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Recent progress of SPAN towards neutrino mass spectroscopy

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Abstract. SPAN (SPectroscopy of Atomic Neutrino) project aims to determine the absolute neutrino mass. The process we plan to use is a cooperative de-excitation of atoms in a metastable level emitting a neutrino pair associated with a photon. The photon energy spectrum of this process contains information on the absolute mass of neutrino. Key items of this experiment are a rate amplification using macro-coherence in a target medium in case of plural particles emission and an external triggering of the emission in order to scan the spectrum. We have demonstrated the rate amplification in two-photon emission from para-hydrogen gas which was coherently excited to its first vibrationally excited state. The coherence in the medium was generated by irradiating two driving laser pulses. The emission was stimulated by irradiating a mid-infrared laser pulse. The enhancement factor of more than 10^{18} with respect to the spontaneous emission was achieved. This paper briefly summarizes the results.

1. Introduction

The neutrino absolute mass has being measured for a long time but is still undetermined. There has been three major methods which have tried obtaining the information: cosmological observation, neutrinoless double beta decay, and direct measurement using beta decay. The cosmological study has sensitivity of $\sum m_\nu < 0.28$ eV [1] and neutrinoless double beta decay experiment has sensitivity of 0.2–0.4 eV [2, 3]. Their measurements depend on their physics models. On the other hand, the sensitivity of model-independent direct measurement is 2.05 eV (95% C.L. [4]) so far. The future experiment aims to achieve the sensitivity of 0.2 eV level [5]. These types of experiments have long history and it becomes difficult to improve the experimental sensitivity.

Our group has proposed a new principle of the absolute mass measurement. The principle is to use a cooperative de-excitation of atoms in a metastable level emitting a neutrino pair associated with a photon. We call this process as RENP (Radiative Emission of Neutrino Pairs). The detail theoretical aspect can be found in Ref. [6]. In addition to the absolute mass, this spectrum may sensitive to the CP violation phases in the mixing matrix [7] and the temperature of the cosmic neutrino background [8]. To use the atomic de-excitation process, a coherence is one of the essential parameter. Coherence in macroscopic volume, macro-coherence, can enhance the de-excitation rate. We recently reported experiments which focused on the rate amplification using macro-coherence[9, 10], and this paper briefly summarizes the latest results.

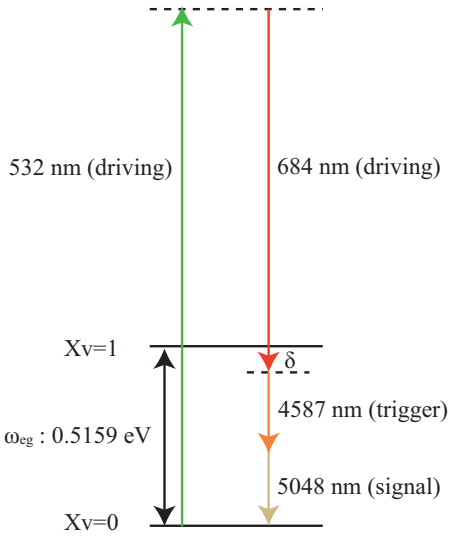

Figure 1. Level diagram of para-hydrogen and energy of each photon. First electrically excited states are around 11 eV.

2. Experiments

To demonstrate the rate amplification by using the macro-coherence, we used a para-hydrogen (p-H_2) gas as a target medium for the coherence generation and tried to enhance the two-photon emission rate from its first vibrational excited state ($Xv = 1$) whose excited energy $\omega_{eg} = 0.5159$ eV [11] with respect to the ground state ($Xv = 0$). This process is one-photon transition (E1) forbidden and two-photon transition (E1×E1) allowed. The spontaneous emission rate of two-photon transition integrated with the photon energy is 5×10^{-12} Hz. The level diagram of p-H_2 molecule is shown in Fig. 1. The arrows in the figure represent energy of each photon in laser pulses used in the experiment.

The experimental setup is shown in Fig. 2. Before the detail, the experimental procedure is simply introduced: at first, all p-H_2 molecules are in ground state; irradiating two driving lasers into the p-H_2 to generate the coherence between the ground state and excited state; irradiating the trigger laser to stimulate the two-photon emission; measuring the signal energy and spectrum.

