Electron Beam Ion Trap For Study Of Fusion Reactions In Nuclear Astrophysics

T. Itahashi*, N. Kudomi, Y. Sakemi, T. Shima, S. Yoshida, and T. Sakamoto* and E.D.Donets and E.E.Donets†

*Research Center for Nuclear Physics, Osaka Univ. Ibaraki, Osaka, Japan
†Joint Institute for Nuclear Research, Dubna, Russia

Abstract. The laboratory condition where charged particle fusion reactions have been done is not exactly the same as that of stellar condition. To probe details of reaction and to test the prediction of standard solar model we need more precise data for charged particle fusion experiments in the laboratories. We propose several experimental approaches to reduce the ambiguity of the estimation of screening potential value which is crucial for obtaining the astrophysical S-factor. Experiment with bare target and bare beam interaction will be done by using proposed Electron Beam Ion Trap apparatus (NARITA).

INTRODUCTION

The laboratory condition where charged particle fusion reactions have been studied is not exactly the same as stellar condition. To probe details of solar fusion and to test the prediction of standard solar model we need more precise data for charged particle fusion reactions in the laboratory [1, 2].

The enhancement of cross section for charged particle fusion reaction due to the electron screening effects has been an entangled problem. We already proposed NARITA (Nuclear Astrophysics Researches in Ion Trap Apparatus) project to solve this problem by studying the fusion reaction with bare beam and target. It consists of various installation such as BeTa (Beam Target) apparatus by creation of the so-called electron string state of confining electrons. In order to store large amount of bare nuclei in an ion trap as a target or both projectile and/or target particles, other approach for ion traps than that has been extensively applied for atomic or nuclear physics studies is needed. We constructed the test bench by using ANAC ionizer as an apparatus for the reflex mode of EBIS with an axial ion injection system for storing nucleus generated with 2.45 GHz ECR ion source. We have a plan to investigate the amount and lifetime of stored ions in this warm bore EBIT by observing the extracted beam with several diagnostic devices. We injected ion beam into the drift tube and the transmission is measured. We prepared a particular cathode for this application by using E-GUN program. The detailed design and operation of these devices are under progress.
SCREENING POTENTIAL

In order to deduce the nuclear astrophysical S-factor from the measurement of fusion cross section, it is crucial to refer experimental results of atomic physics studies such as stopping power, equilibrium charge state, charge transfer cross section and so on.

Generally, the screening potential enhances the cross section in usual laboratory experiments due to the bound electrons present in a target and projectile. This enhancement has already been reported in many experiments [3, 4, 5, 6, 7, 8, 9]. Despite considerable efforts to reduce the ambiguity for the electron screening potential by collecting the data using various atomic states of projectile or target for fusion reactions, the problem is not yet completely solved. Indeed, the values of the screening potential in the astrophysical S-factors calculated from the measured excitation functions for several reactions show unexplained quantitative differences from theoretical values. The theoretical study toward these problems manifests the larger screening potential value than the adiabatic limit [10, 11, 12, 13, 14]. The shielding effect reduces the Coulomb potential and eases the penetration of the coulomb barrier. During the discussion we use following expressions for astrophysical S-factor with screening potential U_e and enhancement factor f:

When electron density is supposed to be unchanged during the collision, one can consider electrostatic screening potential, as a sudden limit. In the case of smaller relative velocity of the nuclei compared with the electron velocity, the electron density is changed accordingly to any relative configuration of the nuclei. Thus the electrons have an impact on a kinetic energy shift of the nuclei. This is considered in the adiabatic approach which comes from the well known Born-Oppenheimer method: i) Sudden limit

ii) Adiabatic limit

VARIOUS EXPERIMENTAL STUDIES

Bound electron effect

It would be remarkable that precise nuclear studies suggested atomic effects might give important corrections in nuclear resonance studies. Sharp resonance in the $^{12}$C(p,p) reaction interprets 0.6 keV of the width as an atomic effect associated with excitation of the final atoms [15]. More sophisticated experiments for the atomic effect to the nuclear reaction are the alpha–alpha scattering to the $^{6}$Be ground state by using the crossing beams technique. It demonstrates the first observation of the influence of atomic electrons on nuclear resonances: the $E_r = 184$ keV resonance was not characterized by a single nature but was split into three apparent dips [16, 17, 18]. Atomic effects on alpha–alpha scattering to the $^{6}$Be ground state are investigated using crossing beam technique with an energy resolution of 26 eV. The observed atomic effect as splitting of the resonance is dominated by the evolution of the electrons of the entrance channel into two-electron configuration of $^{6}$Be$^{++}$ with the third electron ejected into the continuum [12].
Screening effect for identical mass in the entrance channel

