Proton and Boron-11 nuclear fusion reaction experiment using proton accelerator

Bong Seong Oh, Jeong Ik Lee*
Dept. Nuclear & Quantum Eng., KAIST, 373-1, Guseong-dong, Yuseong-gu, Daejeon, 305-701, Republic of Korea
**Corresponding author: jeongiklee@kaist.ac.kr*

1. Introduction

Nuclear fusion is one of the most promising options for generating large amounts of carbon-free energy in the future. Among many nuclear fusion reactions, aneutronic fusion reactions which do not release neutron particle have a lot of benefits in terms of safety and economy because radiation shielding does not matter for the reactions. Table I is the list of the typical nuclear fusion reactions.

Table I: Fusion Reaction Properties [1]

Reaction	Energy release per fusion (MeV)	Thermonuclear reaction temperature Threshold (keV)
$D+T \rightarrow n+{}^4He$	17.6	4
$D+{}^3He \rightarrow p+{}^4He$	18.3	100
$p+7Li \rightarrow {}^4He+{}^4He$	17.5	> 900
$p+{}^{11}B \rightarrow {}^4He+{}^4He+{}^4He$	8.7	300

Deuterium and tritium fusion reaction has large amount of energy release and lowest threshold comparing other reactions but the reaction generates a neutron. Otherwise, deuterium and helium-3 reaction is an aneutronic reaction and has largest amount of energy release and quite low threshold energy but deuterium and helium-3 is not abundant. Proton and litium-7 reaction has large amount of energy release and substances of the reaction are abundant but the threshold is too high to react. Therefore, proton and boron-11 reaction (pB_{11}) is the most suitable aneutronic fusion reaction because the substances of the reaction are abundant and the reaction has quite low threshold energy than other aneutronic fusion reaction. The annual production of boron in the world is 4,550,000 tone (2011) [2] and the atomic ratio of boron-11 in the natural boron is 80%. If this amount of boron-11 in the world be transferred into electrical energy with 50% thermal efficiency cycle, the amount of electrical energy is $3.85x10^7$ TWh. This is 1,842 times of the world electric power demand. Therefore, only 0.0543% of world production of boron can support the world electrical energy demand.

The previous efforts to make the pB_{11} reaction power system has been proceeding in a few research institutes. Lawrenceville Plasma Physics Incorporate (LPP) invented the dense plasma focus (DPF) device for pB_{11} reaction [3]. A pulse of electricity from a capacitor bank is discharged across the electrodes which consist of two cylindrical metal, nested inside each other. For a few millionths of a second, an intense current flows from the outer to the inner electrode through the decaborane gas ($B_{10}H_{14}$). This current starts to heat the gas and creates an intense magnetic field. Because of this magnetic field, the current forms itself into a thin sheath of tiny filaments as shown in Fig. 1.

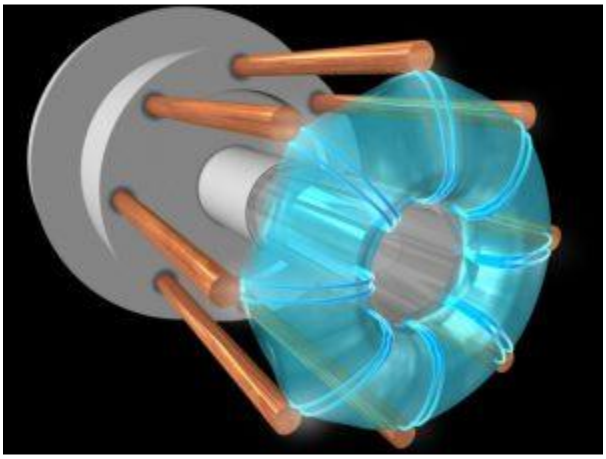

Fig. 1. Sheath of pB_{11} plasma filaments

This plasma filaments travels to the end of the inner electrode where the magnetic field produced by the currents and the magnetic field make pB_{11} plasma into coil shape. Finally, the coiled pB_{11} plasma becomes more unstable, so that the plasma beam is released from the central electrode. While the beam travels, the plasma is strongly compressed by the electromagnetic force. This compression makes nuclear fusion of the pB_{11} plasma.

Another research institute is Tri Alpha Energy whose researchers make pB_{11} fusion reaction with field reversed configuration (FRC) which is a kind of compact toroids (CT). CTs are a class of toroidal plasma configurations that are self-stable and whose configuration does not require magnet coils running through the center of the toroid. How to operate the reactor of Tri Alpha Energy, called C-2 device is firstly two diverters at the end of the reactor shoot proton and boron beam to slam them and the pB_{11}'s plasmoid is confined at the center of the reactor as shown in Fig. 2.