2.1. Para-Hydrogen

We used a p-H_2 gas with purity of better than 500 ppm ortho-hydrogen contamination. We prepared the p-H_2 gas by converting from a normal hydrogen gas. The normal hydrogen gas was passed through a copper pipe filled with iron(III) oxide hydrated ($HFeO_2$) powder at a temperature of 13.5 K, then was converted to p-H_2 due to nuclear spin flip.

The p-H_2 gas was filled in a copper cylindrical cell with the diameter of 20 mm and the length of 150 mm which was located in a liquid-nitrogen cryostat. The both ends of the cell and the cryostat were sealed with 5-mm-thick magnesium fluoride windows and indium gaskets. The experimental condition was a temperature of 78 K and a pressure of 60 kPa. The number density assuming an ideal gas was 5.6×10^{19} cm^{-3}. These conditions were determined by maximizing the decoherence time. Thanks to the collisional narrowing, the decoherence was nearly slowest; it was estimated as 130 MHz [12] at our condition.

2.2. Lasers

Two driving lasers were used to excite the p-H_2 molecules and generate the initial coherence. The wavelengths of driving lasers were determined so that their energy difference was equal to ω_{eg}, except for a small detuning (δ in Fig. 1). The detuning was able to be adjusted to maximize the signal intensity by compensating the AC stark shift. In addition, a mid-infrared laser [13], whose wavelength of 4587 nm, was used to stimulate the two-photon emission. Their

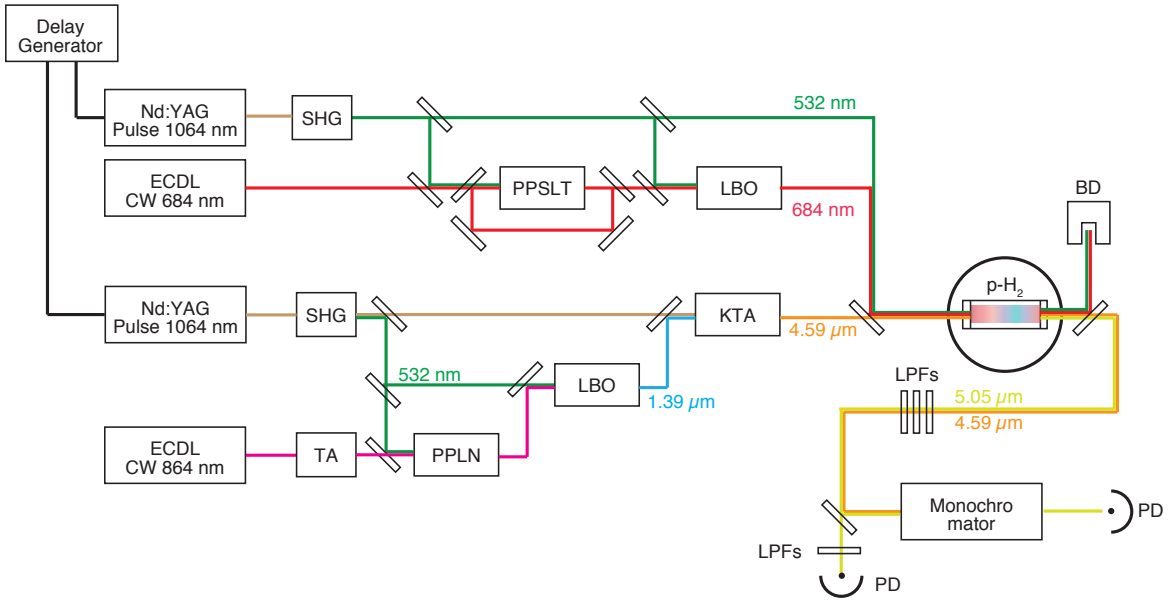

Figure 2. Schematic of the experimental setup. PPSLT, LBO, PPLN, and KTA are nonlinear optical crystals used for the optical parametric generation (OPG) and the optical parametric amplification (OPA), respectively. SHG: second harmonic generation; ECDL: external cavity diode laser; TA: tapered amplifier; BD: beam dumper; LPFs: long-pass filters; PD: photo detector

Table 1. Properties of three laser pulses.

