Application of beam physics to nuclear astrophysics research

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Abstract

A design of an ion trap apparatus for measurements of excitation functions of d(d,p)t and ^{3}He(d,p)^{4}He reactions with bare beam and target at energies below the Coulomb barrier is presented. It aims to deduce the exact astrophysical S-factor (cross section) without any modification due to the atomic electrons of target or both projectile and /or target particles in the region $1.5 < E_{cm} < 12$ keV and $6.5 < E_{cm} < 15$ keV. The technology of Electron Beam Ion Sources and Traps(EBIT) has been applied substantially to solve luminosity and background problems for the measurement of nuclear reactions with less than nano-barn cross section for astrophysical interest.

1 INTRODUCTION

During the last two decades considerable experimental and theoretical research has been devoted to studying electron screening effects of fusion reactions in nuclear astrophysics [1, 2, 3, 4, 5, 6]. To obtain the information concerning the screening effect from experimental excitation functions based on measurements at higher energies, one usually applies the astrophysical S-factor $S(E) = s(E)exp(2\pi\eta)$ with $2\pi\eta = 31.29\, Z_1 Z_2 (m/E)^{1/2}$ where m is the reduced mass, since the cross section exponentially decreases to the Gamow energy region. This procedure is not free from theoretical bias and may bring an additional uncertainty. 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 [1, 2, 3, 4, 5, 6], the problem is not yet completely solved. Indeed, the values of the screening potential in the astrophysical $S(E)$ factors, calculated from the measured excitation functions, show unexplained quantitative differences from theoretical values [5]. There are various reasons for the differences: insufficient accuracy of the experimental data such as stopping power, and imperfect theory of many body systems for fusion reaction including bound electrons. In addition, one has to mention that experimental data for cases of bare nuclides, participating in such fusion reactions, were not obtained until recently.

In order to diminish the uncertainties the idea that exploits an Electron Beam Ion Source(EBIS) as an installation for measurements of fusion cross sections among bare nuclides at low energies has been introduced [7, 8]. In this article we apply this idea to the design in which an electron beam (or an electron string) is used for the production of bombarding bare nuclides, and also used for their confinement. We shortly describe the construction of this apparatus, which was named BeTa (Beam and Target), and various modes of its operation. The basic experimental procedures are also considered and the expected detection rates of fusion events and accuracy of cross section measurements for several fusion nuclear reactions are evaluated.

2 DESCRIPTION OF THE BETA APPARATUS

An Electron Beam Ion Source (EBIS) [9] consists of an electron gun, a drift tube, a super conducting solenoid, an electron collector, ion injection, confinement, extraction and charge state analysis system, gas injection and an ultra high vacuum system. The electron gun usually produces an electron beam of 0.1 - 1 A current and 0.1 - 1 mm diameter.

To save on electron beam power one can use the reflex mode of EBIS operation, which leads to the creation of the electron string state of confining electrons [10, 11] and is also used for the production of highly charged ions. Similar to an EBIS, the proposed BeTa apparatus (see Fig. 1) consists of an electron gun, a drift tube, an electron collector (or an electron reflector for the Reflex mode of operation), a cryo magnet system with a super conducting solenoid, an ion charge state analyzer and an ultra high vacuum system. In addition, the BeTa has an assembly of semiconductor detectors surrounding the trapped target for the spectrometry of reaction products. The cryo magnet system of BeTa includes a 5 T super conducting solenoid of 1.4 m length and 5 cm inner diameter of bore, an appropriate power supply and a cryo cooler. Two different electron guns will be used: a) Pierce type gun IrCe cathode of 1.5 mm diameter and 1.4×10^{-6} A/V$^{3/2}$ perveance. The use of this type of emitter material allows one to get a current density up to 50 A/cm^2. Only a small modification of the gun, is necessary for the Reflex mode of operation. b) The circular gun with a cathode of 28 mm radius and 1.5 mm width and a perveance of about 200×10^{-6} A/V$^{3/2}$. These electron guns are situated in a fringe field of $B = 1/8\ B_{max}$, which provides at least 400 A/cm^2 electron current density in the ion trap region.

The magnetically shielded electron collector for the Pierce type gun is installed on the ground potential terminal and is located on the opposite side (compared to the gun) of the solenoid. In the case of using the Reflex mode of operation, the electron reflector with a similar structure to the electron gun will be installed in the fringe field of the solenoid. The drift tube structure consists of two parts: The first part which will surround a region of a nuclear beam has a length about 50 cm and is assembled from solid drift tubes, while the second one, which will surround a region of a nuclear target is about 70 cm length and consists of highly transparent tubes for detecting reaction products. These two parts are separated from each other by means of the ion accelerator tube. The accelerator tube serves as a vacuum separator between the beam and the target sections of the drift tube. A similar tube will also be installed between the electron gun and ion beam production regions.

