Present Status of the Solar ^{3}He(^{3}He, 2p)α Fusion Experiment

Kyo KUME, Takahisa ITAHASHI, Hideaki OHSUMI, Keiji TAKAHISA, Nobuyuki KUDOMI,
Masataka KOMORI, Sei YOSHIDA, Kaoru YAMASAKI, Hiroshi TOKI, Hiyorasu Ejiri, and Yasuki NAGAI
Research Center for Nuclear Physics, Osaka Univ., Ibaraki , Osaka 567-0047, Japan

Abstract

The solar ^{3}He(^{3}He, 2p)α solar fusion reaction experiment setup is now being developed. The whole system is shown capable of real events from identifying huge background events.

1 Introduction

The so-called solar neutrino problem has been an attractive topic in astro-, nuclear and particle physics in this decade. It is pointed out that this problem is strongly connected to the neutrino's properties of its oscillation, mass and so on. On the other hand, there still exists a question for the MSW effect. To solve this question, it should be a powerful evidence to measure the cross section of the ^{3}He(^{3}He, 2p)α reaction, which is a direct reaction after pp-chain, down to a few ten keV or even to a few keV.

This reaction has been extensively measured by LUNA collaboration at Gran Sasso, whose results cover a wide range of energy below the center of the solar Gamov peak (E_0 =22keV), although the problem of the screening effects remains unsulved and unknown[1][2]. The present work (OTO-SUN project) aims to cover the energy range between 25 and 50keV where LUNA cannot cover and hence supply the comprehensive data to understand the pp-chain reaction of the solar fusion.

2 Facility Design and Performances

2.1 Ion Source

For highly efficient, low-power ion source of helium ions, there are duoplasmatron ion source and electron cyclotron resonance (ECR) ion source. In addition, we also investigated other high current ion source such as duopigatron ion source (PIG), however as a low-powered high brightness ion source here remain former two candidates. By comparison of particular performances between these sources we seriously considered the simpler structure of source and power supply and longer lifetimes of used elements such as filament lifetime. In addition, an ECR ion source is favoured for molecular interference reduction since the electron temperature of an ECR plasma becomes higher than that of duoplasmatron and thus molecular ions such as HD$^+$ molecule decrease so much. A very compact ECR source (NANOGUN) can afford 1.7 mA ^{3}He^{1+} or 200 μA ^{3}He^{2+} with very small rf power[3]. Even though among these sources beam emittance of duoplasmatron has better qualities than ECR ion source the inferior could be compensated with a specially designed low energy beam transport from source to target.

We have tested the production of helium ions of each charge state and the obtained current at the target was 660μA at the extraction voltage of 10kV with the vacuum of 6×10^{-6}Torr and the rf power of 11.26W.

The required energy range of ^{3}He ions should be between 30keV to 50keV, in which the astrophysical S-factor data for ^{3}He+ ^{3}He fusion reaction can be deduced inside the solar Gamov peak. To obtain data on every hundred eV for the incident ^{3}He beam, it is desirable that condition at the target site be kept optically constant throughout the whole energy change. For this purpose we employ the multi-electrode extraction system, as well as calculated optimum electrode structures at each potential. The multi-electrodes extraction system is advantageous for two reasons: first it improves the beam emittance even under condition of a strong space charge force, and secondly, it moderates the electric field gradient ascribed from the higher extraction potential. Actually we need to add only one electrode to the original NANOGUN design in order to have independently positioning electrodes. In order to match the size and divergence of the beam at the target as less than a 7mm diameter and small angular divergence, we optimized the potential, structures and positions of the electrodes by using computer code FUGUN. At various energy, a substantial brightness could be achieved by simply applying the different potentials to the beam forming electrode with a different position. The final result of the extraction region of NANOGUN is determined and fabricated along with making new insulator between source and grounded materials. These design consideration and test results are detailed in accelerator report and ion source conference proceedings[4][5].

The high voltage application test for NANOGUN has been examined and the aging process up to 43kV (designed goal is 50kV) has already been achieved.

As we mentioned in a total performance of OTO-SUN-project, the plasma potential would be larger than that of usual duoplasmatron ion source, JAERI group measured the value for NANOGUN source and reported in a meeting of RCNP workshop that its plasma potential is 21.3+2.4eV[6] by using a method developed by Z.Q.Xie et.al.[7].

2.2 Low energy beam transport

Non-contaminated high current beam transport (>1mA) should be designed for a gas target or a plasma target without deterioration of the beam qualities and reduction of the beam current. For this purpose, we introduced strong focusing system by using quadrupole doubles which can be zoomed for image points for various beam energy. We calculated the beam optics with transport programs (GIOS) including the space charge effect. As discussed in the target design later we will use a differential pumping for the gas target or plasma target system, therefore the aperture slits in front of the target in the low energy beam transport are strongly limited by its evacuating condition with the pumping system. In order to discriminate molecular interference or contaminated intrusion of accelerated species we must analyze the ion beam. Luna group used the 90 degree bending magnet with adjustable devices for the angles of entry and exit faces to get good astigmatic focusing. With our separating functioned system, focusing properties and analyzing power would be more powerful in operation and in performances.