In recent studies the additional enhancement should be absent in fusion reactions involving the entrance channel with nearly identical charge to mass ratio, such as $d + d$, $^3He + ^3He$ and $d + ^6Li$ [20]. From these facts, Rolfs et al. summarize and stressed that there are additional effect for enhancement could be obtained if the target nuclides have a momentum distribution through a nuclear recoil from atomic electrons [21].

Isotopic dependence of screening effect

The fusion reactions $^6Li(p,\alpha)^3He$, $^6Li(d,\alpha)^4He$ and $^7Li(p,\alpha)^4He$ have been studied to investigate the isotopic effects on electron screening by using solid and gas target [22]. They concluded the deduced values of $U_e$ for all three reactions are identical within experimental error that is, no evidence for these effects. In addition, the difference between atomic and molecular targets was explained by the effects of Coulomb explosion.

Recent experimental studies for screening potential problem

There are several experimental efforts to deduce the screening potential:
1) By using invert reaction between target and projectile, such as $^3He(d,p)^4He$ and $d(^3He,p)^4He$ has been measured at the center of mass energies $E = 35$ to $60$ keV and 10 to 40 keV. The experiment determined the respective screening potential energy $U_e = 319 \pm 7$ and $109 \pm 9$ eV [23]. They are both higher than the values from atomic physics models $U_e = 320$ and $65$ eV.
2) By changing the target pressure the experiment establish the values for the energy loss used in data reduction and screening potential energy for $d(^3He,p)^4He$, $U_e = 332 \pm 9$ eV [24]. The data so far obtained in various reactions for screening potential problem are summarized in Figs. 1 to 4.

Trojan Horse method

Experimental comparison for screening potential values obtained by different methods has been extensively discussed [25, 26]. With the advent of new technique such as Trojan Horse Method (THM), it would provide direct data for bare and bare nucleus interaction at extreme low energy region if the kinematical condition is satisfied in THM. The principle of the THM is described in detail [27]. With this method applied to $^7Li+p$ reaction, the energy dependence of the astrophysical $S$-factor of bare nucleus interaction has been obtained down to the relevant energies free of the Coulomb barrier and electron screening. The result of a fit at the energy larger than 100 keV including two sub-threshold resonances agrees fairly well with the data obtained with the THM, although absolute values of the $S$-factor for bare nucleus should be normalized by using a direct measurement at energies where the effects are negligible. It is noticed that the
screening potential remarkably enhances the $S$-factor by a factor two or three in low center of mass energy. Therefore, it seems that $S$-factor data obtained so far and the value of screening potential might have a large ambiguity at the real stellar condition [27].
FIGURE 3. Screening potential for d(³He,p)⁴He interaction obtained by (a)[4], (b)[7], and (c)[22].

FIGURE 4. Screening potential for ⁶Li(d,d)⁴He and ⁷Li(p,α)⁴He interaction obtained by (a)[1] and (b)[43].