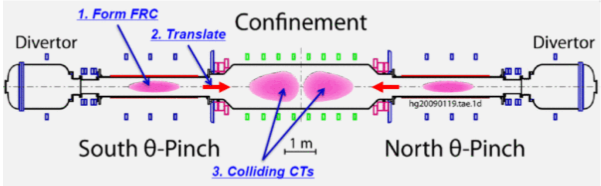

Fig. 2. Tri Alpha Energy diagram of C-2 machine

Making the plasmoid as CT which is separated from external magnetic field and the plasmoid is kept rotating by external charged beam to increase the confinement time of the pB_{11} plasma [4].

Even though the pB_{11} reaction system is under investigation, Korean research on this theme is limited. For understanding and quantifying pB_{11} reaction rate, KAIST research team utilized a proton accelerator called tandem accelerator which is able to accelerate proton particles with 1~2MeV energy for fundamental experiment. In this paper, $NaBH_4$ is used as the fuel substance of pB_{11} and the mass defect of the substance is predicted with very simple calculation for evaluating amount of pB_{11} reaction.

2. Methods and Results

2.1 Tandem accelerator

In Table I, threshold energy of pB_{11} reaction is 300 keV, so that tandem accelerator is capable of understanding the pB_{11} reaction. Table II shows the specifications of tandem accelerator.

Table II: Specifications of tandem accelerator

Particle energy	0.3~3MeV
Maximum current	2 μA
Ion	Proton
Maximum irradiation area	4cmX4cm

Figure 3 and 4 represent picture and beam window chamber of tandem accelerator, respectively.

Fig. 3. Picture of tandem accelerator

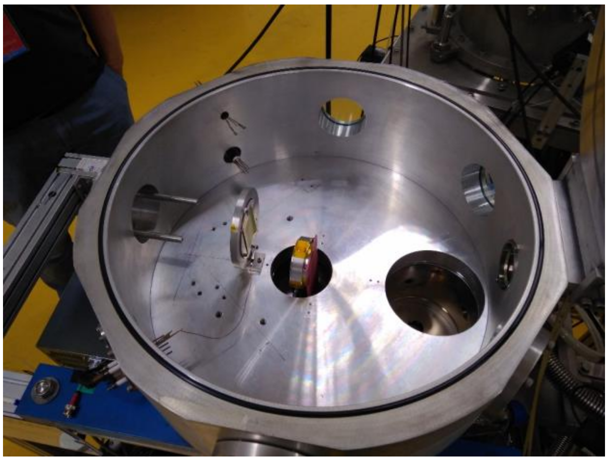

Fig. 4. Beam window chamber of tandem accelerator

Figure 5 shows schematic diagram of test section. The target material will be irradiated from the accelerated proton beam by tandetron.

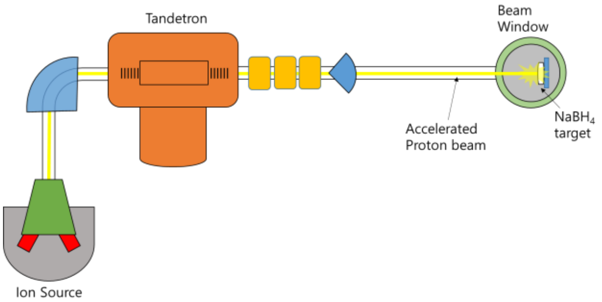

Fig. 5. Schematic diagram of experiment by tandem accelerator

2.2 Results

The target material of tandem accelerator is $NaBH_4$ granule. Figure 5 is the picture of fresh $NaBH_4$ granule and its weight before irradiated of proton beam. Figure 6 shows the picture of irradiated $NaBH_4$ granule and its weight.