The transport efficiency at low energy is more than around 40%, since about 900μA is transported successfully through three collimators to the target when analyzed 2mA $^3He^{1+}$ beam is obtained at the exit of the magnet.

2.3 Gas target

The design of the windowless gas target is a crucial problem for studies of the ^{3}He(^{3}He,2p)^{4}He reaction. It consists of differential pumping system and gas recirculation and purification system. We prepared a few turbomolecular pumps. For ^{3}He gas of less than 1 mbar pressure in the target chamber, the pumping system should evacuate the several stages between the chamber and beam transport (less than 1×10^{-5}mbar). In particular, target gas is compressed by the turbo-molecular pumps and finally recirculated into the target chamber. The recirculation system consists of purification via a modified cryopump liquid backed by other turbomolecular pump for further compression and strong vessel for batch type process. As a first optional we consider the purification and recirculation by using low temperature cooled charcoal traps which might need a regular supply of liquid nitrogen. Thus, we developed a new purification system and tested recirculation in a higher pressure than a normal operating pressure for cryopump which is overcome by adding another turbo-molecular pump between a cryopump and a target chamber. Purity of recirculating gas will be measured by a quadrupole mass filter continuously. A regulated and constant target pressure will be realized by a gas dosing system. The electrical signal from a capacitance manometer (Barocel-655) at the target is transmitted to the RVG040 control unit which regulates an RME010 electric valve. It ensures to maintain a desired constant target pressure.

As a final purification we would like to introduce a purification device applied for updated semiconductor technology.

By these evacuation system we realized an ideal target pressure and proper vacuum level in various points of beam transport.

In addition we measured HD^+ component for accelerated ions with the accelerator mass spectrometry in RCNP AVF cyclotron. Obtained result shows a usual commercial ^{3}He gas results in ppm deuterium contamination[8].

2.4 Detection and detectors

In order to detect the energetic reaction particles of protons (Q=12.86MeV), we should install the counter telescopes which surround the gas target. We are studying the Monte Carlo simulation calculation (MC) with GEANT program to find the optimum detector setup for an efficient and background free measurement. Dalitz plot and the energy correlations between emitted particles show the maximum energy of a particle is about 4MeV. On the other hand two protons share the more higher energy of 9MeV to 12MeV. The expected ultra rare reaction rate is around a few events per day or less, and the typical single background rate of the silicon detectors is one event per hour or more. To remove such fake events, two proton coincidences are required for the identification of present reaction. Four Δ-E telescopes are places around the beam axis.

Option(1)

The Δ-E and E detector in each telescope which has an active area of 2500mm^2, the ΔE detector has a thickness of 140mm and the E detector has a thickness of 1500mm, both of which have been brought from MICRON Semiconductor Limited. One of the major background comes from ^{3}He+d$\rightarrow \alpha$ + p (Q=18.35MeV) due to the deuterium contamination in both ^{3}He beam and ^{3}He gas target. The cross section of this reaction is 10^6-10^7 times larger than that of the ^{3}He+ ^{3}He$\rightarrow$ 2p+α. The former reaction was estimated by our MC and it is noted that the emitted proton has fixed energy due to a two body decay which can be separated from those of the contamination reaction. The estimated efficiency for the present reaction is about 13% for two proton coincidence with ΔE-E counter telescope techniques (the reason for p-p coincidence is stated in MC).

By using MC, deuterium contamination from ^{3}He(d,p)^{4}He and d(^{3}He,p)^{4}He reactions can be almost distinguished from our desired events. However, in low energy loss region of ΔE, escaping protons from the edge of an E counter extend up to 15MeV in E-signal which makes a false signal for ^{3}He(^{3}He,2p)^{4}He event. Thus we will additionally require proton-proton coincidence where either proton stops in a ΔE counter. Then, if we discriminate these particles with an energy less than 1MeV, it is helpful to reduce a cosmic ray contribution and electric noise in a detector. Option(2)

If we arrange the detector assembly of multi-layerd system, we can identify the background events more efficiently. Background origins such as cosmic muons and single proton events from ^{3}He(d,p)^{4}He and d(^{3}He,p)^{4}He reactions which occur with the presence of the contamination of deuterium in a beam and in a target gas, has to be avoided by the energy or timing information of detector. Proposed geometry can also reduce an electrical noise which comes from leak current in a detector system. Each side of this detector system consists of four squared Si-detectors. Each detector is used for as follows;

