Cosmic Quarkonium: A Probe of Dark Matter

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If our galactic halo is composed of heavy (several gigaelectronvolts), weakly interacting particles, pair annihilation into a heavy-quark–antiquark bound state plus a monochromatic photon can produce potentially observable sharp peaks in the diffuse cosmic-γ-ray background.

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The nature of the matter forming dark galactic halos is an important unanswered question for both astrophysics and elementary-particle physics.[1] It is essential to know as many signatures as possible for each plausible candidate. Here we explain how heavy, neutral, weakly interacting particles could produce monochromatic peaks at energies of a few gigaelectronvolts in the diffuse cosmic-γ-ray spectrum. The mechanism is the annihilation of two halo particles into a virtual quark-antiquark pair, $\bar{Q}Q$; one of the quarks then radiates a hard photon of definite energy, and the pair becomes a quarkonium state of definite mass. If this process occurs sufficiently often, the radiated photons will form a series of peaks, one for each allowed quarkonium state, in the observed γ-ray spectrum.

Hypothetical heavy-particle candidates for halo dark matter include the photino, Higgs fermion, and scalar neutrino predicted by supersymmetric models, and a heavy neutrino (with either a Dirac or Majorana mass). Let us denote the dark-matter particle as λ. To be definite, we will concentrate on the case that λ is a Majorana fermion (photino, Higgs fermion, Majorana neutrino), but emphasize that our proposed signature could occur in other cases as well. Supposing that λ is a Majorana fermion enhances our signature, since at low energies the $\lambda\lambda \to \bar{Q}Q$ annihilation cross section is proportional to the squared mass of the outgoing quark Q.[2] Thus heavy quarks (and leptons) are the only ones produced. (Here we are assuming that the properties of λ are not specifically arranged to suppress $\bar{c}c$, $\bar{b}b$, or $\bar{t}t$ production somehow.)

The process $\lambda\lambda \to \psi\gamma$, where ψ designates a generic $\bar{Q}Q$ quarkonium state, proceeds via the diagrams of Fig. 1. If λ is one of the previously mentioned Majorana fermions, the effective $\lambda\lambda\bar{Q}Q$ interaction is

$$L_{\text{int}} = \bar{\lambda}\gamma_\mu\gamma_5\lambda\bar{Q}\gamma^\mu(a+b\gamma_5)Q. \qquad (1)$$

At the low velocities ($v \sim 10^{-3}c$) associated with halo particles, only the s-wave part of the annihilation cross section is important. Fermi statistics then demand that the $\lambda\lambda$ pair be in a state with $J^{PC}=0^{-+}$. (Note that this is different from high-energy e^+e^- annihilation, where the e^+e^- pair is in a 1^{--} state.) We now concentrate on the case that ψ is a vector meson with $J^{PC}=1^{--}$; these are the best studied quarkonium states. The process $\lambda\lambda \to \psi\gamma$ then occurs via the parity-conserving coefficient b, which also governs the low-energy annihilation of $\lambda\lambda$ pairs into free $\bar{Q}Q$ pairs. In the limit $v \to 0$, the annihilation cross section for $\lambda\lambda \to \bar{Q}Q$ is[2,3]

$$\sigma_{\bar{Q}Q} = (2\pi v)^{-1} b^2 m_Q^2 (1 - m_Q^2/m_\lambda^2)^{1/2}, \qquad (2)$$

with $\hbar = c = 1$. To calculate $\sigma_{\psi\gamma}$, we treat ψ as a fundamental massive vector particle coupling to $\bar{Q}Q$ via the interaction

$$L_{\text{int}} = f\psi_\mu\bar{Q}\gamma^\mu Q, \qquad (3)$$

where f is a momentum-independent coupling constant. Furthermore, since ψ is a narrow resonance, we can treat it as if it were stable.[4] These approximations

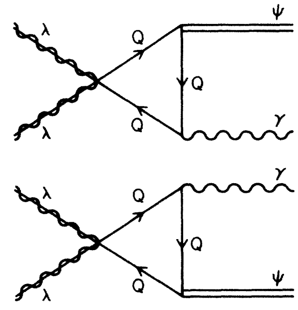

FIG. 1. Feynman diagrams for $\lambda\lambda \to \psi\gamma$.

yield the following amplitude to $\lambda\lambda \to \psi\gamma$:

$$T_{\psi\gamma} = (2\pi^2)^{-1} 3qefb\epsilon_{\mu\nu\rho\sigma}\epsilon_\psi^\mu \epsilon_\gamma^\nu p_\gamma^\rho (\bar{u}\gamma^\sigma\gamma_5 v)[-A + I(m_\lambda, m_\psi, m_Q)],$$

$$I(m_\lambda, m_\psi, m_Q) = 2\pi^{-2} i m_Q^2 \int d^4k\,[k^2 + m_Q^2 - i\epsilon]^{-1}[(k+p_\psi)^2 + m_Q^2 - i\epsilon]^{-1}[(k-p_\gamma)^2 + m_Q^2 - i\epsilon]^{-1}. \quad (4)$$

