a constant potential U , which is independent of the spatial location $r = |\vec{r}|$ of the light quark

states [4]. This has explicitly been verified in a fit to the spectrum of K -mesons [4]. The prediction can be tested in the following experiment, depicted in Fig. 1.

The annihilation $e^+e^- \rightarrow D_0^*D_0^*$, $D_0^*D_2^*$ and $D_2^*D_2^*$ allows for the extraction of the D_0^* and D_2^* electromagnetic static form factors and the D_0^* to D_2^* electromagnetic transition form factor. The photon interaction γ_μ ensures that all radial wave functions of the light quark are accessed, because it acts both diagonally and off-diagonally, and because it does *not* act on the (infinitely) heavy quark. When spin symmetry is realised, there are only two independent radial momentum space wave functions, which should enable the prediction of one of the three form factors in terms of the other two. This should enable the verification of the predictions of spin symmetry. The proposed experiment can be carried out at the Beijing Electron Positron Collider at an energy of approximately 1 GeV above the $\psi(4040)$ peak in the final state $DD\pi\pi$. An equivalent experiment for K -mesons would involve detection of the $KK\pi\pi$ final state, which has already been measured at DM2. If B -mesons also exhibit spin symmetry, one can do equivalent experiments around 1 GeV above the $\Upsilon(4S)$ peak at the SLAC, KEK or CESR B-factories.

If $\hat{s}_i$ and $\hat{\tilde{s}}_i$ are interchanged in Eq. 2 one finds a symmetry of the hamiltonian in Eq. 1, $[H, \hat{\tilde{S}}_i] = 0$, when $V_V(\vec{r}) = -V_S(\vec{r}) + U$. This symmetry, called pseudospin symmetry, has been identified as being responsible for the pseudospin degeneracies observed in nuclei, for example the particle or hole states in double magic ^{208}Pb [6]. These are nuclei obtained from ^{208}Pb by subtracting or adding either a neutron or a proton.

What may the QCD origins of pseudospin and spin symmetry on different hadronic scales be? It has been argued by considering QCD sum rules in an infinite nuclear medium that the ratio of the scalar and vector self-energies of the nucleon is $-\sigma/(8m) \approx 1$, where σ is related to chiral symmetry breaking, and m is the light quark current mass [7]. These scalar and vector self-energies in an infinite nuclear medium inform about the scalar and vector potentials of the nucleon, with exactly the relation needed for the validity of pseudospin symmetry. The case for how spin symmetry can arise from QCD has been made in ref. [4].

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