1. first one from inside will be used for ΔE counter in telescope mode,
2. second one will be used for trigger counter, and the coincidence events of first and second detectors will be selected as a real event signal in off-line analysis,

3. third one is used to detect the proton of real events, where the proton penetrates first and second detectors, and

4. last one will be used for anti-coincidence detector, which has larger size than the other detectors,

in order to reject fake events such as cosmic muons or protons with energy of 14.7MeV from ^{3}He(d,p)^{4}He reaction. The pattern of the first to the third detectors from inside will be used for the particle identification, where proton signal has to be extracted. The enlargement of an outer most detector stated in (4) is expected to reject the proton background event which escape from the edge of a second or third detector with the same energy deposit as that of the real event in these detectors. The adequate size of a fourth detector was estimated by MC (GEANT3.21). It is noticed that the fake events will not contribute seriously to real ones even if the contamination of deuterium in target gas (^{3}He) or in beam is less than 10ppm. The contribution of cosmic muons will be of the order of $10^{-1\sim-2}$ counts/dey at the surface (not underground), without taking into account of the secondary generated particles.

This type of detection system would be useful to determine the reaction point along the interaction region in the gas target.

2.5 Calorimeter

The beam current passing through a gas target, could be measured using a (digital) calorimeter. The beam is stopped in the calorimeter, where the kinetic energy of the projectile is converter into heat. The converted heat is transfered through a heat flux sensor (OMEGA HFS-3) to a water cooled constant temperature copper base. It is designed for the precise measurement of heat transfer through ant materials. In principle, since the heat transfer rate is directly proportional to the temperature difference across the thermal barrier. The sensor consists of thermocouples wired in series on the Kapton surface, thus the sensor can be directly interfaces to a standard microvolt meter with no cold-junction compensation required.

The detection of photo-emission or X-ray emission would be helpful to know the luminosity of collision between the charged particle and gas target. The design details are under progress.

2.6 Underground laboratory

The total system will be installed into a new underground laboratory Oto Cosmo Observatory (OCO) where the measurement of the extremely small cross section of the order of pico-barn is possible. It is already reported that muon and neutron fluxes are reduced down to 4×10^{-3}/m^2/s and 4.1×10^{-5}/cm^2/s respectively. The reported data by double beta groups shows that the cosmic ray intensity at OCO is five orders of magnitude smaller than that observed at the surface level laboratory[9].

Table 1

Count rate for ^{3}He(^{3}He, 2p)α reaction with p-p coincidence. S_0=5.4MeV is used.

E_{cm} (keV)	σ (barn)	count rate (count/day)
30	1.3×10^{-10}	5.9×10^1
40	4.0×10^{-9}	2.0×10^3
50	4.1×10^{-8}	2.0×10^4

Table 2

Count rate for ^{3}He(d, p)α reaction with p-p coincidence. S_0=6.0MeV is used.

E_{cm} (keV)	σ (barn)	count rate (count/day)
30	7.3×10^{-4}	1.3×10^1
40	2.9×10^{-4}	5.1×10^1
50	7.4×10^{-3}	1.3×10^2

3 Experimental feasibility

It is noted that our compact accelerator facility which has a capability to measure a thermonuclear cross section of pico-barn has been realized. In these estimation we assumed the astrophysical S factor for both reactions as S_0 =5.4MeVb and S_0 =6.0MeVb respectively. We will have a significant result of the S factor data for ^{3}He+ ^{3}He reaction in on year operation. As stated in the Section 2-(4), we simulate a fake event from deuterium contamination as large as ppm level which is so far observed amount for commercial gas and would be improved to less than ppb. In most difficult case of the lowest center of mass energy such as $E_{^3\mathrm{He}}$ = 20keV, proton-proton coincidence events of ^{3}He+ ^{3}He reaction is 1.5×10^{-1} per day while the value of fake events will be considerable reduced as $1/2 \times 10^{-4}$. The estimated rates for ^{3}He+ ^{3}He and ^{3}He+d reactions are listed in Tables 1 and 2.

References

[1] U. Grife et al., Nucl.Inst. and Meth. A350(1994)327
[2] M.Junker et al., Phys.Rev.C57(1998)2700
[3] P. Sortais et al., Proc.of the 12th Intern. Workshop on ECT ion sources, (1995)44
[4] T. Itahashi et al., Proc. of the 11th Symps. on Accelerator Sci. and Tech., Harima 151(1997) and T. Iki, Osaka Univ., Master thesis(1997)
[5] Z.Q. Xie et al., Rev. of Sci.Instr. 65, 2947(1994)
[6] T. Itahashi et al., Rev. of Sci. Instr. 69, 1032(1998)
[7] Y. Saito, private communications
[8] T. Itahashi, Symp. on Origin of Matter and Evolution of Galaxies 97, pp169(1997)
[9] H. Ohsumi et al., RCNP Annual Report 1994(1995)45