Laboratory condition for fusion reactions in nuclear astrophysics

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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. 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. The laboratory experiments of reactions with bare target and bare beam will be achieved by using proposed Electron Beam Ion Trap Apparatus (NARITA).

§1. Introduction

During the last two decades, considerable experimental and theoretical research has been devoted to studying low energy fusion reactions in terrestrial condition. There has been aim to study fusion reactions in p-p chain concerned mainly with astrophysical argument for neutrino deficient problem. The measurements by Super-Kamiokande, SNOW and other radio chemical experiments confirmed the solution of large mixing angle for neutrino parameters such as $\delta m^2$ and $\tan^2\theta$. Although, the neutrino puzzle could be solved by the convincing evidence of the solar $\nu$-oscillation, there have been estimated uncertainties in predicted solar neutrino fluxes. When, we estimate the total neutrino flux by the solar luminosity, it is not true for the p-p flux as stressed by Bahcall. The way of proving the solar interior and determining experimentally which terminating reaction of the p-p chain, $^3\text{He}+^3\text{He}$ or $^3\text{He}+^4\text{He}$ is faster in the solar interior, is the solar neutrino experiments. The simple relation is introduced between the rate of $^3\text{He}+^3\text{He}$ to the rate of $^3\text{He}+^4\text{He}$ reactions averaged over the sun as the ratio can be expressed in terms of the p-p and $^7\text{Be}$ neutrino fluxes. The ratio could be a critical probe of the solar fusion. It should be noticed that the accurate measurements of the total p-p and $^7\text{Be}$ neutrino flux is so important to test the detailed prediction of the standard solar model. In addition, it needs a rigorous way to estimate the rates for both reactions averaged over the Sun than that ever achieved. Our recent study of cross section measurement for the $^3\text{He}+^3\text{He}$ fusion reaction will be helpful for this estimation. Generally, to obtain the precise data of fusion rate in terrestrial condition there are problems ascribed to the electron screening enhancement. The ambiguities of cross section enhancement prevent to deduce a precise reaction rate at stellar temperature. In this article, we introduce the theoretical background, and secondly we describe experimental results concerned with these problems and finally we propose the new experimental approaches to determine the electron screening potential of various atomic configurations for fusion reactions.
§ 2. Screening potential

In order to deduce the nuclear astrophysical S-factor or reaction rate in stellar condition from the measurement of fusion cross section, it is crucial to refer experimental results of atomic physics studies on charge state, charge transfer cross section and so forth. Generally, the screening potential enhances the cross section in usual laboratory experiments due to the atomic electrons present in the target and the projectile. This enhancement has already been reported in many experiments. Despite considerable efforts to reduce the ambiguity for the electron screening potential by using reaction data with various atomic states of projectile or target, the problem is not yet completely solved. Indeed, the values of the screening potential in the astrophysical S-factors estimated 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.

2.1. Adiabatic and sudden limit for screening potential

During the discussion, we use following expressions for astrophysical S-factor with the screening potential $U_e$ and the enhancement factor $f$:

$$
\sigma(E) = \frac{S(E)}{E} \exp(-2\pi\eta(E)), \quad \eta(E) = Z_1 Z_2 \alpha (2E/\mu c^2)^{-1/2},
$$

(2.1)

where $\eta(E)$ is the Sommerfeld parameter. $S(E)$ is the astrophysical S-factor, $Z_1$ and $Z_2$ are initial nuclei charge, and $\mu$ is the reduced mass, and enhancement factor $f$,

$$
f \equiv \frac{\sigma(E + U_e)}{\sigma(E)} = \frac{S(E + U_e)}{S(E)} \frac{E}{E + U_e} \frac{\exp(-2\pi\eta(E + U_e))}{\exp(-2\pi\eta(E))} \approx \exp(\pi\eta(E) U_e/E) \tag{2.2}
$$

