Possibility of Observing Dark Matter via the Gyromagnetic Faraday Effect

Susan Gardner
Department of Physics and Astronomy, University of Kentucky, Lexington, Kentucky 40506-0055, USA
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If dark matter consists of cold, neutral particles with a nonzero magnetic moment, then, in the presence of an external magnetic field, a measurable gyromagnetic Faraday effect becomes possible. This enables direct constraints on the nature and distribution of such dark matter through detailed measurements of the polarization and temperature of the cosmic-microwave background radiation.

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Introduction.—The existence of dark matter (DM) was first inferred in 1933 from Zwicky's observations of extragalactic nebulas [1]. In recent years, our ability to assay its abundance has sharpened considerably, and a concordance of disparate observations reveal that DM comprises some twenty-three percent of the energy density of the universe, with a precision of a few percent [2]. Yet, despite this progress, the fundamental nature of DM remains unclear. One cannot say whether DM consists of a single species of particle, or of many, or even if it consists of stable, elementary particles at all. Dark matter could comprise aggregates of some kind, or be mimicked, in part, by a modification of gravity at large distances [3–5]. We do know that light, massive neutrinos cannot explain the galactic rotation curves [6], so that non-standard-model particles, arguably of the Fermi scale, are commonly invoked to explain it [7]. Accordingly, little, if anything, is known of each species' quantum numbers, mass, or mass distribution. In this Letter we consider the possibility that DM consists of neutral objects, which need not be elementary particles, of mass M with nonzero magnetic moments. The empirical limits on this possibility vary with the particle's mass [8,9] and can be evaded if the particle is composite.

Although our scenario naturally permits the dark constituents to be mutually interacting [10], it does differ significantly from usual ideas. For example, models of electroweak symmetry breaking with an additional discrete symmetry can yield viable DM candidates. In models with supersymmetry, the DM candidate—the "lightest supersymmetric particle"—is a Majorana particle, and its static magnetic moment is identically zero. Thus if the effect we discuss is observed, it demonstrates that supersymmetry does not provide an exclusive solution to the DM problem. On the other hand, models with "large" extra dimensions, such that their compactification radius R has $R^{-1} \lesssim$ 1 TeV, offer DM candidates which are nominally consistent with our scenario [11]. In particular, models with universal extra dimensions [12] yield DM candidates which are known to be compatible with observed constraints and which could also possess magnetic moments [13–15].

Let us now consider how cold DM with a nonzero magnetic moment can be observed. A medium of particles with either electric charges or magnetic moments develops a circular birefringence when subjected to an external magnetic field, even if the medium is isotropic. Consequently, the propagation speed of light in the medium will depend on the state of its circular polarization, so that light prepared in a state of linear polarization will suffer a rotation of the plane of that polarization upon transmission through the medium. If we define $k_\pm$ to be the wave number for states with right- $(+)$ or left-handed $(-)$ circular polarization, then the rotation angle is given by $\phi = (k_+ - k_-)l/2$, where l is the length of transmission through the medium. If the medium contains free electric charges, this is the Faraday effect known for light travelling through the electrons and magnetic fields of the warm interstellar medium (ISM) [16]. A Faraday effect can also occur in a magnetizable medium which is electrically neutral [17,18]. We term these the gyroelectric (GE) and gyromagnetic (GM) Faraday effects [19], respectively. We study the GM Faraday effect associated with cold DM carrying a nonzero magnetic moment. We begin by comparing the Faraday effects in the ISM, for which the GE effect is familiar, before turning to a discussion of their impact on the cosmic-microwave background (CMB) polarization and the constraints such measurements can yield on models of DM.

Faraday effects in the ISM.—The ISM contains free electrons and external magnetic fields; it is GE and gives rise to a Faraday effect. We consider an external magnetic field $\mathbf{H}_0$ in the $\hat{\mathbf{x}}$-direction with circularly polarized electromagnetic waves propagating parallel to it. In this case, an electron with charge $-e$ and mass m suffers a displacement $\mathbf{s}$ via the Lorentz force

$$m\ddot{\mathbf{s}} = -e(\mathbf{E} + \dot{\mathbf{s}} \times \mathbf{H}_{\rm tot}), \tag{1}$$

