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Vector dark matter detection using the quantum jump of atoms

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ABSTRACT

The hidden sector U(1) vector bosons created from inflationary fluctuations can be a substantial fraction of dark matter if their mass is around 10^{-5} eV. The creation mechanism makes the vector bosons' energy spectral density $\rho_{cdm}/\Delta E$ very high. Therefore, the dark electric dipole transition rate in atoms is boosted if the energy gap between atomic states equals the mass of the vector bosons. By using the Zeeman effect, the energy gap between the 2S state and the 2P state in hydrogen atoms or hydrogen like ions can be tuned. The $2S$ state can be populated with electrons due to its relatively long life, which is about 1/7 s. When the energy gap between the semi-ground $2S$ state and the 2P state matches the mass of the cosmic vector bosons, induced transitions occur and the 2P state subsequently decays into the 1S state. The $2P \to 1S$ decay emitted Lyman-α photons can then be registered. The choices of target atoms depend on the experimental facilities and the mass ranges of the vector bosons. Because the mass of the vector boson is connected to the inflation scale, the proposed experiment may provide a probe to inflation.

1. Introduction

The existence of dark matter has been widely accepted due to the discovery of ample evidence such as the galactic rotational curves, the large scale structures, the gravitational lensings and the observations of the cosmic microwave background anisotropy etc. [1–8]. The properties of dark matter particles include that they are non-baryonic, weakly interacting and stable. There are many theories that can provide a proper dark matter candidate and a large part of these dark matter candidates can be categorized into two classes: 1, axions/axion like particles (ALPs) [9–17,29] created by the misalignment mechanism and massive vector dark bosons [20–22,29] created from the misalignment mechanism or inflationary fluctuations; and 2, weakly interacting massive particles (WIMPs) such as the TeV scale supersymmetric particles [23] created from the thermal production in hot plasma. The axions/ALPs and the vector dark matter are bosons with a typically smaller mass (<eV) and higher phase space density, which makes them behave more like waves or condensate. The WIMPs are much heavier (>GeV) and have a thermal distribution so they behave more like particles. Experiments searching for axions/ALPs, vector dark bosons, or WIMPs are currently proceeding or in planning in laboratories around the world [24–41].

The hidden massive U(1) vector boson, dark photons, can be a substantial fraction of dark matter. The cosmic dark photon populations are generally non-thermally created by the misalignment mechanism and/or from inflationary fluctuations. The inflationary fluctuation creation of dark photons [18,19,22] is appealing because it connects the dark matter mass with the Hubble scale of inflation. It is found that although the well known scalars and tensors power spectra created from the inflation fluctuations are scale invariant, the vector power spectrum peaks at intermediate wave length. Therefore, long-wavelength, isocurvature perturbations are suppressed so the production is consistent with the cosmic microwave background anisotropy observations.

The number density N of sub eV dark photons is currently very high, of the order of $N = \rho_{cdm}/M \gtrsim 3*10^8/\mathrm{cm}^3$, where ρ_{cdm} is the dark matter energy density. Therefore we can treat the cosmic dark photons as a classical field. The dark photon field is mostly composed by the dark electric filed $|\vec{E}'_0| \approx \sqrt{2\rho_{cdm}}$, and in addition, the cosmic dark photons have a very high phase space density because their velocity dispersion is the order of $\delta v \sim v \sim 10^{-3}c$. Thus the electric dipole transition induced by the dark photons in an atom is enhanced. This makes the quantum transitions of atoms or ions a suitable method for detecting cosmic dark photons.

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Many proposed and current experimental studies are looking for cosmic dark photons [28–30,34,36,38–41]. The proposed and current experiments include electromagnetic resonator experiments (such as the ADMX), LC oscillator experiments, Xenon10, and the newly proposed absorption of dark matter by a superconductor. Each experiment suits a different mass range. The proposed study presented here is suitable for $M \lesssim 2*10^{-4}$ eV with a higher sensitivity when the mass is smaller, please refer to Fig. 3.

2. Vector dark matter

The hidden U(1) vector boson has a small mass and a very weak coupling to the standard model photon. Let us use A'_μ to denote the new vector field, the effective Lagrangian therefore can be written as:

$$\mathcal{L} = -\frac{1}{4}(F^{\mu\nu}F_{\mu\nu} + F'^{\mu\nu}F'_{\mu\nu} + 2\chi F'^{\mu\nu}F_{\mu\nu}) - \frac{M^2}{2}A'_\mu A'^\mu - e\bar{\psi}\gamma^\mu\psi A_\mu + \dots \ , \tag{1}$$

where $F'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu$, χ is the mixing parameter, M is the mass of the hidden U(1) boson, and ψ are fermions with ordinary electric charge in the standard model sector. The mixing term results in oscillations between the two U(1) bosons. We can redefine the field to mass eigenstates to get a massive vector boson and a massless vector boson without mixing up to $O(\chi^2)$:

$$A_\mu \to A_\mu - \chi A'_\mu$$
$$\mathcal{L} = -\frac{1}{4}(F^{\mu\nu}F_{\mu\nu} + F'^{\mu\nu}F'_{\mu\nu}) - \frac{M^2}{2}A'_\mu A'^\mu - e\bar{\psi}\gamma^\mu\psi A_\mu - \chi e\bar{\psi}\gamma^\mu\psi A'_\mu + \dots \ . \tag{2}$$

We see that the new massive vector boson, the dark photon, couples to the standard model charged fermions very weakly with an effective coupling constant χe. The value of the two parameters, the mass M of the dark photon, and the coupling suppression factor χ are crucial to the phenomenologies of this model.

