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Neutrino Spectroscopy with atoms

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Abstract

In this paper, two atomic processes, neutrino-less double electron capture ($0\nu\epsilon\epsilon$) and radiative emission of neutrino pair (RENP), are described. The $0\nu\epsilon\epsilon$ process has the same physics objective as the neutrino-less double beta-decay, and thus its observation proves non-conservation of the total lepton number and the rate measurement would provide information on the effective neutrino mass. The RENP process is sensitive to the neutrino absolute mass scale, the mass hierarchy pattern, the mass type (Majorana or Dirac), and the CP violating phases. Its key idea is to amplify otherwise small rates of $|e\rangle \to |g\rangle + \gamma + \nu_i\nu_j$ (with ν_i, ν_j mass eigenstates), by developing the macro-coherent medium polarization among target atoms strongly coupled to fields inside the medium. Experiments using these two processes are now being planned to reveal nature of neutrinos.

Keywords: neutrino mass, Majorana, CP phases, macro-coherence

1. Neutrino-less double electron capture

Neutrino-less electron capture ($0\nu\epsilon\epsilon$) is a process in which two atomic electrons orbiting around the nuclei get absorbed by protons via weak interaction, turning into two neutrons and two neutrinos which further annihilate each other. See Fig. 1. This process has the same physics objective as its inverse, the neutrino-less double beta-decay ($0\nu\beta\beta$). Thus its observation establishes non-conservation of the total lepton number and the rate measurement would provide information on the effective neutrino mass $\langle m_{\beta\beta}\rangle \equiv |\sum_i m_i U_{ei}^2|$ [1]. This process was considered in detail some time ago[2]. Its interest is renewed recently due to a remarkable progress in technology searching for suitable candidate atoms as described below.

The $0\nu\epsilon\epsilon$ rate is given by $1/T^{(0\nu)} = R|V_{\epsilon\epsilon}|^2$ where $V_{\epsilon\epsilon}$ is the transition amplitude between the initial (A, Z) and final $(A, Z-2)$ atoms, and R is a factor related to the energy degeneracy between the two atomic states (resonance enhancement factor). The amplitude $V_{\epsilon\epsilon}$, which is proportional to $\langle m_{\beta\beta}\rangle$, can be calculated with the knowledge of nuclear matrix elements and wavefunctions of captured electrons, *etc.*. The resonance enhancement factor R is expressed by [1]

$$R = \frac{\Gamma_{2h}}{\Delta^2 + (\Gamma_{2h}/2)^2}, \quad \Delta \equiv Q - B_{2h} \tag{1}$$

where $Q = M(Z) - M(Z-2)$ is the mass difference between the initial and final atoms, B_{2h} (Γ_{2h}) is the binding energy (width) of the captured electron pair. The relevant energy levels are illustrated in Fig.1.

It has been known that $0\nu\epsilon\epsilon$ experiments can be realistic only if the resonance condition is satisfied, namely Δ is less than or comparable to Γ_{2h} so that R becomes large. Since the quantities B_{2h} and Γ_{2h} can be calculated accurately enough, identification of the best suited nuclide, the mandatory step for actual experiments, amounts to experimental determination of Q. Note that required accuracy for Q relative to M is an order of $\sim 10^{-9}$, considering typical values of $\sim$ 100 GeV for M and $\sim$ 100 eV for Γ_{2h}, the precision needed for Q. This has become possible by the remarkable progress in Penning-trap mass spectroscopy.

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[1] The $0^+ \to 0^+$ nuclear transition is assumed for simplicity. If the final nuclear state is an excited state, Δ should be replaced by $\Delta = Q - B_{2h} - E_\gamma$, with E_γ the excitation energy of the daughter nuclide, and Γ_{2h} should include the width of the nuclear excited state.

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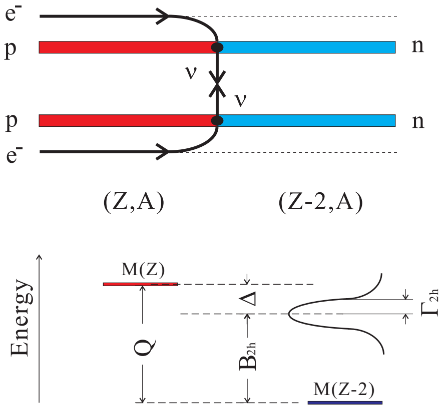

Figure 1: Neutrino-less double electron capture. Schematic diagram of the process (upper part) and its energy levels (lower part).