Hence $q = \frac{2}{3}$ or $-\frac{1}{3}$ is the electric charge of Q, ϵ_ψ and ϵ_γ are the polarization four-vectors of the ψ meson and the photon, p_ψ and p_γ are their four-momenta, $\bar{u}$ and v are spinors for the incoming λ particles (normalized as $\bar{u}u = 2m_\lambda$), and A is a regularization-dependent constant that accounts for the triangle anomaly. We will set $A = 0$, since any nonzero A leads to an unphysically large $\sigma_{\psi\gamma}$ when $m_\lambda >> m_Q$. This is an artifact or our letting the coupling f be independent of momentum, which is certainly incorrect for quark momenta much larger than m_Q. The remaining integral is dominated by loop momenta of order m_Q, and so $f = \text{const}$ should be an adequate approximation. After evaluating the integral, we find

$$I(m_\lambda, m_\psi, m_Q) = \left(\frac{m_Q^2}{m_\lambda^2}\right)\left(1 - \frac{m_\psi^2}{4m_\lambda^2}\right)^{-1}\left\{\left[\chi\left(\frac{m_\lambda^2}{m_Q^2}\right) - \chi\left(\frac{m_\psi^2}{4m_Q^2}\right)\right] + i\pi\left[\theta(m_\lambda - m_Q)\phi\left(\frac{m_\lambda^2}{m_Q^2}\right) - \theta(m_\psi - 2m_Q)\phi\left(\frac{m_\psi^2}{2m_Q^2}\right)\right]\right\}, \quad (5)$$

$$\phi(x) = \tanh^{-1}[(1 - 1/x)^{1/2}],$$

$$\chi(x) = \begin{cases} \phi(x)^2 - \frac{1}{4}\pi^2, & x \geq 1, \\ -\{\tan^{-1}[(1/x - 1)^{-1/2}]\}^2, & x \leq 1, \end{cases}$$

where $\theta(x)$ is the step function. The final result for $\sigma_{\psi\gamma}$, averaged over initial spins and summed over final polarizations, is

$$\sigma_{\psi\gamma} = (8\pi^4 v)^{-1}(3q)^2 \alpha f^2 b^2 m_\lambda^2 (1 - m_\psi^2/4m_\lambda^2)^3 |I(m_\lambda, m_\psi, m_Q)|^2. \quad (6)$$

We still need to know f^2. We expect that f^2 is of order unity for any quarkonium state. For the $J/\psi(3100)$ and $\psi(3685)$, f^2 has been calculated. The parameter g of Novikov *et al.*[5] is related to f via

$$|g| = |3f\Pi(m_\psi^2)/m_\psi^2|, \quad (7)$$

where $\Pi(m^2)$ is defined on p. 63 of Ref. 5. For $m_\psi^2 = 4m_Q^2$,

$$|3\Pi(m_\psi^2)/m_\psi^2| = 2/3\pi^2. \quad (8)$$

This result is fairly insensitive to variations in $m_\psi^2/4m_Q^2$; it would be 3% smaller for $m_Q = 1.25$ GeV. With use of Eq. (8), the values of g quoted in Ref. 5 yield

$$f_{J/\psi(3100)}^2 = 3.6,$$

$$f_{\psi(3685)}^2 = 1.2. \quad (9)$$

If we form the branching ratio $\sigma_{\psi\gamma}/\sigma_{\bar{Q}Q}$, the parameter b^2 drops out. This branching ratio, for $J/\psi(3100)$ production, is plotted in Fig. 2 for the two cases $m_Q = \frac{1}{2}m_\psi$ and $m_Q = 1.25$ GeV [the latter is favored by the analysis of Ref. 5 which leads to Eq. (9)]. For most of the range of m_λ, our computed branching ratio is 10^{-3} or larger. We expect this to be the case for b-quarkonium and t-quarkonium as well as charmonium.

