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Selective Field-Ionization Electron Detector at Low Temperature of 10 mK Range

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Combined with a dilution refrigerator, selective field-ionization detection system with a channel electron multiplier optimized at 10 mK-range temperature was developed. The detection efficiency of the ionized electrons from the n~110 Rydberg states of Rb is 98% at the lowest achieved temperature of 12 mK.

Keywords : Dark matter/axion/Rydberg atoms/field ionization/channel electron multiplier

Highly excited atoms, so called Rydberg atoms, have been utilized for many fields in fundamental physics including cavity quantum electrodynamics, quantum computation, and the quantum measurements as well as their own spectroscopic studies. Recently important application of the Rydberg atoms has been forwarded to detect extremely low-power microwave photons in resonant cavities: indeed the detection of each single microwave photon in a resonant cavity with Rydberg atoms has been utilized to search for dark matter axions in the Universe [1-6]: in this scheme, the axion is first converted to single photon in the strong magnetic field (Primakoff process) and the microwave photons thus produced are absorbed by Rydberg atoms passed through the cavity and the excited Rydberg atoms are then selectively field-ionized and detected (Rydberg-atom cavity detector). The microwave power expected from the dark matter axions in the cavity is extremely small, less than 10^{-26} W.

One of the essential ingredients of the Rydberg-atom cavity detector is the selective field ionization (SFI) system. Specifically the cavity and the SFI system should be cooled down to 10 mK range in order to reduce the background thermal blackbody photons in the cavity, the number of which is still comparable with the expected axion-converted photon number. To our knowledge, no SFI detectors usefull at such low temperature have been developed so far.

The SFI detection system for the above requirement was developed with a channel electron multiplier (CEM) together with a dilution refrigerator of the modified Oxford Kelvinox 300. Overall view of the detection system is shown in Fig.1. The field ionization electrode of a few V/cm was located just outside of the microwave cavity, which is attached to the bottom plate of the mixing chamber of the dilution refrigerator, thus the cavity and the SFI detector being able to be cooled down to 10 mK range. Since the CEM dissipate much higher power (more than mW) than the cooling power of the dilution

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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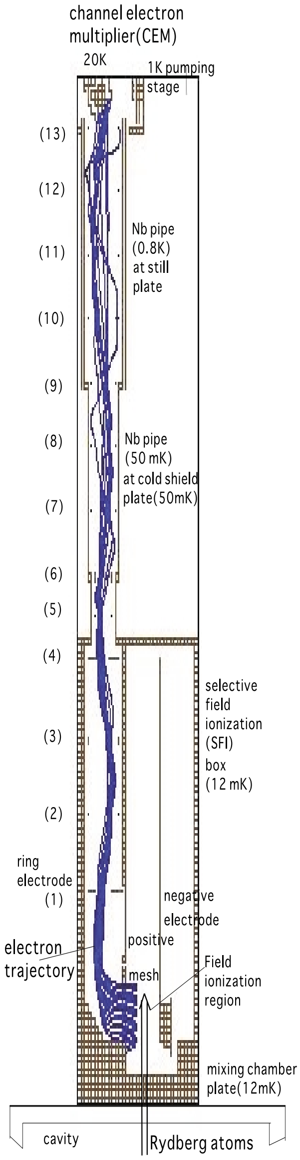

Figure 1. Overall view of the present system for the field ionization electron detector. Rydberg atoms passed through the detection cavity are ionized at the field ionization region shown in the figure. Field ionization electrode is set inside of a Nb box located at the mixing chamber plate of a dilution refrigerator of 12 mK temperature. The ionized electrons are transported to the channel electron multiplier (CEM) at the 1K pumping stage through a series of ring-electrodes of 13 elements. All the ring electrodes are surrounded by Nb pipes to expel out the external megnetic field (except the earth's field). The simulation of the electron transport was done by taking into account the earth's magnetic field as well as Nb pipes and other materials of ground potential. Typical electron trajectories are shown in the figure. Overall transport length of electrons is about 30 cm. The Nb pipes are anchored to the still plate (0.8K) and the cold-shield plate at the heat exchanger region (~50mK), respectively. The CEM electron detector (Channeltron) is heated up to ~ 20 K with a heating coil surrounding it.

refrigerator, the CEM channeltron was located at the 1K pumping stage which is about 30 cm apart from the mixing chamber plate. Thus the ionized electrons resulting from the field ionization process have to be transported with good efficiency from the ionized point to the detector region. A series of ring electrodes was adopted to transport electrons efficiently in the present system where the available space for the trasportation is very limited due to the structure of the dilution refrigerator system.

The ring electrodes are set inside of two Nb pipes and a field ionization box made of Nb, which are anchored to the still plate (0.8K), cold-plate shielding stage at the heat exchanger position (~50 mK), and the mixing chamber stage (~10 mK), respectively. The Nb pipes and box are chosen to expell out the external magnetic field to get rid of the complicated electron trajectories due to the strong external magnetic field applied for the axion conversion into photons. The overall electron trajectory was simulated with the ion trajectory code SIMION where all the relevant materials including the surrounding ground plates and the CEM detector potential were taken into account. In Fig. 1 also shown are typical electron trajectories.

Typical signal of the field-ionized electrons is shown in Fig.2, where the ionized electrons were detected as a function of the second laser wavelength to excite the n=110 Rydberg states of Rb atoms. The overall detection efficiency is 98 % at the lowest achieved temperature of 12 mK. Note that the CEM was heated up to ~ 20K in order to get enough amplification gain of electrons.

Although this SFI system and the CEM electron detector have been developed primarily for the dark matter axion detection, this detection scheme is general and applicable to more broad research area.

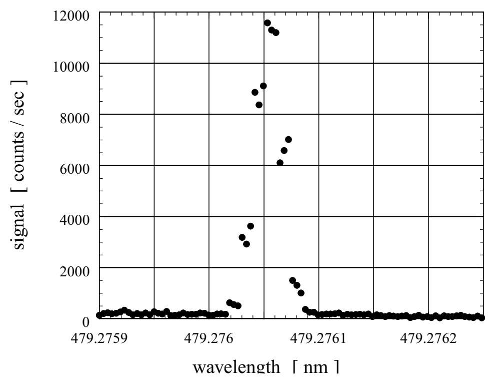

Figure 2. Typical field ionization signal of electrons from the n=110 Rydberg states of Rb measured with the present detector system at 12 mK temperature as a function of the second laser wavelength. The Rb Rydberg states are produced with two-step laser excitation.

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