NEW EXPERIMENTAL APPROACHES

In order to achieve the collision experiments for state selective and to obtain more experimental results many diagnostic tools developed for the fusion devices such as LHD, JT-60 and JET are extensively useful for collision experiment in astrophysical reaction experiment (NIFS compilation for atomic physics data are available). In addition, various devices developed for ion source technology to obtain the data of electron or ion density and their temperature are also helpful for this purpose [28]. Among these di-
agnostic devices photon spectroscopy is very useful to identify concerning states for the collision. For instance, 1) the total cross section for charge exchange of He$^{2+}$ ions with He are measured. State selective measurement for collision on the system He$^{2+}$ ions on neutrals by using ECR ion source and photon detection instrument (PES Photon Emission Spectroscopy) at KVI for a diagnostic tool of astrophysics [29]. (2) Capture, ionization and loss in He$^{1+}$ or He$^{2+}$ to He collisions are investigated by cold target recoil ion momentum spectroscopy (COLTORIMS) [30]. (3) Photon spectroscopy is applied for slow He$q^+ +$ He ($q$=1,2) collisions and double capture process are ascertained by observing the $1s^2\;1S_0 \rightarrow 1snp\;1P_1$ transition [31]. (4) Visible light spectroscopy are applied for studying ECRIS plasma [32]. (5) Various charge charge exchange and transfer cross section data are reported in the compilation for atomic physics study [33].

$^3$He($^3$He,2p)$^4$He reaction by using $^3$He$^{1+}$ and $^3$He$^{2+}$ ion beams

The experiments by using $^3$He$^{1+}$ and $^3$He$^{2+}$ ion beams with exactly the same center of mass energy which will be done with OCEAN in RCNP as shown in Fig. 1 [2]. In order to reduce systematic errors in experiments and theoretical ambiguity for estimation of screening potential energy, we are planning to follow the first experimental run of center of mass energy higher than $E_{cm} = 30$ keV for the $^3$He + $^3$He reaction by going down to the Gamow energy region. With OCEAN we are capable of taking the reaction data with $^3$He$^{1+}$ and $^3$He$^{2+}$ at their incident energy 50 keV (for $^3$He$^{1+}$ we raise the acceleration voltage to 50 kV while for $^3$He$^{2+}$ the value is half of that).

PES measurement for state selective reaction

Here we propose new experimental approach to determine the screening potential for fusion reaction. Since bare target atoms have never been available until now, we could propose a possible approach to investigate the atomic effect for screening potential of fusion reaction. Based on the present experiments of $^3$He($^3$He,2p)$^4$He reaction at low center of mass energy around 28 keV, it is noticed that incident beam remains partially charged and interacts with neutral target atoms. Thus, there happen various kinds of interaction between target and beam in charge states, such as $^3$He$_b$(0) + $^3$He$_t$(0), $^3$He$_b$(0) + $^3$He$_t$(1+), $^3$He$_b$(0) + $^3$He$_t$(2+), $^3$He$_b$(1+) + $^3$He$_t$(1+), $^3$He$_b$(1+) + $^3$He$_t$(2+), $^3$He$_b$(2+) + $^3$He$_t$(2+); where b and t means beam and target respectively.

These are possible combination of atomic states for target and beam though the target excitation might be hardly happened. In order to discriminate each contribution from these states to the screening potential, we are trying to introduce the electric or magnetic filter similar to the velocity filter (Wien Filter) before the target and detector assembly (Fig. 5). Observation of photon with a similar apparatus used in atomic physics study or diagnostic tools for plasma devices will be useful to discriminate for the atomic state participate to the nuclear reaction.
An experimental direct observation in a bare nucleus and bare nucleus interaction is crucial for the precise measurement for charged particle nuclear reaction [34, 35, 36, 37, 38, 39, 40]. For this purpose, we propose Beam Target apparatus by using an Electron Beam Ion Source as an installation for measurements of fusion cross sections among bare nuclei at low energies shown in Figs. 6 to 8. This will be most suitable installation for the measurement of astrophysical S-factor in the stellar condition. We already constructed the test bench by using ANAC ionizer as an apparatus for the reflex mode of EBIS with an axial ion injection system for storing nucleus generated with 2.45 GHz ECR ion source as shown in Fig. 5. We have a plan to investigate the amount and lifetime of stored ions in this warm bore EBIT by observing the extracted beam with several diagnostic devices.
CONCLUSION

To meet a terrestrial experimental condition as stellar state we can select temperature, density, pressure, atomic state and also do material such as solid, liquid, gas, and plasma. Of these, we showed importance and feasibility for bare to bare nuclear fusion reaction at similar condition of measurements as stellar state. We proposed BeTa and NARITA installation and they would be possible tools to study astrophysical $S$-factor free from the enhancement of screening potential.

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