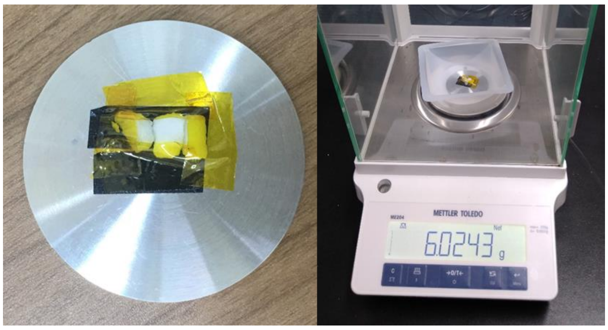

Fig. 5. Configuration and weight of fresh $NaBH_4$

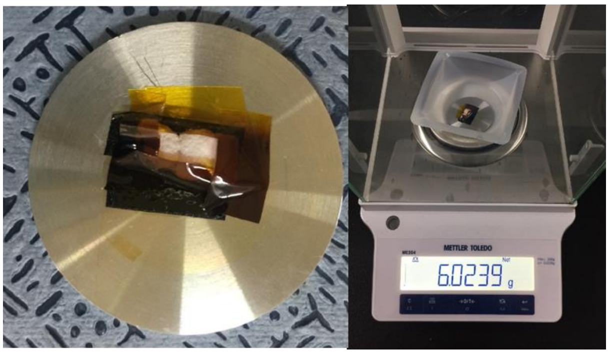

Fig. 6. Configuration and weight of irradiated $NaBH_4$

Irradiation time and proton beam intensity on the $NaBH_4$ fuel are 6 hours and 7.84x10^{16}/sec, respectively. With simple nuclear reaction rate calculation, the amount of mass defect can be calculated. The fusion cross section of proton to boron-11 is assumed as a constant, 0.9barn. Actual cross section is different along with proton energy but constant cross section is selected for simple calculation. The density of $NaBH_4$ fuel is 1.074g/cc which is equivalent to 1.3458x10^{22}#/cc, atomic density of B_{11} in $NaBH_4$. Penetration depth of proton particle to boron is calculated 0.0024cm by SRIM code [5].

$$\sigma NdIt = R \tag{1}$$

σ: cross section, N: atomic density, d: penetration depth,
I: proton beam intensity, t: irradiation time,
R: amount of reaction

Therefore, the calculated amount of reaction is 4.9227x10^{16} which is equivalent to 8.1745x10^{-8} mole. It means 8.99x10^{-7}g of boron-11 disappears according to simple nuclear reaction calculation. However, amount of defected mass from experiment is 0.0004g, which is different to the calculated mass defect. There are several reasons why both mass defects are different.

First, the calculation formula is too simple to predict mass defect. A constant cross section was used and irradiated area was not correctly measured. Moreover, since order of the mass fraction is so small, uncertainty from the measurement device could leads to a large error. Second reason is quite low boiling point of $NaBH_4$. The boiling point of $NaBH_4$ is 500^{o}C so that little $NaBH_4$ target might be able to locally be boiled by the proton beam. Therefore, little of $NaBH_4$ becomes vapor and the vapor is ejected via vacuum pump attached to the beam window chamber. Third reason is additionally accelerated protons from $NaBH_4$. The daughter nuclei of pB_{11} reaction are three alpha particles with 8.7MeV. The three alpha particles might be able to transfer enough momentum and energy around hydrogen atoms of $NaBH_4$ to lead to another pB_{11} reaction because the threshold energy of pB_{11} reaction is only 300keV. Thus, this additional pB_{11} reaction by three alpha particles cause to additional mass defect than prediction.

3. Conclusions

To find clean, safe and abundant new energy sources, nuclear scientists and engineers have been focusing on nuclear fusion reaction. Among various nuclear fusion reactions, pB_{11} reaction shows the most promising future in terms of safety and feasibility. Many international companies and research institutes are also studying the pB_{11} fusion system. KAIST research team used a proton accelerator with $NaBH_4$ target to understand the mechanism of pB_{11} reaction by first checking any mass defects. The result shows large difference between measured mass defect and simply calculated mass defect from nuclear reaction. This large difference might come from the measurement error, local boiling of target and additional mass defect from newly accelerated protons by momentum and energy transfer of daughter nuclei of pB_{11} reaction.

REFERENCES

[1] D. Jackson, W. Selander, and B. Townes, "A review of fusion breeder blanket technology, part 1," Canadian Fusion Fuels Technology Project1985.

[2] I. ORE, "2011 Minerals Yearbook," *US Geological Survey,* 2013.

[3] E. J. Lerner, S. K. Murali, and A. Haboub, "Theory and experimental program for p-B11 fusion with the dense plasma focus," *Journal of fusion energy,* vol. 30, pp. 367-376, 2011.

[4] M. Tuszewski, A. Smirnov, M. Thompson, T. Akhmetov, A. Ivanov, R. Voskoboynikov, *et al.*, "A new high performance field reversed configuration operating regime in the C-2 device a," *Physics of Plasmas,* vol. 19, p. 056108, 2012.

[5] J. Ziegler, J. Biersack, and U. Littmark, "The stopping and range of ions in matter (SRIM Code)," ed: Version, 2000.