Cosmic dark photons can be created from inflationary fluctuations. Inflation during the early universe addresses many cosmological puzzles and is therefore a compelling model of the evolution of the universe [42,43]. The inflationary fluctuation that produces dark photons is purely gravitational thus only requires the dark photons to couple to the standard model sector particles weakly to avoid over production in hot plasma. The large scale isocurvature perturbations of the dark photons are suppressed so the power spectrum is dominated by adiabatic perturbations, which is consistent with current observations. The abundance of dark matter in this scenario is determined by the Hubble scale of inflation and the mass of dark photons:

$$\Omega_{A'}/\Omega_{cdm} = [M/(6*10^{-6}\,\text{eV})]^{1/2} \times [H_I/10^{14}\,\text{GeV}]^2 \ , \tag{3}$$

where H_I is the Hubble scale of inflation.

The cosmic dark photons are currently free streaming. Using the Lorentz gauge condition

$$\partial_\mu A'^\mu = 0 \ , \tag{4}$$

then the field obeys the wave equation: $(\partial_\mu\partial^\mu + M^2)A'_\mu = 0$. As the cold dark matter particles are non-relativistic, in the momentum space we have:

$$A'_\mu(\vec{v}, t) \approx A'_\mu e^{i(-Mt - \frac{M}{2}v^2 t + M\vec{v}\cdot\vec{x})} \ , \tag{5}$$

up to the second order of velocity v. From Eq. (4) and Eq. (5) we find that the time component of the vector field is suppressed by velocity v and is therefore small. For our subsequent discussions it is convenient to use the dark electric field $\vec{E}'$ and dark magnetic field $\vec{B}'$ instead of the vector field A'_μ. Because the spacial part of the vector field is much larger than the time part, we have $\vec{E}' = -\partial\vec{A}'/\partial t \approx -iM\vec{A}'$ and $\vec{B}' = \nabla \times \vec{A}' \approx 0$. The energy distribution is:

$$I_{A'} = \frac{\rho_{cdm}}{\Delta E} \approx \frac{0.3\text{GeV/cm}^3}{(1/2)M\Delta v^2} = \frac{6*10^5}{Mc^2}\ \text{GeV/cm}^3, \tag{6}$$

where $\Delta v \sim 10^{-3}c$ is the typical estimate of the cold dark matter velocity distribution. As $\Delta v \approx 2\sqrt{T/M}$, where T is the effective temperature of the dark matter, the energy distribution is higher when the dark matter is colder. Literature [44] finds $T_{today}/M \sim 10^{-14}$ which corresponds to a $\Delta v \sim 10^{-7}c$. This result will boost the number of events or the signal of our experiment order of 10^8 comparing to the $\Delta v \sim 10^{-3}c$ case (see Eq. (13)). In the following discussions, we still use the more conservative estimation $\Delta v \sim 10^{-3}c$.

3. Design of the experiment

The hidden photon couples to fermions via:

$$\mathcal{L}_{\bar{\psi}\psi A'} = -\chi e\bar{\psi}\gamma^\mu\psi A'_\mu \ , \tag{7}$$

where ψ is the electron field and χ is generally suppressed by loops in a more fundamental theory. The dark photons created from inflationary fluctuations have a mass of 10^{-5} eV if they are a major part of the dark matter. However, the creation mechanism itself puts little constraint on the coupling χ.

The Compton wavelength of the dark photon is $\lambda = 2\pi(M)^{-1}$. If we use the standard assumption that $M \sim 10^{-5}$ eV, the wave length is much larger than the Bohr radius $a_0 \approx 5*10^{-11}$ m of atoms. Therefore the dark electric field can be treated as a homogeneous field in atoms:

$$|\vec{E}| = \sqrt{2\rho_{cdm}}cos(Mt) \ . \tag{8}$$

In the non-relativistic limit, Eq. (7) leads to the Hamiltonian:

$$H = -\chi e(\vec{E}'\cdot\vec{x}) - [\chi e/(4M)]\vec{\sigma}\cdot\vec{B}' + \dots \ , \tag{9}$$

where σ is the Pauli matrices. We see that the first term is similar to the coupling of the electric dipole interaction and the second term plays the role of the magnetic momentum interaction. The second term is negligible when the dark magnetic field is small. The dark dipole coupling of atoms cause $\Delta l = \pm 1$, $\Delta m = 0, \ \pm 1$ transitions if the energy gap between two states matches the energy of the dark photons, where l is the orbital angular momentum and m is the third component of angular momentum. The energy gap between two states can be adjusted by using the Zeeman effect with an external magnetic field $\vec{B}$ (see Fig. 1). The general Hamiltonian of the Zeeman effect is $H = -\vec{\mu}\cdot\vec{B}$, where $\vec{\mu}$ is the magnetic moment of the electron. The mass range that can be scanned is limited by the available magnetic field strength. Given today's technology, $B \sim 18$ T [45], we have $M \sim 240$ GHz.

The transition rate R of atoms or ions from an initial state $|\ i>$ to an excited state $|\ f>$ is

$$R = 2\pi\chi^2 e^2 \frac{<|\vec{E}'_0|^2>}{max(\Delta\omega_{A'}, \Delta\omega_{if}, \Delta\omega)}|\ \vec{r}_{i,\ f}\ |^2 \ , \tag{10}$$

where $|\vec{r}_{i,\ f}|$ is the quantum matrix element between states $|\ i>$ and $|\ f>$, $\Delta\omega_{A'} = \frac{1}{2}M\Delta v^2$ is the bandwidth of cosmic dark photons, $\Delta\omega_{if} = 1/\tau$ is the bandwidth of the excited state, $\Delta\omega =$