	Driving 1	Driving 2	Trigger
Wavelength	532.2 nm	683.6 nm	4587 nm
Pulse Energy in the Target	5 mJ	5 mJ	0.15 mJ
Beam Diameter in the Target	0.30 mm	0.35 mm	0.75 mm
Line Width	< 100 MHz	< 200 MHz	1.4 GHz
Pulse Duration	9 ns	6 ns	2 ns
Polarization	linear (horizontal)		
Repetition Rate	10 Hz		

properties are summarized in Table 1. They were colinearly aligned at a dichroic mirror in front of the cryostat. Their mutual timing was adjusted by using a delay generator (Stanford Research Systems, DG645). The standard deviation of the time jitter between the driving lasers and the trigger laser was 0.8 ns. The intensity and timing of all three laser pulses were monitored shot-by-shot by using silicon photo-diodes (Hamamatsu S5973) for driving lasers and an indium-antimony detector (Hamamatsu P5968-100) for the trigger laser.

3. Results

If the driving lasers can generate coherence in the p-H_2 target, the coherently enhanced two-photon emission can be stimulated by the trigger laser. The resultant wavelength of the two-photon partner of the trigger laser was 5048 nm due to the energy conservation, and the

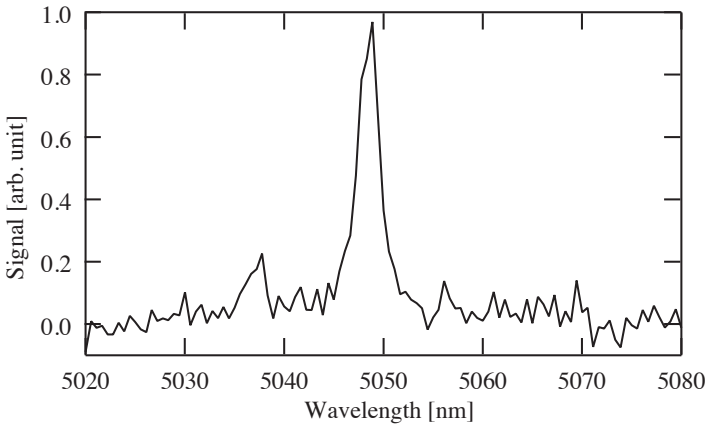

Figure 3. Observed spectrum of two-photon emission. The resolution of 1 nm was limited by the monochromater.

Table 2. Parameters for the calculation of the enhancement factor.

Factor	Value
Spontaneous Decay Rate	3.2×10^{-11} s^{-1}
Energy Bandwidth of the filter	$4.4 \times 10^{-2} \times 5048$ nm
Measurement Time	70 ns
Detector Solid Angle Fraction ($\Delta\Omega/4\pi$)	1.7×10^{-4}
Number of Excited Molecules	$< 1.3 \times 10^{16}$
Calculated Spontaneous Emission (5048 nm)	$< 2.1 \times 10^{-7}$ photons/pulse
Observed Emission (5048 nm)	$(6.1 \pm 0.9) \times 10^{11}$ photons/pulse

emission direction was same as the other lasers due to the momentum conservation among the photons. The signal spectrum of 5048 nm was measured by using a monochromator (Princeton Instruments Acton SpectraPro SP2300) and a mercury-cadmium-tellurium (MCT) detector (Daylight Solutions HPC-2TE-100). The measured spectrum is shown in Fig. 3. We observed the clear signal peak at the 5048 nm.

The signal energy of 5048 nm was detected by using another MCT detector (Vigo system PV-2TE-6). It was calibrated by comparing a well calibrated pyroelectric energy detector (Gentec-EO QE8SP-B-MT) whose calibration uncertainty of $\pm 4\%$. Several band-pass filters and neutral density filters were used in order to separate the signal pulses from other pulses and to prevent saturation of the detector. The detector's output was digitized by an oscilloscope. The estimated number of emitted signal photons as $(6.1 \pm 0.9) \times 10^{11}$ photons/pulse with correcting the optical transmittance of all optics between the target and the detector. We compared this result to the spontaneous emission with our experimental acceptance (Table 2). The resultant enhancement of more than 10^{18} can be understood in the presence of the macro-coherence. More detail results and discussion can be found in Ref. [10].

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