where $\mathbf{H}_{\rm tot} = \mathbf{H}_0 + \mathbf{H}$. The electric field, e.g., associated with the wave is $\mathbf{E}(\mathbf{x}, t) = E_\pm \mathbf{e}_\pm \exp(ik_\pm x - i\omega t)$, where $\mathbf{e}_\pm \equiv \hat{\mathbf{y}} \pm i\hat{\mathbf{z}}$. We define the polarization state with positive helicity, $\mathbf{e}_+$, to be right-handed. Assuming $|\mathbf{H}_0| \gg |\mathbf{H}|$, the steady-state solution for $\mathbf{s}$ yields, for a medium of electrons with number density n_e, the polarization $\mathbf{P} = -n_e e\mathbf{s}$ and the electric susceptibility χ_e, recalling $\mathbf{P}_\pm = \epsilon_0 \chi_{e\pm} \mathbf{E}_\pm$. We thus determine the permittivity $\epsilon_\pm$:

$$\frac{\epsilon_\pm}{\epsilon_0} \equiv 1 + \chi_{e\pm} = 1 - \frac{\omega_P^2}{\omega(\omega \mp \omega_H)}, \tag{2}$$

where the plasma frequency ω_P is given by $\omega_P^2 \equiv n_e e^2/\epsilon_0 m$ and $\omega_H = eH_0/m$. With $k_\pm = (\omega/c)\sqrt{\epsilon_\pm/\epsilon_0}$ and with $\omega \gg \omega_H, \omega_P$, we have $\phi = -\omega_P^2 \omega_H l/2c\omega^2$ to leading order in ω. Generalizing this to variable electron densities and magnetic fields along the line of sight yields

$$\phi = -\frac{e^3}{2c\omega^2\epsilon_0 m^2}\int_0^l dx n_e(x)H_0(x), \tag{3}$$

where $x = 0$ marks the location of the source. The ω dependence makes knowledge of the intrinsic source polarization unnecessary; one measures the position angle of linear polarization, in a fixed reference frame, as a function of ω, so that the line integral of $n_e(x)H_0(x)$ can be inferred [20,21]. A pulsed radio source also permits the measurement of the frequency dependence of the arrival time, to yield the line integral of $n_e(x)$ [20], so that the average magnetic field along the line of sight can also be determined.

If the electrons can be aligned to yield a magnetization, the ISM can be regarded as GM as well. We shall treat the GE and GM effects independently. Applying a magnetic field in a GM medium induces a magnetization $\mathbf{M}_{\rm tot}$, i.e., a net magnetic moment per volume, where $\mathbf{M}_{\rm tot} = \hat{\mathbf{x}}M_0 + \mathbf{M}$ and M_0 results from H_0 alone. The resulting magnetization obeys

$$\dot{\mathbf{M}}_{\rm tot} = \gamma \mathbf{M}_{\rm tot} \times \mathbf{H}_{\rm tot}, \tag{4}$$

where γ is the gyromagnetic ratio of the magnetic-moment-carrying particle. If the constituents possess an electric dipole moment as well, an additional term appears in Eq. (4) [22]. We assume $|\mathbf{H}_0| \gg |\mathbf{H}|$, $|\mathbf{M}_0| \gg |\mathbf{M}|$, and the conventions of the GE case to determine the steady-state solution, which, neglecting the $\mathbf{M}\times\mathbf{H}$ term, is

$$M_\pm = \pm\frac{\chi_0\omega_H}{\omega \pm \omega_H}H_\pm \equiv \chi_\pm H_\pm, \tag{5}$$

where $\chi_0 \equiv M_0/H_0$ and $\omega_H \equiv \gamma H_0$. We recall the magnetic susceptibility χ_m obeys $\mathbf{M} = \chi_m \mathbf{H}$, so that

$$\frac{\mu_\pm}{\mu_0} \equiv 1 + \chi_{m\pm} = 1 \pm \frac{\chi_0\omega_H}{\omega \pm \omega_H}, \tag{6}$$

where $k_\pm = (\omega/c)\sqrt{\mu_\pm/\mu_0}$. Noting $\omega_H/\omega \ll 1$ and working to leading order in this quantity, one has $k_{\rm diff} = k_+ - k_-$, which controls ϕ, with

$$k_{\rm diff} = \frac{\chi_0\omega_H}{c} + \frac{\chi_0\omega_H^3}{c\omega^2} + \frac{\chi_0^2\omega_H^3}{2c\omega^2} + \ldots. \tag{7}$$

