Strong Decay of $\phi$ (1 s), $\Upsilon(4s)$ and $\Sigma^{\pm*}$ in Magnetic Field

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Strong Decay of $\phi(1s)$, $\Upsilon(4s)$ and $\Sigma^{\pm*}$ in Magnetic Field

Peter Filip
Institute of Physics, Slovak Academy of Sciences, Dúbravská cesta 9, Bratislava 84511, Slovakia
E-mail: peter.filip@savba.sk

Abstract. The influence of static magnetic field on decays $\phi(1020) \to K\bar{K}$, $\Upsilon(4s) \to B\bar{B}$, and $\Sigma^{\pm*} \to \Lambda\pi^{\pm}$ is discussed. In particular, we estimate how much the ratio of decay widths $\Gamma(K^+K^-)/\Gamma(K^0\bar{K}^0)$ and $\Gamma(B^+B^-)/\Gamma(B^0\bar{B}^0)$ can be modified by magnetic fields of strength $B \approx 10^{14}$ T created in relativistic collisions of heavy nuclei at LHC and RHIC colliders. Due to interaction of charged $K$ and $B$ mesons with the magnetic field, branching ratios for $K^+K^-$ and $B^+B^-$ decays of $\phi(1020)$ and $\Upsilon(4s)$ mesons may become reduced by 50% or completely closed. We study also the influence of magnetic field on strong decay $\Sigma^{\pm*}(1385) \to \Lambda + \pi^{\pm}$.

1. Introduction
It has been suggested recently [1], that static magnetic fields of strength $B \approx 10^{15}$ T can prolong the lifetime of $\rho(770)$ mesons via suppression of $\rho^0 \to \pi^+\pi^-$ decay channel, as a consequence of increasing energy of the lowest Landau level of charged pions in the magnetic field. Magnetic fields created in heavy ion collisions [2] at LHC and RHIC accelerators may reach extremal values $B \approx 10^{14} - 10^{15}$ T for a very short time, and the presence of expanding partonic plasma (QGP) can slow down [3] rapid decrease of the magnetic field intensity.

We have investigated the response of $s\bar{s}$-quark containing hadronic resonances $\Lambda^*(1520)$, $\Xi^*(1535)$ and $K^*(892)$ to such extremal magnetic fields [4], and it was found that particular strong decay channels (containing charged daughter particles) are affected much more than neutral channels. In this contribution we investigate the behavior of baryonic resonance $\Sigma^{\pm*}$ in very strong static magnetic fields.

![Figure 1](image-url)  
**Figure 1.** Strong decays of $\phi(1020)$, $\Upsilon(4s)$ mesons and $\Sigma^{\pm*}$ baryons by $(u\bar{u})$, $(d\bar{d})$ pair creation.

Additionally, we estimate how much decay widths of $\phi(1020) \to K^+K^-$ and $\Upsilon(4s) \to B^+B^-$ channels are suppressed in the magnetic field, due to the reduction of phase-space occurring...
in the magnetic field. The effects we discuss here can be of experimental significance, only if lifetimes of particles considered are comparable to the duration of extremal magnetic field created in heavy ion collisions. The lifetime \( \tau_{\Sigma^*} \approx 5 \text{fm}/c \) of \( \Sigma^*(1385) \) resonance is reasonably short, while lifetimes of \( \Upsilon(4s) \) and \( \phi(1020) \) mesons are considerably longer: 10fm/c and 46fm/c.

### 2. Energy of charged baryons in the magnetic field

Dispersion relation of proton [5] in fields \( B < B_p^c = 1.5 \cdot 10^{16} \text{ T} \) can be expressed as

\[
E[B] = \left[ p_c^2 + \left( \frac{M^2}{B_p^c} + (1 - 2s_z) \frac{B}{B_p^c} M^2_c - (2s_z) \kappa_B \frac{B}{2B_p^c} M^2_p \right) \right]^{1/2}
\]

where critical field \( B_p^c = M_p/2\mu_N = M_p^2c^2/eh \), anomalous part of proton magnetic moment \( \kappa_p = 1.79 = \mu_p/\mu_N - 1 \), and \( \mu_N = 3.152 \cdot 10^{-14} \text{ T} \). For weak fields \( B \ll B_p^c \) and \( p_z \to 0 \) one has

\[
E[B, s_z] \approx m_p + eB/2m_p - (2s_z)[1 + \kappa_p]\mu_N B .
\]

Term \( E = eB/2m_p \) corresponds to \( (n = 0) \) Landau level energy of proton, and interaction of proton magnetic moment \( \mu_p = (1 + \kappa_p)\mu_N \) with external field is simply \( E = -\vec{\mu}_p \vec{B} \). One can rewrite Eq. (1) also for \( \Sigma \) hyperons. Anomalous magnetic moment is \( \kappa_{\Sigma} = (M_\Sigma/M_p)\mu_{\Sigma}/\mu_N - 1 \), and small field approximation \( B \ll B_p^\Sigma = B_p^c(M_\Sigma/M_p)^2 \) gives formula identical to Equation (2) with replacements \( m_p \to m_\Sigma \) and \( \kappa_p \to \kappa_{\Sigma} \).

