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Modification of meson properties in the vicinty of nuclei

Peter Filip[1,a]

[1] *Institute of Physics, Slovak Academy of Sciences, Dúbravská cesta 9, 845 11, Bratislava, Slovakia*

Abstract. We suggest that modification of meson properties (lifetimes and branching ratios) can occur due to the interaction of constituent quark magnetic moments with strong magnetic fields present in the close vicinity of nuclei. A superposition of (J=0) and (J=1, m_z=0) particle-antiparticle quantum states (as observed for ortho-Positronium) may occur also in the case of quarkonium states $J/\Psi, \eta_c, \Upsilon, \eta_b$ in heavy ion collisions. We speculate on possible modification of $\eta(548)$ meson properties (related to C parity and CP violation) in strong magnetic fields which are present in the vicinity of nuclei.

1 Introduction

It has been pointed out already by Gell-Mann and Pais [1] that rigorous conservation of C parity should be expected only in the absence of external fields. Indeed, if Positronium (e^+e^-) is created in magnetic field, admixture of para-Positronium $J^{PC} = 0^{-+}$ wavefunction in ortho-Positronium (o−Ps) $J^{PC} = 0^{--}$ substate (m_z=0) allows for decay o−Ps $\rightarrow \gamma\gamma$ (originally forbidden by C parity). This results in the "magnetic field quenching" of ortho-Positronium $\rightarrow 3\gamma$ decays [2], and the fraction of "forbidden" o−Ps $\rightarrow \gamma\gamma$ decays depends on the external magnetic field strength.

We have suggested [3] that similar mechanism may apply to quarkonium mesons $J/\Psi, \eta_c$ and Υ, η_b, when subject to extremal magnetic fields ($B \approx 10^{14}$ T) created in heavy ion collisons [4]. In this short note we point out that this phenomenon may take place also in the case of $\eta(548)$ meson if bound to specific nuclei (for example ^{93}Nb) with large magnetic moments (e.g. $\mu_{Nb} = 6.2\mu_N$).

2 Positronium and quarkonium decays in magnetic field

Interaction term $\mathcal{H}_{int} = -\vec{\mu}_e \cdot \vec{B}$ for electron and positron magnetic moments ($\mu_{e^+} = 5.79 \cdot 10^{-5}$ eV/T) in Positronium subject to external magnetic field B is responsible for the mixing of (m_z=0) state $\Psi_o = (\uparrow\downarrow + \downarrow\uparrow)/\sqrt{2}$ (having quantum numbers $J^{PC} = 0^{--}$), with $J^{PC} = 0^{-+}$ state $\Psi_p = (\uparrow\downarrow - \downarrow\uparrow)/\sqrt{2}$:

$$\Psi_o^+ = \cos(\alpha)\Psi_o + \sin(\alpha)\Psi_p \quad ; \quad \Psi_p^- = \cos(\alpha)\Psi_p - \sin(\alpha)\Psi_o \ . \tag{1}$$

The mixing angle parameter $y = \tan(\alpha) = x/(1 + \sqrt{1+x^2})$, where $x = 4\mu_e B/\Delta E_{hf}$ depends [5] on the energy difference ΔE_{hf} between ortho Ψ_o and para Ψ_p states and magnetic field B. Decay rates $\Gamma = 1/\tau$ of new mixed Ψ_p^- and Ψ_o^+ states are $\Gamma_p^- = (\Gamma_p + y^2\Gamma_o)/(1+y^2)$ and $\Gamma_o^+ = (\Gamma_o + y^2\Gamma_p)/(1+y^2)$, while energy of Ψ_p^-, Ψ_o^+ eigenstates changes in field B as $E_{o,p}^{\pm} = \frac{1}{2}\Delta E_{hf}(1 \pm (1+x^2)^{1/2})$. Hyperfine splitting in Positronium is $\Delta E_{hf} \approx 10^{-3}$ eV and field B=1 T generates significant mixing effects [5]. For quarkonium $\Delta E_{hf} \approx 100$ MeV, and fields 10^{14}-10^{15} T are needed [3] to influence $\Upsilon, \Psi \rightarrow l^+l^-$ decays.

