BRIEF COMMUNICATIONS

Steady-state thermonuclear plasma as a source of nuclear-physics data

V. G. Kiptilyi and V. O. Naïdenov

A. F. Ioffe Physicotechnical Institute, Russian Academy of Sciences, 194021 St. Petersburg, Russia
(Submitted July 10, 1997)
Zh. Tekh. Fiz. 69, 114–118 (January 1999)

Measurements of cross sections of nuclear reactions of charged particles in the kiloelectron-volt range present a difficult experimental problem because of their small size. At the same time, the need for accuracy in the determination of such cross sections continues to grow in connection with the active development of such branches of science as controlled thermonuclear fusion, astrophysics, cosmology, and nuclear physics itself. The present communication discusses the motivation for performing experiments in this energy range and the difficulties such experiments involve, and proposes a new experimental approach to measuring the cross sections of such reactions using the steady-state plasmas available in thermonuclear facilities.

INTRODUCTION

Nuclear physics has made it possible to place the solution of many problems of cosmology, astrophysics, and plasma physics on a quantitative basis. In turn, the development of these sciences poses new problems for nuclear physics, the prospects for solution of which depend on the level of knowledge and experimental database of nuclear physics. A striking example of this interaction is provided by ongoing research on the problem of solar neutrinos. The nuclear-physics approach to the solution of this problem is to examine peculiarities of the mechanisms of low-energy nuclear reactions. This is not the only example of this kind, and for this reason it is of interest to consider a number of basic problems whose solution requires a knowledge of cross section data on the nuclear reactions of light nuclei at astrophysical energies. We did not set it as our goal in Sec. 1 to provide an exhaustive review, rather this paper should be viewed as an attempt to highlight what in our opinion are the most important directions in this field. Section 2 discusses the difficulties of experimentally examining low-energy nuclear reactions, and also problems of analysis and interpretation of data. Section 3 provides a description of a new experimental approach to obtaining information about nuclear cross sections and represents an attempt to put it on a solid basis. It is proposed to use a thermonuclear plasma like those existing in tokamaks as a source of low-energy nuclear reactions.

1. SOME LOW-ENERGY NUCLEAR-PHYSICS PROBLEMS

a) Liberation of heat in stars. Self-consisting stellar models which yield observable characteristics (brightness, size, mass, temperature, etc.) are based on the assumption of the thermonuclear nature of the liberated energy as a result of an entire train of exothermic nuclear reactions. For example, static nucleosynthesis in stars of the main sequence such as the Sun pass through the hydrogen \((p - p)\) and the carbon–nitrogen (CNO) cycle. At the same time, the cross section of the main reaction of the \(p - p\) cycle \(p + p \rightarrow d + e^+ + \nu\) and of an entire train of others in this chain have either not been measured or have been measured with insufficient accuracy, e.g., the reaction \(7\text{Be} + p \rightarrow 3\text{B} + \gamma\). None of the cross sections of the reactions of the \(p - p\) cycle have been measured at energies of the order of 1.5 keV, corresponding to the temperature at the center of the Sun. At present, physical conclusions are based on cross sections extrapolated from values measured at higher energies.

To solve the problem of solar neutrinos, additional data on cross sections of the reactions \(^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + 2p\), \(^3\text{He} + ^4\text{He} \rightarrow 7\text{Be} + \gamma\), \(^7\text{Be} + p \rightarrow ^3\text{B} + \gamma\), and \(^15\text{N} + p \rightarrow ^{16}\text{O} + \gamma\) can be of great significance.

Stars at later stages of the evolution of “hot matter” contain the heavier elements \(^4\text{He}, ^{12}\text{C}, ^{14}\text{N}, ^{16}\text{O}, \text{ etc.}\) And although the temperature in the interiors of such stars is higher than for the Sun, the higher Coulomb barrier significantly lowers the probability of nucleosynthesis. Here the situation with the experimental data is even more dramatic. Thus, the authors of Ref. 2, for example, use the most recent nuclear data, which differ from the data published earlier in the review of Ref. 3 — by a factor of 1.7 in the case of the reaction \(^{12}\text{C} (\alpha, \gamma) ^{16}\text{O}\), and by two to three orders of magnitude for the reactions \(^{17}\text{O}(p, \gamma) ^{18}\text{F}\) and \(^{17}\text{O}(p, \alpha) ^{14}\text{N}\).

b) Nucleosynthesis. The problem of nucleosynthesis can be divided into two parts: synthesis of primordial elements and synthesis of elements in subsequent stages of the evolution of the Universe. The first direction, if we retain the model of a hot Universe, does not touch directly upon the problem discussed in the present paper, since the process of formation of primordial elements occurs at relatively high energies (0.1–1 MeV) and the necessary reactions are quite well known. Problems still arise here, associated with experimental difficulties of absolute measurements. Thus one can...
discern a clear pattern over the last 20 years in which papers have periodically appeared which do not address the fundamentals of the theory but rather apply new, refined cross-section data. The abundance of primordial elements such as H, D, 3He, 4He, and 7Li, serves as a starting point for models of the chemical evolution of stars, galaxies, interstellar matter, etc. The most sensitive to the parameters of the evolutionary models are D, 3He, and 7Li. In this regard, the deuterium content, in contrast to 4He and 7Li, during the evolution of a star can only decrease relative to the content of a primordial element. Comparison of calculations with experiment is hindered as a result of the large spread of data in the elemental content of various objects of the Universe. Thus, the deuterium content of the protosolar matter, if we identify the latter with the atmospheres of Saturn, Jupiter, Uranus, and Neptune, varies from \((1.6 \pm 1.3) \times 10^{-5}\) (Ref. 5) to \((3.6 \pm 1.4) \times 10^{-5}\) (Ref. 6), given as the D/H ratio. Evolutionary models\(^7\) predict a decrease of the D/H ratio by a factor of 2–2.5 between the primordial state and the present state of the Universe. At the same time, the first measurements of the primordial deuterium content\(^8,9\) in the direction of the quasar Q0014+813 (\(z = 3.32\)) gave D/H = 2 \(\times 10^{-4}\). If direct measurements of primordial deuterium are confirmed, then it will become necessary to reconsider the evolutionary model of the Universe and introduce into consideration as-yet unknown processes of rapid burnup of deuterium.