For \( J = 3/2 \) baryons (\( \Sigma^{+*} \), \( \Xi^{-*} \) and \( \Omega^- \)), Equation (2) can still be used, if term \( (2s_z) \) is substituted by \( (2J_z/3) \). For neutral baryons (\( \Lambda^0 \) for example) Landau energy term \( eB/2m \) vanishes and term \( [1 + \kappa_p]\mu_N \to \mu_{\Lambda^0} \), while magnetic moment interaction of spinless hadrons (pseudoscalars \( \pi, K, \eta \)) is zero \( \mu = 0 \) (if their magnetic polarizability [6] is neglected [7]).

![Figure 2](image-url)

**Figure 2.** Energy plots for \( \Upsilon(4s) \to BB \) and for \( \Sigma^{+*} \to \Lambda^0 + \pi^+ \) decays in the magnetic field.

In Figure 2, we show the energy plot for \( \Upsilon(4s) \to BB \) and \( \Sigma^{+*} \to \Lambda^0 + \pi^+ \) strong decays (using \( p_z = 0 \)). Large \( \Sigma^{+*}_{3/2} \) quadruplet energy splitting comes from \( \mu_{\Sigma^{+*}_{3/2}} \approx 3.1\mu_N = 2\mu_u + \mu_s \), magnetic moment interaction. Behavior of \( \Sigma^{+*} \) is similar \( (\mu_{\Sigma^{-*}_{3/2}} \approx -2.6\mu_N = 2\mu_d + \mu_s) \) to that shown for \( \Sigma^{+*} \), while quadruplet splitting of \( \Sigma^{0*} \) is much smaller. We observe that 25% of \( \Sigma^{+*} \) decays are energetically forbidden at \( B = 5 \cdot 10^{14} \text{ T} \), and only 50% are possible at \( B = 10^{15} \text{ T} \). Allowed \( \Sigma^{+*} \) decays at \( B > 10^{15} \text{ T} \) would behave as originating from a polarized \( J=3/2 \) baryon.

Decay \( \Upsilon(4s) \to B^+B^- \) is kinematically closed for \( B \geq 2 \cdot 10^{15} \text{ T} \), while \( \Upsilon(4s) \to B^0\bar{B}^0 \) channel remains unaffected in our approximation. Landau level energy \( E_L = |Q|B/2m \) is always increasing, while interaction of particle magnetic moment \( E = -\vec{\mu} \vec{B} \) splits the energy of particles with non-zero magnetic moments. As energy difference between decaying hadron and its decay products decreases, phase space of that particular decay channel gets reduced (see next section).
3. Magnetic field dependence of decay widths

Isospin conservation for strong decays of φ(1020) and Υ(4s) mesons into $K^+K^-$, $K^0\bar{K}^0$ and $B^+B^-$, $B^0\bar{B}^0$ pairs predicts equal branching ratios for neutral and charged decay channel (Clebsch-Gordan coefficients are $\pm \sqrt{1/2}$). This agrees quite well with BR($\Upsilon \to B^+B^-$) = 51.6% and BR($\Upsilon \to B^0\bar{B}^0$) = 48.4% observed experimentally (a small deviation from equality is expected due to Coulomb effects [8]). However, BR($\phi(1020) \to K^+K^-$) = 49.2% and BR($\phi(1020) \to K^0\bar{K}^0$) = 34.0% which gives experimental ratio $R_{\phi}^{00} = \Gamma_{\phi}^0/\Gamma_{\phi}^{00} = 1.45 \pm 0.04$. Such a deviation from the expectation may originate from phase-space effects.