When electron density is supposed to be unchanged during the collision, one can consider the electrostatic screening potential, as a sudden limit. In the case of smaller relative velocity of the nuclei compared with the electron velocity (Bohr velocity), electron densities are 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

$$
V_{\text{proj}} \ll V_{\text{bohr}},
$$

(2.3)

where $V_{\text{bohr}} = \alpha c$ and $u_e = \frac{\mu}{m_{\text{proj}}} u_{\text{target}}$.

ii) Adiabatic limit

$$
V_{\text{proj}} \ll V_{\text{bohr}}, \quad u_e = E^A(Z_1 + Z_2) - E^A(Z_2).
$$

(2.4)

2.2. Semi-classical mean-field theory

In ref. Takigawa et al. estimate the screening effects at extremely low energies in laboratory based on a semi-classical mean field theory for quantum tunneling. They present a method which can be applied to the problem lying between the adiabatic and the standard tunnelling (the dynamic norm method). Recently they expand ideas to the tunneling region which gives more close value to the adiabatic value.
2.3. **Thomas Fermi model**

Recently T.E. Liolios et al. derive analytical formula that establishes a lower and upper limit for the associated screened energy by means of the Thomas-Fermi model.\(^{14}\) It showed us the screening potential enhances the non-resonant cross section by several times larger than that of the bare nucleus.

2.4. **Bound electron effect**

Recently, Belyaev et al.\(^{10}\) estimate the effects of screening by bound electrons in the \(^7\text{Be} + p \rightarrow ^8\text{B} + \gamma\) reaction in the framework of the adiabatic representation of the three particle problem. In this, the screening effect of bound electrons is reduced to 10 %\(^{10}\).

### §3. Various experimental studies

3.1. **Isotopic dependence of screening effect**

The fusion reactions \(^6\text{Li}(p,\alpha)^3\text{He}, \ ^6\text{Li}(d,\alpha)^4\text{He}\) and \(^7\text{Li}(p,\alpha)^4\text{He}\) have been studied to investigate the isotopic effects on electron screening with solid and gas target by several groups.\(^{15}\) 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.

3.2. **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 \(^{12}\text{C}(p,p)\) reaction interprets 0.6 keV of the width as an atomic effect associated with excitation of the final atoms.\(^{16}\) More sophisticated experiments for the atomic effect to the nuclear reaction are the \(\alpha - \alpha\) scattering to the \(^8\text{Be}\) ground state (g.s.) 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.\(^{17} - ^{19}\) Atomic effects on \(\alpha - \alpha\) scattering to the \(^8\text{Be}\) g.s. are investigated 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 \(^{2+}\text{Be}\) with the third electron.\(^{20}\)

Although the enhancement due to the electron screening are suggested in many experiments 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 \(d + d, \ ^3\text{He} + \ ^3\text{He}\) and \(d + \ ^6\text{Li}\).\(^{11}\) 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.\(^{21}\)

3.3. **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 \(^3\text{He}(d,p)^4\text{He}\) and \(d(^3\text{He},p)^4\text{He}\) has been measured at the center of mass energies \(E = 5\) to 60 keV and 10 to 40 keV. The
experiment determined the respective screening potential energy,\cite{18)

\[ U_e = 219 \pm 7 \text{ and } 109 \pm 9 \text{ eV} \] (3.1)

which are both higher than the values from atomic physics models \( U_e=120 \) and \( 65 \text{ eV}, \)\cite{21)} \( 2) \) By changing the target the experiment establish the values for the energy loss used in data reduction, for \( d(^{3}\text{He},p)^{4}\text{He} \), \( U_e=123\pm9 \text{ eV}, \)\cite{4) \( U_e=132\pm9 \text{ eV}. \)\cite{22)}

These are summarized in Figs. 1 to 4.

