Search for Dark Matter Axions with Rydberg Atoms in a Resonant Cavity

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Based on quantum electronic techniques, novel methods to search for dark matter axions have been proposed. The experimental systems are being used and/or developed to detect axions in the mass range between 5 to 12 μeV.

Keywords: Dark matter in the Universe/ Cosmic axions/ Quantum electronics/ Rydberg atoms/ Axion-photon-atom interactions in a resonant cavity

It is now well established that there exists the dark matter in the Universe which exceeds 10 to 100 times more the normal visible baryonic-matter like light-emitting stars. However no definite evidence for the constituent particles of the dark matter has yet been found so far. One of the mostly attractive candidates of the non-baryonic dark matter particles is the axion which is a hypothetical pseudo-scaler particle proposed to solve the so-called strong CP problem in the QCD theory of strong interactions. The mass of the axion is constrained from astrophysical and cosmological arguments and the window still open is from 1 μeV to 1 meV. Due to the extremely weak interactions of axions with the ordinary matter, it is inevitably difficult to detect axions, although a few tries have been reported.

We have proposed a number of novel sensitive methods to search for dark matter particles with quantum electronic methods [1–4]: The most sensitive method (CARRACK: Cosmic Axion Research with Rydberg Atoms in a resonant Cavity in Kyoto) to detect axions among them is to firstly convert the axion into a microwave photon in a resonant cavity via the Primakoff effect in a strong magnetic field [1, 3]. The converted photons are then detected by Rydberg atoms passed through the cavity. The cavity is cooled down to 10 mK so that the background due to thermal blackbody radiations from the wall of the cavity is appreciably suppressed. Since the Rydberg atom is expected to have inherently no noise, this scheme is much more sensitive compared to conventional amplifier-heterodyne method. Schematic diagram of the experimental system with the method is shown in Fig. 1. The axions are converted to microwave photons in the conversion cavity which is in a magnetic field of 7 T. These photons thus produced are transferred to the detection cavity and absorbed by Rydberg atoms. The external magnetic field at the detection cavity is less than 0.9 kG due to the cancellation coils set between the main magnet and the cavity. The inside of the detection cavity made of Nb is kept to be free from magnetic field due to the Meissner effect in

NUCLEAR SCIENCE RESEARCH FACILITY —Beams and Fundamental Reaction—

Scope of research

Particle beams, accelerators and their applications are studied. Structure and reactions of fundamental substances are investigated through the interactions between beams and materials such as nuclear scattering. Tunable lasers are also applied to investigate the structure of unstable nuclei far from stability and to search for as yet unknown cosmological dark-matter particles in the Universe.


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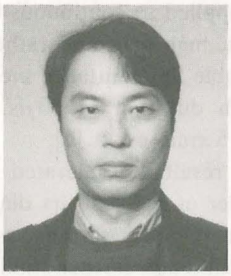
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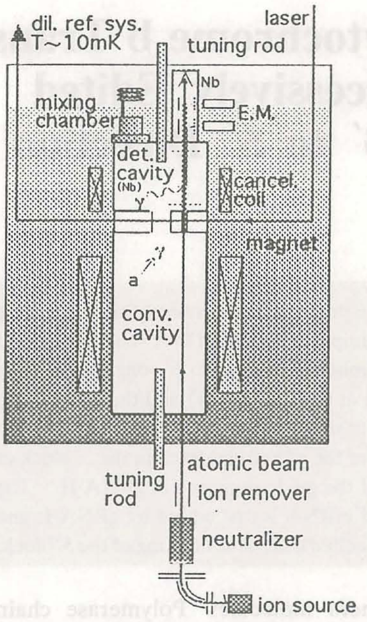

Figure 1. Schematic experimental diagram of CARRACK to search for dark matter axions with Rydberg atoms in a resonant cavity. The detection and the conversion cavities are cooled down to 10 mK with a dilution refrigerator.

superconducting Nb, the critical field of which is 1.2 kG.

The Rydberg atoms, prepared by three-step laser-excitation of alkaline atoms just before entering into the detection cavity, are passed through the detection cavity and analyzed with the field ionization method out of the cavity. In order to get atomic beam with higher velocity than thermal and also with narrow velocity spread, the atomic beam is produced by neutralizing ions accelerated to a suitable energy (200 eV to 5 keV). Both the cavities are cooled down to about 10 mK to suppress the background thermal photons from the cavity wall with a dilution refrigerator (Oxford, Kelvinox 300). Quantum theory of axion-photon-atom interactions in a resonant cavity was developed [5] by taking into account the dissipation effect of the cavity. The vacuum Rabi splitting due to the dressed atom-photon interactions in a resonant cavity arises also in this case. The detection efficiency of the axion-converted photons is thus evaluated precisely from the theory by numerical calculations.

The whole experimental system was divided into several parts and each part has been successfully tested separately with bench-test systems. The dilution refrigerator was installed in this summer. Cooling test was successfully performed, the lowest temperature achieved being 8 mK. A laser system for producing Rydberg atoms was constructed with three diode lasers. The wavelengths of the first and the second stage lasers are stabilized on resonance by using the Doppler-free saturation-absorption spectroscopy with a resonance cell [6]. The frequency stability of these lasers was found to be better enough to continuously excite the levels for more than 5 hours. The wavelength of the third stage laser is varied together with the resonance frequency of the cavity to scan the mass of the axion.

To confirm the excitation of Rydberg atoms with this laser system, a prototype cavity and an atomic beam apparatus were constructed. The cavity can be cooled down to 0.5 K with a liquid ^{3}He cryostat system. The Rydberg states with the principal quantum number (n) of around 40 were successfully excited with the diode laser system and detected with the filed ionization method out of the cavity, thus indicating satisfying performance of the laser-Rydberg system. This experimental system is now being used to search for cosmic axions by directly detecting axions with Rydberg atoms [1, 6]: Due to the axion-electron coupling, the axions are directly absorbed by Rydberg atoms, inducing the transition from the lower to the upper fine-structure states. The cavity is tuned out of the resonance to suppress the excitation of the upper state with photons. With this scheme, the upper limit of the coupling strength of the axion-electron interaction is obtained, giving more severe constraint than the previous laboratory experiments. The mass of the axions now searching for is around 5 μeV.

After finishing the search experiment with the direct detection method mentioned above, the whole experimental parts of CARRACK system are to be assembled. The first run of search with this system is scheduled in the middle of the next year, 1995.

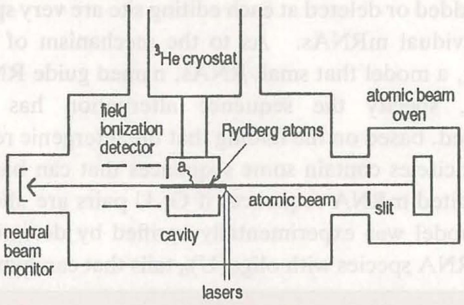

Figure 2. Schematic experimental diagram to search for dark matter axions by directly detecting axions with Rydberg atoms. Due to the axion-electron coupling, the axions are directly absorbed by Rydberg atoms, inducing the transition from the lower to the upper fine-structure states.

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