[a] e-mail: peter.filip@savba.sk

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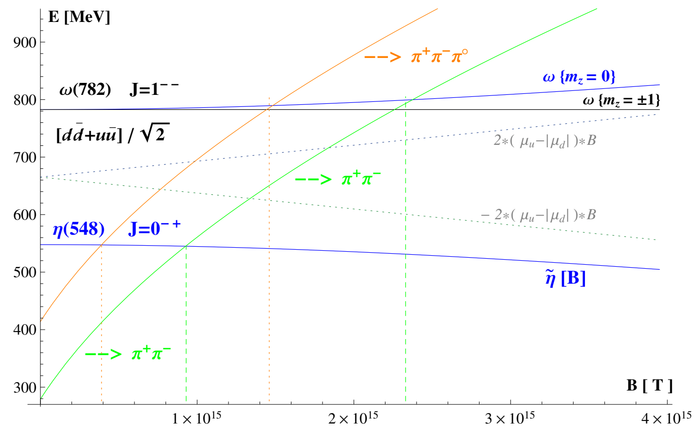

Figure 1. Energy of ω and η mesons in static magnetic field in comparison with Landau levels of decay products $\pi^+\pi^-\pi^0$ and $\pi^+\pi^-$. A superposition of η and $\omega\,(m_z\!=0)$ state opens $\eta \rightarrow \pi^+\pi^-$ channel due to admixture of ω state in $\tilde{\eta}$ meson. At $B > 4{\cdot}10^{14}$ T, $\eta \rightarrow \pi^+\pi^-\pi^0$ channel is energetically closed. The same happens [6] for ρ^0 and $\omega \rightarrow \pi^+\pi^-$ if $B > 2.3{\cdot}10^{15}$ T. CP - violating decay $\eta \rightarrow \pi^+\pi^-$ is possible for $B < 9{\cdot}10^{14}$ T. Measurable fraction of $\pi\pi$ decays of η meson can be expected for $B \approx 10^{11}$ T, if ortho-Positronium quenching effect [5] works also for meson decays [3].

For this quantum "mixing" phenomenon to occur in the case of hadrons (mesons), it is necessary that constituent quarks have magnetic moments μ_q. In this way, properties of QCD bound state (its C parity and decay channels) can be influenced by the external magnetic field, without direct involvement of gluonic (strong) interaction. In particular, 2-gluon decay $J/\Psi \rightarrow gg$ becomes possible in the magnetic field, because C parity of m_z=0 $(c\bar{c})$ meson substate Ψ^+_o is undefined - see Eq. (1). One may also suppose, that spurion-type γ^* is involved in seemingly C-violating $J/\Psi^+_o \rightarrow gg$ decays (channel $J/\Psi \rightarrow gg\gamma$ is allowed [7]), and this "hidden" γ^* is absorbed by the external magnetic field.

Measured magnetic moments of proton, neutron and hyperons [8] suggest that constituent quarks have their magnetic moments: μ^*_u=1.85 μ_N, μ^*_d=−0.97 μ_N, μ^*_s=−0.61 μ_N (here μ_N=3.1$\cdot$10^{-8} eV/T), and for c and b quarks μ^*_c=0.40 μ_N and μ^*_b=0.07 μ_N can be expected (from Dirac equation). The response of quarkonium states to extremal magnetic fields [4] created in collisions of nuclei at LHC and RHIC may be experimentally observable, for example, as anomalous suppression [9].

It is tempting to suggest [3], that behavior of quarkonium in strong magnetic field might apply also to $(s\bar{s})$ meson $\varphi(1019)$. However, the closest $J = 0^{+-}$ mixing partner for $\varphi(s\bar{s})$ state is $\eta'(958)$, and the mixing phenomenon may be non-trivial due to non-$s\bar{s}$ components in η' wave function. In the next section we discuss $\eta(548)$ meson behavior (neglecting its $s\bar{s}$ content) in the magnetic field.

3 Meson $\eta(548)$ in external magnetic field

Conservation of C parity in $\eta(548)$ decays has been experimentally measured [8] and it is the goal of intense experimental activity at JLAB. Therefore, a possibility of the modification of C parity properties of $\eta(548)$ meson in the magnetic field is a relevant subject.

The closest J^{PC}=1^{--} partner for η meson is $\omega(782) = (u\bar{u} + d\bar{d})/\sqrt{2}$ state with ΔE_{hf} = 235 MeV. Also $\rho^0(770) = (u\bar{u} - d\bar{d})/\sqrt{2}$ is present in the region of $\eta(548)$ mass, with isospin structure of its wavefunction orthogonal to (u, d) part of η and ω mesons. We shall *assume* here that quantum mixing in the magnetic field happens preferably between states having the same $u \leftrightarrow d$ isospin symmetry.