An analogous situation arises in the case of 3He; the evolutionary models\(^7\) predict values 5–7 times greater than the values corresponding to the time of formation of the Sun, and 5–20 times greater than the values corresponding to the HII galactic regions (compact blue galaxies with low heavy-element content, which are identified with the smallest chemical evolution. Calculations by the authors of Ref. 7 show that the problem can be eliminated if there exists a hypothetical energy resonance below 10 keV in the nuclear reaction 3He + 3He \(\rightarrow\) 4He + 2p. The existence of this resonance was first proposed to solve the solar neutrino problem.\(^10,11\) In fact, a special accelerator was built just to study this reaction at low energies (Project LUNA) under ultralow background conditions.\(^12\)

c) Controlled thermonuclear fusion (CTF). Most thermonuclear facilities of tokamak type use DD plasma at temperatures of 0.5–15 keV. For additional high-frequency heating, small amounts of H and 3He are added to the plasma. Recent experiments with DT plasma at the large JET and TFTR thermonuclear facilities have shown that self-sustained burning can now be achieved in an experimental thermonuclear reactor. Obviously, the accuracy requirements on the cross section data on the nuclear reactions taking place in the plasma increase with the approach of the practical use of thermonuclear energy.

There is another aspect to the problem of nuclear reactions in CTF, namely the search for “cleaner” fuels and final products (in the sense of their radioactivity) 6Li + H \(\rightarrow\) 3He + 4He, 11B + H \(\rightarrow\) 3He, 7Li + H \(\rightarrow\) 4He, 10B + H \(\rightarrow\) 7Be + 4He. The lowest energy at which the last reaction was studied was 18.7 keV (Ref. 13). The results indicate that a resonance can be expected at 10 keV, which corresponds to a plasma temperature around 4.9 \(\times 10^6\) K. A study of this problem would be incomplete without a parallel study of the competing channel of the reaction 10B + H \(\rightarrow\) 7Li.

d) Nuclear-physics problems. A study of nuclear interactions of small-nucleon systems and especially reactions of radiative capture occupies a special place in nuclear physics since in some cases it allows one to calculate the contributions of different reaction channels. As was already noted, problems of low-energy resonances are very important.

In this sense, the reaction \(D(d, \gamma)\)\(^3\)He is of special interest since a study of this reaction can provide information about the structure of the wave functions of a system of two deuterons in the region of the continuum and the ground state of 4He. Cross sections of the reaction \(D(p, \gamma)\)\(^3\)He at low energies are needed to investigate scattering in \(n – d\) and \(p – d\) three-nucleon systems and also capture of p and s protons with subsequent transition to the ground state 2S\(^1\)\(_2\) of the \(^3\)He nucleus via E1 and M1 transitions. The authors of Ref. 14 calculated the contributions of E1 and M1 amplitudes to the total cross section of the reaction \(D(p, \gamma)\)\(^3\)He. They showed that their ratio varies quite noticeably as a function of the reaction energy: \(E1:M1 = 3:2\) for 1.2 MeV and \(E1:M1 = 1:9\) for 12 keV. It may be expected that this effect is manifested in the excitation function of the reaction at low energies. Analogous problems arise in the analysis of the reaction \(7\)Li\((p, \gamma)\)\(^8\)Be (Ref. 15).

2. EXPERIMENTAL PROBLEMS OF CROSS-SECTION MEASUREMENTS

The small value of the cross sections is the main difficulty in experiments performed in the kilovolt energy range. Thus, the cross section of the above-mentioned reaction 3He + 3He \(\rightarrow\) 4He + 2p at 25 keV is \((7 \pm 2) \times 10^{-12}\)b (Ref. 16). To measure such cross sections, it is necessary to undertake special measures such as have been undertaken in the German–Italian Project LUNA (Laboratory for Underground Nuclear Astrophysics).\(^12\) A special 50-keV accelerator has been assembled in an underground laboratory (Gran Sasso), where the background level in the case of the reaction 3He + 3He \(\rightarrow\) 4He + 2p is of the order of one event per day. Nevertheless, sufficient statistical accuracy at 15 keV is achieved for an exposure of around six months.

In the traditional experimental setup for measuring cross sections of low-energy nuclear reactions there is one more problem, connected with electron screening of the nucleus. This question has been worked out in plasma physics\(^17\) and examined for the case of an astrophysical plasma at various densities and temperatures.\(^18,19\) In the thermonuclear plasma contained in tokamak-type setups, this effect is negligibly small. However, for solid-state and gaseous targets the problem of taking this effect into account has still not been solved. Experiments provide clear evidence of the influence of atomic-shell electrons on the cross section of the nuclear reaction.\(^12,13\)

Screening lowers the Coulomb barrier for the bombarding particle and thus increases the yield of the reaction. The penetrability of the Coulomb barrier at an energy \(E\) in the center-of-mass system enters into the expression for the