Table 1: Properties of $0\nu\epsilon\epsilon$ candidates, ^{152}Gd and ^{180}W.

Transition	$^{152}\mathrm{Gd} \rightarrow ^{152}\mathrm{Sm}$	$^{180}\mathrm{W} \rightarrow ^{180}\mathrm{Hf}$
Q [keV]	55.7 (0.2)	143.2 (0.3)
Δ [keV]	0.9(0.2)	11.2(0.3)
Γ_{2h} [eV]	24.8	71.8
natural abundance [%]	0.20	0.12
$T^{0\nu}_{1/2}\langle m_{\beta\beta}\rangle^2$ [year·eV^2]	10^{26}	$5 \cdot 10^{27}$
reference	[5]	[6]

It measures actually the ratio of the cyclotron frequency ν_c of singly-charged parent/daughter ions with a technique called time-of-flight ion cyclotron resonance. Those measurements include ^{112}Sn, ^{74}Se, ^{136}Ce [3], ^{156}Dy, ^{96}Ru, ^{162,164}Er, ^{166}Yb [4], ^{152}Gd [5] and ^{180}W [6]. Out of the heroic works, several candidates have emerged so far. The properties of the two most promising ones, ^{152}Gd and ^{180}W, are listed in Table 1. [2]

Having found the promising candidates, what is the prospect for real experiments? Experimentally the $0\nu\epsilon\epsilon$ process has some advantages over $0\nu\beta\beta$; physics backgrounds due to the two-neutrino double electron capture process are negligible because of its small phase space, and coincidence between gamma rays can be obtained if the daughter nucleus is in excited states. As in the case of $0\nu\beta\beta$, the decisive signature is a monochromatic peak in the spectrum when entire single-event energies are summed. Unfortunately, the natural abundance of these nuclides are not large; 0.20 % for ^{152}Gd and 0.12 % for ^{180}W. Considering the expected half-lifetime of $10^{26} \sim 10^{28}$ years (for $\langle m_{\beta\beta}\rangle \simeq 1$ eV), tens of tons of target material are required. Detailed studies are in progress towards realization of $0\nu\epsilon\epsilon$ experiments [7].

2. Radiative emission of neutrino pair

2.1. Experimental principle

The RENP (radiative emission of neutrino pair) experiment [8] focuses on the process

$$|e\rangle \rightarrow |g\rangle + \gamma + \nu_i + \nu_j, \tag{2}$$

where $|e\rangle$ ($|g\rangle$) is a metastable (ground) state of atoms, and ν_i's are neutrino mass eigenstates. An advantage in using atomic process is smallness of energy level spacings; neutrino's mass effects should appear clearly due to closeness of their energy scales. Smallness of the event rate, the largest disadvantage, is overcome by exploiting a new type of coherent amplification mechanism (called macro-coherence amplification [9]) discussed below. In the experiment, one observes photon spectrum, in particular the spectrum near its threshold region given by

$$\omega_{ij} = \frac{\epsilon_{eg}}{2} - \frac{(m_i + m_j)^2}{2\epsilon_{eg}}. \tag{3}$$

where ω_{ij} is the photon threshold energy related to the neutrinos with masses $m_{i(j)}$, and ϵ_{eg} is the energy difference between the ground $|g\rangle$ and metastable $|e\rangle$ states. The photon spectrum contains the neutrino property information such as (1) neutrino absolute mass scale, (2) mass hierarchy pattern (normal or inverted), (3) mass type (Dirac or Majorana), (4) CP violating phases (α and $\beta - \delta$). Detailed discussion of the physics objectives can be found in [12][13].

A key notion in our experimental principle is the macro-coherent amplification mechanism. In a word, the amplification is based on their collective de-excitation among all of the coherent atoms. It may be easier to understand the statement with a help of a simple rate formula. When plane wave functions of emitted particles are extracted, the rate from an ensemble of atoms is proportional to

$$\left| \sum_a e^{i \sum_j \vec{k}_j \cdot (\vec{r} - \vec{r}_a)} \mathcal{A}(\vec{r}, t) \right|^2, \tag{4}$$

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[2] ^{156}Dy and ^{164}Er are two other interesting candidates.