What can happen to η meson decays if its wavefunction $\tilde{\eta}$ acquires admixture of ω meson state $\tilde{\eta}[B] = (\eta + \varepsilon \cdot \omega)/\sqrt{1 + |\varepsilon|^2}$ in magnetic field? The following decay channels may become possible

$$\tilde{\eta}[B] \rightarrow \pi^+\pi^- \qquad \tilde{\eta}[B] \rightarrow \pi^0\gamma \qquad \tilde{\eta}[B] \rightarrow \pi^0\pi^0\gamma\,, \tag{2}$$

simply because $\omega \rightarrow \pi^+\pi^-$, $\omega \rightarrow \pi^0\pi^0\gamma$ and $\omega \rightarrow \pi^0\gamma$ decays are allowed. The situation is rather delicate, because $\pi^+\pi^-$ decay channel of η meson would be P and CP violating [8]. One may suggest that external magnetic field allows spurion-type unobserved γ^* to be involved, which covers both P and CP conservation issue ($\eta \to \pi^+\pi^-\gamma$ decays are allowed). Since $\omega \to \pi^+\pi^-$ process is G-parity violating, occurence of $\tilde{\eta}[B] \to \pi^+\pi^-$ decays in magnetic field (due to $\eta - \omega_{m_z=0}$ mixing) is related to isospin breaking, which is known to affect measurement of CP asymmetries in $B \to \pi\pi$ decays [10]. External field-induced CP violation may be expected also as $\tilde{\eta}_c(2981) \to \pi^+\pi^-$ decays, if J/Ψ (m_z=0) substate admixture occurs in $\tilde{\eta}_c[B] \approx (\eta_c + \varepsilon \cdot J/\Psi)$ state in magnetic field $B \approx 10^{15}$ T.

Because $\omega \to \pi^0\pi^0$ decay is forbidden (by C parity) we have not suggested directly in Eq. (2) that decay channel $\tilde{\eta}[B] \to \pi^0\pi^0$ would become open in a sufficiently strong magnetic field. However, since mixed state $\tilde{\eta}[B] \approx (\eta + \varepsilon \cdot \omega)$ is neither C nor G-parity operator eigenstate, $\pi^0\pi^0$ decays of $\tilde{\eta}[B]$ state may possibly also become enhanced above the expected [12] rates in strong magnetic fields.

4 Meson $\eta(548)$ in the vicinity of nuclei

For η and ω mesons the ratio of their lifetimes is $\tau_\eta/\tau_\omega = 6.45 \cdot 10^3$, which means that $r = 10^{-6}$ admixture of ω meson in $\tilde{\eta}[B]$ superposition state gives $F \approx 0.6\%$ contamination from ω decays. The mixing phenomenon is driven by $x = 4\mu_q B/\Delta E_{hf}$ parameter. Using formulas derived for Positronium [5], one has $r = (1/4)x^2 \to 10^{-6}$, and magnetic field $B \approx (3.7/\mu_q)10^{12}$ T gives F=$6 \cdot 10^{-3}$=0.6% contamination by ω-decays for $\tilde{\eta}(548)$ meson (here $\mu_q = (\mu_u + \mu_d)/2$ can be used in units $[\mu_N]$).

Such magnetic fields are present in magnetars, binary neutron stars [11] and surprisingly also in ^{93}Nb nucleus. For ^{93}Nb$_{9/2}$ magnetic moment $\mu = 6.2\mu_N$, one has $B \approx 10^{11}$ T in the interior [13] or the closest vicinity of ^{93}Nb, what may affect η–Nb (bound state) properties and decays. For $\mu_q \approx \mu_N$ one has $F = 4.64 \cdot 10^{-28} B^2$, which (if multiplied by 0.015=1.5%) gives the estimate for $\tilde{\eta}[B] \to \pi^+\pi^-$ rate.

5 Conclusions

We have suggested that properties of $\eta(548)$ mesons can be affected by magnetic fields in the vicinity of nuclei due to quantum superposition - mixing effect (observed to occur in Positronium). This may be relevant if conservation laws (CP or C parity) are tested in laboratory conditions at high precission.

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