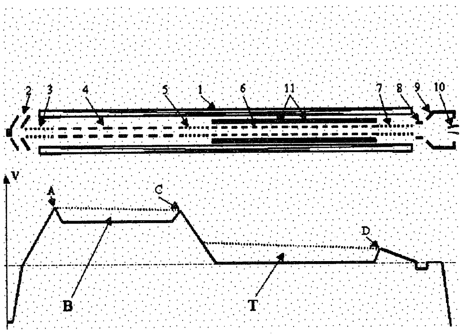

Figure 1: Schematic view of the BeTa apparatus(up) and of the voltage (V) distribution along its axis (down): (1)super conducting solenoid (2)electron gun (3)electron accelerating tube and gun vacuum separator (4)drift tube sections(5)ion accelerating tube and a middle vacuum separator (6)drift tube sections(7)electron collector vacuum separator (8)electron suppressor (9)electron collector (10)ion extractor (A,C,D) potential barriers(B)beam nuclei potential trap (T)target nuclei potential trap.

3 DESCRIPTION OF EXPERIMENTAL PROCEDURES

3.1 Formation of Electron Beam

A schematic view of the BeTa apparatus and the potential along its axis are shown in Fig. 1. Use of the Pierce type electron gun provides an electron beam of 1 A current at 8 keV energy. Taking into account a factor 8 for magnetic compression, this gives an electron density of 5.1×10^{11} e/cm^3 in the space of the regular magnetic field. It is also known [10], that use of the Reflex mode of EBIS operation leads to the creation of an electron string with a number of confined electrons. The electron density will be similar or higher to that in an electron beam produced with the same energy. Although a factor 50 -100 less power is necessary to feed such a string by electrons, the definition of the radial dimension is not so good compared to a magnetically immersed electron beam. Thus, in case of the string mode some additional measurement will be undertaken to get the actual electron densities. The circular structure of a cathode gun has 200 times larger perveance because of 200 times larger emitting space provided it has nearly the same electron density.

3.2 Formation of a Target of Nuclides

In order to form fully stripped ions such as ^{3}He^{++}, a small amount of gas is introduced into the target region of the drift tube. The volume determined by the pumping speed will be only be about 3.5×10^9 molecules or atoms/cm^3, which is sufficiently accumulated during target formation by means of electron beam trap (or string) for the ions. Taking into account the electron impact ionization cross sections for 8 keV electrons as well as the ion trap capacity, the trap is filled with ions during about 6 ms. After such a period of accumulation the target of nuclides gets a final thickness equal to 3.6×10^{13} deuterons/cm^2 or 1.8×10^{13} target of nuclides which is about 150 times thicker than that of residual neutral gas. The total number of the nuclides in a target will be measured by means of their axial extraction and measurement of their total charge with the Faraday cup. The target thickness is determined by using the definite radial dimension of the electron beam, which will be done by measurement of a dependency of an accumulated ion charge on the trapping voltage [10].

3.3 Production of a Beam of Nuclides

The deuteron (or ^{3}He^{++} nuclides) beams are produced in the corresponding region of the drift tube structure of about 50 cm length. In the fusion reaction study of d(d,p)t the particle beams are produced by electron impact ionization of D_2 molecules, followed by ion accumulation and further ionization in the ion trap B as shown in Fig. 1. The corresponding gas flux and pumping speed provides about 1.3×10^{11} molecule/cm^3 concentration in the beam production region. The 50 cm length deuteron trap is filled with deuterons during about 200 ms. A necessary potential energy of the accumulated deuterons is provided by applying the corresponding voltage to the drift tube structure of the beam production sections (see Fig. 1). The deuterons are slowly (during about 10 ms) extracted from the trap and directed to the nuclear target via the acceleration tube by increasing the trap bottom potential by about 10 - 15 eV in the case of deuterons [10]. In addition, this extraction provides the full beam-target overlap since extracted ions travel mostly along the pre-axial part of an electron beam (and a target). After interaction with a target, the beam leaves the drift tube in the axial direction. As a result, about 40 mA equivalent DC ion current is obtained in the case of the Pierce type electron gun, while in the case of the ring cathode gun the equivalent deuteron current reaches 8 mA or more. A more sophisticated, of the BeTa operation the so-called "ping-pong" mode is used for the study of extremely small cross sections so as to increase the repetition rate of the deuteron(or other nucleus) by a factor 5-10. In this mode the deuterons accumulated in the beam production trap and interact with the target one time, are decelerated and trapped again in the ion trap (which is located at the opposite side to the beam production trap of the target as already shown in Fig. 1). They are then sent back to the target and to the beam production region where they are retrapped and so on. Certainly the target nucleus temperature has to increase and some high energy beam particles accumulate in the target region due to very high potential barriers. The removal of such particles is necessary in the "ping-pong" mode for particles retrapping on the both sides of the target as well as for their acceleration.