\section{4. Trojan Horse method}

Recently there have been important techniques to investigate the S-factor without the electron screening effect; they are Trojan Horse method (THM) and the particular apparatus for bare target-beam interaction. Experimental comparison for screening potential values obtained by different reactions has been extensively discussed.\cite{3), 23), 24), 35)} \( 2) \) 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.\cite{25)} With this method applied to the \( ^{7}\text{Li}+p\rightarrow^{3}+\alpha \) 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.\cite{25)}

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
Reaction & \( U_e^{\text{THM}} \) [eV] & \( U_e^{\text{dir}} \) [eV] & \( U_e^{\text{ad}} \) [eV] \\
\hline
\( ^{6}\text{Li}(d,^{3}\text{He})^{4}\text{He} \) & 320\pm50 & 330\pm120 & 186 \\
\( ^{7}\text{Li}(p,^{3}\text{He})^{4}\text{He} \) & 330\pm40 & 300\pm160 & 186 \\
\hline
\end{tabular}
\caption{Electron screening potential energy for the studied reactions compared with direct measurement and the adiabatic prediction.\cite{25)}
\end{table}

\section{5. New experimental approaches}

Many diagnostic tools developed for the fusion devices such as the LHD, the JT-60 and the JET are extensively useful for collision experiment for astrophysical study (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.\cite{26)} Among these diagnostic devices photon spectroscopy is very useful to select the concerning states for the collision. For instance, (1) the total cross section for charge exchange of \( ^{2+} \text{He} \) ions with \( ^{4}\text{He} \) are measured. State selective measurement for collision on the system \( ^{2+} \text{He} \) ions on neutrals by using ECR ion source and photon detection instrument (PES Photon Emission Spectroscopy) at KVI for a diagnostic tool.\cite{27)} (2) Capture, ionization and loss in \( ^{1+} \text{He} 2+ \) to \( ^{4}\text{He} \) collisions are investigated by
cold target recoil ion momentum spectroscopy (COLTORIMS). Photons are applied for slow \( \text{He}^{q+} \) + He (\( q=1,2 \)) collisions and double capture processes are ascertained by observing the 1s\(^{2}S_{0} \) 1snp\(^{1}P_{1} \) transition. Visible light spectroscopy is applied for the studying ECRIS plasma. Various charge exchange and transfer cross section data are reported in the compilation for atomic physics study, such as total cross section data for charge exchange of He\(^{2+} \) ions with He and Ar atoms.
5.1. $^3$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 (Fig. 5). In order to reduce systematic errors in experiments and theoretical ambiguity for estimation of the screening potential, we are planning to follow the first experimental run of center of mass energy higher than $E_{\text{c.m.}}=30$ 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 incident energy 50 keV.

![Fig. 5. Complete layout of OCEAN.](image)

5.2. 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 the screening potential of fusion reaction. Based on the present experiments of the $^3$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+), b and t means beam and target respectively.

These are possible combination of atomic states for beam and target 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. 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 which participates in the reaction.
5.3. **Nuclear astrophysics researches in ion trap apparatus (NARITA)**

An experimental direct observation in a bare nucleus and bare nucleus interaction is crucial for the precise measurement for charged particle nuclear reaction.\(^{32} - 34\) For this purpose, we propose Beam Target apparatus (BeTa) and NARITA 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. 8 and 7.\(^28\) 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 the 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.

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**Fig. 6.** Similarity between beam production (ion source) and gas target interaction.

**Fig. 7.** The apparatus of NARITA.

**Fig. 8.** Principle of Electron Beam Ion Trap.

**Fig. 9.** Prototype apparatus for EBIT.
§ 6. Conclusion

We have stressed that to solve the entangling problem for enhancement due to the electron screening is to reduce the ambiguity for experimental condition at the laboratory. For this purpose we proposed the fusion experiment $^3\text{He} + ^3\text{He} \rightarrow 2\text{p} + ^4\text{He}$ reaction at Gamow energy by using existing facility (OCEAN). We expect the first experiment with bare target and bare beam could open new era for precise laboratory experiment of nuclear astrophysics.

References

30) O. Tuske, I. Maunoury, er al., to be published in Proc. 10th International conference on Ion sources.