The energy of the photon is

$$E_\gamma = m_\lambda - m_\psi^2/4m_\lambda. \quad (10)$$

Thus we expect a set of monochromatic lines in the high-energy γ-ray spectrum with energies given by Eq. (10) using (for charmonium) $m_\psi = 3100$, 3685, 3770, etc., MeV, or (for b-quarkonium) $m_\psi = 9460$, 10025, etc., MeV. The widths of the peaks are determined by

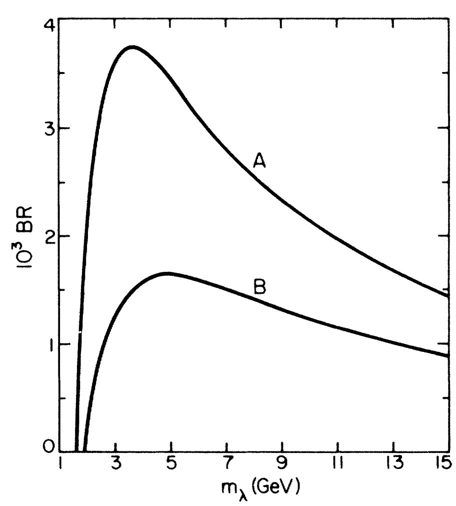

FIG. 2. The branching ratio $\sigma_{\psi\gamma}/\sigma_{\bar{Q}Q}$, times 10^3, vs the mass of the halo particle for (curve A) $m_Q = \frac{1}{2}m_\psi$ and (curve B) $m_Q = 1.25$ GeV.

Doppler broadening to be

$$\Delta \simeq (v/c) m_\lambda \simeq 10^{-3} m_\lambda. \quad (11)$$

To estimate the γ-ray flux corresponding to one of the peaks, we need to know $\sigma_{\bar{Q}Q}$. If the halo particles were in thermal equilibrium at very high temperatures, then we know that the thermally averaged annihilation cross section times relative velocity (at the temperature at which the particles went out of equilibrium) is approximately $\langle \sigma_A v \rangle \simeq 10^{-26} \Omega_\lambda^{-1}$ cm^3 s^{-1}, where Ω_λ is the mean mass density of λ particles in units of the critical density needed for closure.[6] The total mass known to be in dark halos corresponds to $\Omega_\lambda \simeq 0.1$, a value close to that obtained by astronomical determinations of the overall value of Ω. At low energies, only the s wave contributes to σ_A, resulting in a value of $\sigma_A v$ somewhat lower than $10^{-26} \Omega_\lambda^{-1}$ cm^3 s^{-1} as $v \to 0$. This effect is most significant for heavy Majorana fermions, but in this case we expect $\sigma_{\bar{Q}Q}$ to be a large fraction of σ_A. For illustrative purposes we will take $\Omega_\lambda = 0.1$, $\sigma_{\bar{Q}Q} v = 3\times 10^{-27} \Omega_\lambda^{-1}$ cm^3 s^{-1}, and $\sigma_{\psi\gamma} v = 10^{-29} \Omega_\lambda^{-1}$ cm^3 s^{-1}. Taking our halo to have mean mass density $\rho_\lambda = 0.3$ GeV/cm^3 and effective radius $R = 40$ kpc, we get a γ-ray line flux of

$$F_{\rm line} \simeq \sigma_{\psi\gamma} v R (\rho_\lambda / m_\lambda)^2 (4\pi\ {\rm sr})^{-1} \simeq (10^{-8}\ {\rm cm^{-2}\ s^{-1}\ sr^{-1}}) [(3\ {\rm GeV})/m_\lambda]^2. \quad (12)$$

Is our predicted line flux observable? The NASA Gamma Ray Observatory (GRO) will have an effective area of $\sim 10^3$ cm^2 sr and energy resolution of $\sim 15\%$ near 3 GeV. The measured differential γ-ray flux below 100 MeV is[7]

$$dF_\gamma / dE_\gamma \simeq (4\times 10^{-7}\ {\rm cm^{-2}\ s^{-1}\ sr^{-1}\ GeV^{-1}}) [(1\ {\rm GeV})/E_\gamma]^{2.7}. \quad (13)$$

If we assume that the same power law holds to much higher energies, and take $m_\lambda \simeq E_\gamma \simeq 3$ GeV, the GRO would see about 300 signal events from the line flux and 300 background events in one year. Of course, all our estimates have large uncertainties, and it is entirely possible that the line flux would stand out clearly. Since the linewidth is only $\sim 10^{-3} m_\lambda$, a larger-effective-area experiment with improved energy resolution of $\sim 0.1\%$ would be able to extract a definitive signal.

To conclude, if halo dark matter is composed of heavy, neutral, weakly interacting particles, a possibly observable signature is a series of monochromatic γ-ray lines with energies given by Eq. (10). We have carried through a definite analysis for Majorana fermions (such as photinos, Higgs fermions, or Majorana neutrinos) as the halo particles, annihilating to produce a 1^{--} quarkonium state plus the monochromatic photon. Observation of these lines would be incontrovertible evidence for a presently unknown heavy particle as halo dark matter. As a bonus, the mass of the particle would be measured to within the detector's energy resolution.

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