3.4 Detection of Nuclear Reaction Products

In the study of the d(d,p)t and ^{3}He(d,p)^{4}He nuclear reactions, the detection of reaction products such as protons is crucial for the measurements of excitation functions. For higher detection efficiency a silicon surface barrier ΔE- E counter telescope is need around the drift tube of the target section. The detectors will be situated in a ultra high vacuum and on a 78 K temperature terminal, which gives better energy resolution and the possibility to apply the necessary high voltage sufficient for 14 MeV protons incident on the detector surface. By taking into account the target thickness, the deuteron beam current for different gun structures and for modes of operation, one can estimate the counting rates of protons for the fusion reaction in the energy region when exploiting the existing cross section data by assuming 50The results are presented in Fig. 2. The counting rate of 1 count/hour seems like the limit for obtaining definite data on the cross section under consideration. This borderline in Fig. 2 indicates that the majority of data for d(d,p)t nuclear reactions in the energy region of interest can be obtained with the use of the simplest(Pierce) type gun and the simplest (beam) mode of operation for electron and deuteron beams, while for ^{3}He(d,p)^{4}He reactions these simplest cases can be used only for energy regions higher than 9 keV. The ring cathode gun and the string and "ping-pong" modes of operation have to be applied to the reactions in the whole energy region of interest.

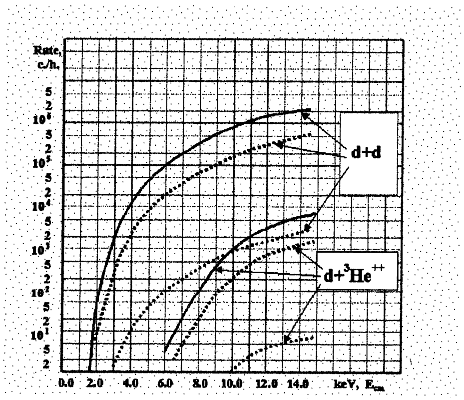

Figure 2: Expected proton counting rate (in counts per hour) for the fusion reaction indicated and for various modes of the BeTa operation: (dots - solid beam/string, pulse deuteron beam mode; squares - tubular beam/string, pulse deuteron beam mode; solid lines - tubular string, "ping-pong" deuteron beam mode).

4 POSSIBLE APPLICATION FOR OTHER FUSION REACTIONS

4.1 ^{3}He(^{3}He,2p)^{4}He fusion reaction

This reaction is one of the most interesting in the problem of the solar energy generation model and therefore it is closely connected with the solar neutrino problem. In the case of successful measurements of the excitation functions of d(d,p)t and ^{3}He(d,p)^{4}He reactions we would expect to use the BeTa apparatus for studying ^{3}He^{++} + ^{3}He^{++} reactions in achievable energy region. It is easy to evaluate that in the case of using a tubular electron string and ^{3}He nucleus pulse beam modes, when $T(^3\mathrm{He}^{++}) = 1.8\times10^{13}$ 1/cm^2 and $i(^3\mathrm{He}^{++}) = 7$ mA, the sensitivity of the BeTa would limit the cross section measurements to a level near 10-34 cm^2. One more order of magnitude could allow use of the "ping-pong" mode for ^{3}He^{++} beam production. To reach a region of about 1 pico barn could then be possible in the case of formation of denser (up to 1000 A/cm^2) electron strings, which would require a strong magnetic field for confinement.

4.2 $p(^7Be, \gamma)^8Be \rightarrow 2\alpha$ reaction

The sensitivity of the BeTa apparatus with respect to the p + ^{7}Be^{4+} reaction would be the same as for ^{3}He^{++} + ^{3}He^{++} reaction if one could provide a sufficient Be+ current to keep the bare Be target always on the level of 1×10^{13} 1/cm^2. The required feeding current will depends mostly on losses of ^{7}Be^{4+} from an electron string ion trap and therefore will be determined by the temperature of Be nuclides trapped. We can expect then that the average life time of Be nuclide in the trap can be about 1 s. To get such a life time and perhaps sufficiently increase it one has to provide a sophisticated procedure of evaporative cooling of ^{7}Be^{4+} by atomic Hydrogen, for example. The evaporative cooling provides keeping ions of heavy elements in an electron ion trap for hours [12], but it is usually not applied for cooling of light elements, and additional researches of ion cooling would be necessary.

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