The magnetization induced by H_0 on a system of spin-1/2 particles each with magnetic moment μ in equilibrium at temperature T is [23]

$$M_0 = n_e\mu\tanh\left(\frac{\mu H_0}{k_B T}\right) = n_e\left(\frac{\mu^2 H_0}{k_B T}\right), \tag{8}$$

where the corrections to the last equality are negligible in the ISM, though diverse environmental conditions do exist. The magnetic field H_0 is no larger than a few μG—and its cold patches are no colder than a few 100 K [20]. We can thus neglect nonleading powers in χ_0. We separate the rotation angle ϕ into frequency-independent and frequency-dependent pieces, so that $\phi = \phi_0 + \phi_\omega$, to yield

$$\phi_0 = \frac{\mu^2\gamma}{2ck_B}\int_0^l dx\frac{n_e(x)H_0(x)}{T(x)}, \tag{9}$$

$$\phi_\omega = \frac{\mu^2\gamma^3}{2c\omega^2 k_B}\int_0^l dx\frac{n_e(x)H_0^3(x)}{T(x)}, \tag{10}$$

where $\gamma = g\mu_B/\hbar$, $\mu_B \equiv e/2m$, and g is the usual Landé factor. The appearance of higher powers in H_0 in ϕ_ω makes it, as well as the time delay, negligible in comparison to ϕ_0 in the ISM. If we neglect any T variation along the line of sight, then the frequency-independent GM and GE effects share a common integral. We can then compare

$$\phi_0 = \frac{\mu^2\gamma}{2ck_B T}\int_0^l dx n_e(x)H_0(x) \tag{11}$$

with

$$\phi = \frac{e^3}{2c\omega^2\epsilon_0 m^2}\int_0^l dx n_e(x)H_0(x) \tag{12}$$

by computing

$$|\tilde{\chi}| \equiv \frac{\gamma\mu^2}{k_B T} = \frac{|g|\mu^2\mu_B}{\hbar k_B T} \sim \frac{2\mu_B^3}{\hbar k_B T} \sim 4.6\times 10^{-19}\left[\frac{300\ \mathrm{K}}{T}\right]\frac{\mathrm{cm}^3}{\mathrm{G\,s}}$$

and

$$\chi \equiv \frac{e^3}{\omega^2\epsilon_0 m^2} = \frac{\alpha}{\pi}\frac{\hbar}{mc}\frac{e}{m}\lambda^2 \sim 1.6\times 10^{-6}\left[\frac{\lambda}{1\ \mathrm{cm}}\right]^2\frac{\mathrm{cm}^3}{\mathrm{G\,s}},$$

where $|g| \sim 2$, $\mu_B \sim 5.79\times 10^{-9}$ eV/G, $k_B T \sim 1/38.7$ eV for $T \sim 300$ K, 1 eV $\sim 4.03\times 10^{-11}$ $\mathrm{G^2\,cm^3}$, $\alpha \sim 1/137$, $e/m \sim 1.76\times 10^7$ rad/G s, and $\hbar/mc \sim 3.86\times 10^{-11}$ cm. Recent surveys have used wavelengths in the $\lambda = 6$ and 20 cm bands [20,24], and most Faraday rotation accrues in the warm ISM, for which $T \sim 5000$ K. We thus find the GM effect to be negligible for radio sources. We note ϕ_ω is smaller than ϕ_0 by a factor of $\gamma^2 H_0^2/\omega^2 \sim 9\times 10^{-21}[\lambda/(1\ \mathrm{cm})]^2$, using $H_0 \sim 10^{-6}$ G.