Spin $J=1$ of hadrons $\phi(1020)$ and Υ(4s), decaying into the pair of spinless particles, is transformed into $P$-wave angular momentum $L=1$ of pseudoscalar meson pair. In such case, phase-space is proportional to the third power of momentum [8]. Decay width is expressed as

$$\Gamma[B] \approx |\mathcal{M}|^2 p^3[B] \quad \text{where} \quad p[B] = \frac{1}{2} \sqrt{M_R^2 - 4m^2[B]} .$$

(3)

$M_R$ is mass of decaying resonant state and $m = m_1 = m_2$ are equal masses of two pseudoscalar decay products, which can depend on external magnetic field. Indeed, using masses $K^\pm = 493.7\text{MeV}/c^2$ and $K^0 = 497.6\text{MeV}/c^2$ gives different decay momenta $p_{K^\pm} = 127\text{MeV}/c$ and $p_{K^0} = 110\text{MeV}/c$ in vacuum ($B=0$), which translates into expected ratio $R_{K^0}^{00} = 1.52$ of decay widths (while we still neglect Coulomb effects [8]). In the magnetic field, one has

$$R_{\pm 0}^{\phi} = \Gamma_{\pm}[B]/\Gamma_{00} = p_{\pm}[B]/p_{00} \quad \text{and} \quad \Gamma_{\text{tot}}^*[B] = \Gamma_{\pm}[B] + \Gamma_{00}^* + \Gamma_{\text{rest}}^* ,$$

(4)

if dependence [10] of strong decay amplitude $|\mathcal{M}|^2$ in Equation (3) on external fields is neglected. We assume $\Gamma_{\text{rest}}^*[B] \approx 0$ for Υ(4s), while $\Gamma_{\text{rest}}^*[B] = 0.75\text{MeV}\approx \Gamma_{\text{rest}}^*[B]$ for φ(1020) meson [9].

In Figure 3 we show magnetic field dependence of ratios $\Gamma_\pm^*[B]/\Gamma_{00}^*$ of charged and neutral decay widths for strong decays of φ(1020), Υ(4s), Ξ^{0*}, and $K^{0*}$ hadrons estimated according to Equation (4). For φ(1020) decay, Coulomb correction [8] factor is used to meet the experimental data [9] in Figure 3 with value $R_{\pm 0}^{\phi} = \Gamma_\pm^* / \Gamma_{00}^* = 1.45$.

Charged decay widths $\Gamma_{\pm}[B]$ can be reduced even more than we suggest here: only $p_z$ momentum component is continuous in $B_z$ magnetic field, and $\left|d\Gamma/(2\pi\hbar)^3\right|$ has to be replaced by the sum [11] of Landau levels $(eB/c) \sum_{n=0}^{n_{\text{max}}} \left[2 - \delta_{n0}^0\right] dp_z/(2\pi\hbar)^2$ for phase-space evaluation. Figure 4 shows our estimate of lifetime $\tau^* = 1/\Gamma_{\text{tot}}^*$ for φ(1020), Υ(4s), Ξ^{0*}, and $K^{0*}$ in $B$ field.
4. Summary and Conclusions

We have studied the influence of static magnetic field on strong decay properties of φ(1020), Υ(4s) mesons and Σ*(1385) baryonic resonance. It is found, that charged decay channels φ → K⁺K⁻ and Υ(4s) → B⁺B⁻ can become completely closed in magnetic fields B_φ > 3·10^{14} T and B_Υ > 2·10^{15} T. For strong decays of Σ⁺⁺ resonance we find no critical field strength. However, decay Σ⁺⁺ → Λ + π⁺ of J_z = 3/2 and J_z = 1/2 substates becomes forbidden in field B > 10^{15} T (see Fig. 2), which results in the effective polarization of decaying Σ⁺⁺ baryons in magnetic field. Our estimates are based on the reduction of phase-space, occurring due to increasing minimal energy (n = 0 Landau level) of charged decay products in the magnetic field.

![Graph showing energy plot for φ(1020) → ℓ⁺ℓ⁻ decays in magnetic field, and estimated lifetimes of Υ(4s), φ(1020), Ξ⁰∗, and K⁰∗ obtained from magnetic field dependences of their decay channels.]

We also find that lifetimes of φ(1020), Υ(4s) mesons and other (e.g. K⁰∗ and Ξ⁰∗) hadrons increase in the magnetic field. Since duration of extremal magnetic fields in relativistic collisions of nuclei is rather short [2], effects studied here might be observable only for short-living resonant states, K⁺⁺ for example. In Figure 4 we suggest that phase-space for φ → e⁺e⁻ decay changes more than φ → μ⁺μ⁻, but separate study is needed to understand the magnetic field influence on dilepton decays. Behavior of Σ⁺⁺ is also non-trivial and more detailed studies are needed.

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