Faraday effects on the CMB polarization.—Our study of the GM Faraday effect shows ϕ_0 to be the most important numerically, though its frequency independence means we must employ sources of known polarization to determine it. To realize this, we turn to the CMB radiation, for the scalar gravitational perturbations which dominate the temperature fluctuations in inflationary cosmologies give rise to E-mode, or gradient-type, polarization exclusively [25,26]. The Faraday effects provide a mechanism by which B-mode, or curl-type, polarization can be produced from an initial state of E-mode polarization; ultimately, we wish to interpret the B-mode polarization as a constraint on DM with a magnetic moment. A variety of sources of B-mode polarization exist, however, and it is important to separate the possibilities. Let us enumerate some of them explicitly. Primordial tensor or vector gravitational perturbations in the CMB can give rise to B-mode polarization [25,26], and B-mode polarization can be generated from primordial E-mode polarization via gravitational lensing [27]. Magnetic fields can also imprint B-mode polarization. Primordial magnetic fields can do this both through the perturbations they engender [28], as well as through the GE Faraday rotation they mediate [29]. Magnetic fields in galactic clusters [24] can also give rise to GE Faraday rotation [30], impacting the CMB polarization at small angular scales [25,26,31]. The GE Faraday effect is distinguished by its ω^{-2} frequency dependence; the B-polarizations engendered by gravitational lensing and radiation are frequency independent.

The GM Faraday effect can operate if the medium has a magnetization; this can occur if a nonzero magnetic field exists while the DM is still in thermal equilibrium in the early Universe. These conditions suffice to polarize it to the degree given by Eq. (8); for cold DM, H/T is a constant over the cosmological expansion. Once DM decouples there is no mechanism to polarize it, and its primordial polarization cannot be lost. The primordial magnetic field changes slowly with respect to the Larmor precession rate, so that the DM magnetization can track the magnetic field as the Universe evolves. In contrast, the electron's charge drives $e + p \leftrightarrow H + \gamma$ as the Universe cools and washes out any primordial polarization it possesses. At much later time scales, the reionized electrons may acquire a nonzero magnetization, but their dilute nature make the associated B-mode polarization immeasurably small. Thus a nonzero, frequency-independent B-mode polarization, induced through GM Faraday rotation, can be attributed to the presence of DM with a nonzero magnetic moment. This effect, in turn, is signaled by the presence of frequency-independent EB cross-correlation power spectra in the CMB. Recent studies of WMAP and BOOMERANG data provide mild evidence for this effect [32], and future studies at PLANCK and CMBpol can provide sharpened constraints [33].

Constraining DM.—We now consider how the GM Faraday effect can be used to constrain models of DM. To evaluate the Faraday rotation we must integrate over the past light cone of the photon, including the cosmological scale dependence of the DM density. We consider the Faraday rotation accrued through the transit of cold DM, so that the scale dependence of the magnetic field and temperature cancel; we assume, moreover, the ratio of these quantities to be constant. Thus we modify Eq. (9)

$$\int_0^l dx n(x) \rightarrow n_o c \int_0^z dz' H(z')^{-1}(1+z')^3 \equiv n_o \tilde{l} \quad (13)$$

to define the effective path length $\tilde{l}$, so that $\phi_0 = \mu^2 \gamma H^o_{\rm prim} n_o \tilde{l}/2ck_B T_o$, where $H^o_{\rm prim}$, n_o, and T_o are the primordial magnetic field, DM number density, and temperature, all scaled to the present epoch. We solve for $H(z)$, the Hubble constant at a redshift of z, using the Friedmann equation in a flat ΛCDM cosmology with a matter energy density of $\Omega_M = 0.27$ and with $H_o = 71\ {\rm km\,s^{-1}\,Mpc^{-1}}$ [34]. For a spin-1/2 DM particle of mass M we define the magnetic moment $\mu \equiv \kappa\mu_M$, so that κ is the Pauli moment, as well as the gyromagnetic ratio $\gamma = 2\kappa\mu_M/\hbar$ with $\mu_M = e/2M$. DM has been established in the recombination era [2], so that we compute the angle ϕ_0 engendered by CMB photons propagating from $z \sim 1100$ to the present. To estimate the present-day DM temperature we consider galactic DM and use the gravitational infall velocity, assuming a Maxwell-Boltzmann distribution in galactic DM velocities, to determine that the root-mean-square velocity obeys $v_{\rm rms}/c = \sqrt{3k_B T/Mc^2}$. Thus

$$\phi_0 \sim 3.6 \times 10^{-18} \frac{\rm cm^3}{\mu{\rm G\,Mpc}} \left(\frac{\mu}{\mu_B}\right)^3 \left(\frac{m}{M}\right)^2 \times \left(\frac{v_{\rm rms}}{c}\right)^{-2} n_o[{\rm cm^{-3}}] H^o_{\rm prim}[\mu{\rm G}]\, \tilde{l}[{\rm Mpc}], \quad (14)$$

where $n_o \sim 2.17 \times 10^{-3}\ {\rm cm^{-3}}$, noting $n_o \equiv \rho_{\rm cdm}/m_e$ and $\rho_{\rm cdm} \sim 1.98 \times 10^{-30}\ {\rm g\,cm^{-3}}$ [34], $v_{\rm rms} \sim 200$ km/s, and $\tilde{l} \sim 1.3 \times 10^{10}$ Mpc. We can consider light cold dark matter because its annihilation cross section is mediated by its magnetic moment [35]. Some observational evidence suggests that M is of MeV scale [36]. Using the bound $H^o_{\rm prim} \lesssim 10^{-3}\ \mu$G, for primordial magnetic fields coherent across the present horizon [37], we find a bound of $|\kappa| \lesssim 0.8$ if $M = m/10$ and if ϕ_0 can be determined to $\phi_0 \sim 10^{-2}$ rad. Precision electroweak measurements also constrain the magnetic moment [9]. The quantity $\Delta\hat{r}$ represents the radiative corrections to the relationship between the fine-structure constant α, the Fermi constant G_F, and the $W^\pm$ and Z masses, M_W and M_Z [38]; the difference between the empirically determined value of $\Delta\hat{r}$ and that computed in the standard model provides a window $\Delta\hat{r}^{\rm new}$ to which a DM particle can contribute. Thus we find from the vacuum polarization correction to the photon self-energy, with $a \equiv (M_Z/M)^2 \gg 1$,

$$\Delta\hat{r}^{\rm DM} \sim -\kappa^2 \frac{\alpha}{4\pi}\left(\frac{a}{6}\log a - \frac{a}{9} + O(1)\right)\left(1 - \frac{M_Z^2}{M_c^2}\right)^{-4},$$

where we include a form factor at each vertex with a compositeness scale of M_c. With $\Delta\hat{r}^{\rm new} < 0.0010$ at 95% CL [39], we find with $M = m/10$ that $|\kappa| < 3.4 \times 10^{-7}$ if $M_c \to \infty$, which relaxes to $|\kappa| < 1.5$ if $M_c = 2$ GeV, e.g., We thus conclude that a useful constraint on κ from a Faraday rotation measurement is possible.

Summary.—A Faraday effect also exists for light transiting a dark medium of electrically neutral particles with nonzero magnetic moments in an external magnetic field. We have shown that this possibility can serve as a new source of B-mode polarization in the CMB and that it can be disentangled from other sources. Thus a nonzero effect due to such DM can be identified, if it exists, with the implication that supersymmetric models do not provide an exclusive solution to the DM problem. The GM Faraday effect can be used to probe the nature and distribution of DM, to realize a picture of our Universe shaped by what we *observe*, rather than by what we believe to be so.

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[1] F. Zwicky, Helv. Phys. Acta **6**, 110 (1933).
[2] D. N. Spergel *et al.* (WMAP Collaboration), Astrophys. J. Suppl. Ser. **148**, 175 (2003); M. Tegmark *et al.* (SDSS Collaboration), Phys. Rev. D **69**, 103501 (2004).
[3] M. Milgrom, Astrophys. J. **270**, 365 (1983); J. Bekenstein and M. Milgrom, Astrophys. J. **286**, 7 (1984); J. D. Bekenstein, Phys. Rev. D **70**, 083509 (2004); **71**, 069901(E) (2005);
[4] N. Arkani-Hamed, H. C. Cheng, M. A. Luty, and S. Mukohyama, J. High Energy Phys. 05 (2004) 074.
[5] D. Clowe *et al.*, arXiv:astro-ph/0608407.
[6] S. Tremaine and J. E. Gunn, Phys. Rev. Lett. **42**, 407 (1979).
[7] J. L. Feng, J. Phys. G **32**, R1 (2006).
[8] M. Pospelov and T. ter Veldhuis, Phys. Lett. B **480**, 181 (2000).
[9] K. Sigurdson *et al.*, Phys. Rev. D **70**, 083501 (2004); **73**, 089903(E) (2006).
[10] D. N. Spergel and P. J. Steinhardt, Phys. Rev. Lett. **84**, 3760 (2000).
[11] N. Arkani-Hamed, S. Dimopoulos, G. R. Dvali, and J. March-Russell, Phys. Rev. D **65**, 024032 (2001).
[12] T. Appelquist, H. C. Cheng, and B. A. Dobrescu, Phys. Rev. D **64**, 035002 (2001).
[13] G. Servant and T. M. P. Tait, Nucl. Phys. **B650**, 391 (2003).
[14] H. C. Cheng, J. L. Feng, and K. T. Matchev, Phys. Rev. Lett. **89**, 211301 (2002).
[15] K. Hsieh, R. N. Mohapatra, and S. Nasri, Phys. Rev. D **74**, 066004 (2006).
[16] A. G. Lyne and F. G. Smith, Nature (London) **218**, 124 (1968).
[17] D. Polder, Philos. Mag. **40**, 99 (1949).
[18] C. L. Hogan, Rev. Mod. Phys. **25**, 253 (1953).
[19] S. J. Orfanidis, ‘‘Electromagnetic Waves and Antennas,’’ http://www.ece.rutgers.edu/~orfanidi/ewa.
[20] R. N. Manchester *et al.*, Mon. Not. R. Astron. Soc. **328**, 17 (2001); J. L. Han *et al.*, Astrophys. J. **642**, 868 (2006), and references therein.
[21] P. P. Kronberg, Rep. Prog. Phys. **57**, 325 (1994); L. M. Widrow, Rev. Mod. Phys. **74**, 775 (2002).
[22] V. Bargmann, L. Michel, and V. L. Telegdi, Phys. Rev. Lett. **2**, 435 (1959).
[23] A. Abragam, *The Principles of Nuclear Magnetism* (Clarendon Press, Oxford, 1978), p. 2.
[24] T. E. Clarke, P. P. Kronberg, and H. Boehringer, Astrophys. J. **547**, L111 (2001).
[25] U. Seljak and M. Zaldarriaga, Phys. Rev. Lett. **78**, 2054 (1997); M. Zaldarriaga and U. Seljak, Phys. Rev. D **55**, 1830 (1997).
[26] M. Kamionkowski, A. Kosowsky, and A. Stebbins, Phys. Rev. Lett. **78**, 2058 (1997); Phys. Rev. D **55**, 7368 (1997).
[27] M. Zaldarriaga and U. Seljak, Phys. Rev. D **58**, 023003 (1998).
[28] T. R. Seshadri and K. Subramanian, Phys. Rev. Lett. **87**, 101301 (2001); A. Mack, T. Kahniashvili, and A. Kosowsky, Phys. Rev. D **65**, 123004 (2002); K. Subramanian, T. R. Seshadri, and J. D. Barrow, Mon. Not. R. Astron. Soc. **344**, L31 (2003).
[29] A. Kosowsky and A. Loeb, Astrophys. J. **469**, 1 (1996); E. S. Scannapieco and P. G. Ferreira, Phys. Rev. D **56**, R7493 (1997); C. Scoccola, D. Harari, and S. Mollerach, Phys. Rev. D **70**, 063003 (2004); A. Kosowsky *et al.*, Phys. Rev. D **71**, 043006 (2005).
[30] H. Ohno *et al.*, Astrophys. J. **584**, 599 (2003).
[31] W. Hu and M. J. White, Phys. Rev. D **56**, 596 (1997).
[32] B. Feng *et al.*, Phys. Rev. Lett. **96**, 221302 (2006).
[33] J. Q. Xia, H. Li, G. B. Zhao, and X. Zhang, arXiv:0708.1111.
[34] D. N. Spergel *et al.* (WMAP Collaboration), Astrophys. J. Suppl. Ser. **170**, 377 (2007).
[35] B. W. Lee and S. Weinberg, Phys. Rev. Lett. **39**, 165 (1977).
[36] J. F. Beacom, N. F. Bell, and G. Bertone, Phys. Rev. Lett. **94**, 171301 (2005).
[37] P. Blasi, S. Burles, and A. V. Olinto, Astrophys. J. **514**, L79 (1999).
[38] W. J. Marciano, Phys. Rev. D **60**, 093006 (1999), and references therein.
[39] W.-M. Yao *et al.* (Particle Data Group), J. Phys. G **33**, 1 (2006) and 2007 partial update: http://pdg.lbl.gov/2007/reviews/stanmodelrpp.pdf.