ANNOTATION

of the dissertation thesis for the degree of "Doctor of Philosophy" (PhD) in the educational program "8D05308 - Nuclear physics" by

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RADIATION CAPTURE AND PERIPHERAL NUCLEAR REACTIONS OF PROTON TRANSFER ON ^{12}C NUCLEI CAUSED BY HEAVY IONS AT ENERGIES NEAR THE COULOMB BARRIER

General description of the work

The purpose of this work is aimed at elucidating the contribution of direct radiation capture of a proton to the reaction of $^{12}C(p,\gamma)^{13}N$ by determining the value of the spectroscopic factor (SF) for $^{12}C+p\rightarrow{}^{13}N_{g.s.}$, which helps to correctly estimate the reaction rate in nuclear processes. To do this, the differential cross sections (DCS) of proton transfer in the reaction $^{12}C(^{10}B,^{9}Be)^{13}N$ at an energy of 41.3 MeV were measured and analyzed using the Distorted Wave Born Approximation (DWBA) method and coupled reaction channels (CRC) using the FRESCO program code. A spectroscopic amplitude (SA) value of 0.65 was obtained, which was used to estimate the astrophysical S(E) factor and the reaction rate of radiation capture of a proton by a ^{12}C nucleus at energies of astrophysical significance. Also, in order to increase the accuracy of the extrapolation of the S(E) factor in the low energy range available to us, additional measurements of the cross sections of radiation capture reactions were carried out on the linear accelerator UKP-2-1 of the Institute of Nuclear Physics of the Ministry of Energy of the Republic of Kazakhstan.

The Relevance of the research

This work is devoted to a comprehensive study of nuclear reactions caused by ^{10}B ions and protons in ^{12}C nuclei associated with nucleosynthesis in the Universe, since the formation of the $^{12}C+p\rightarrow{}^{13}N$ reaction in the process of nucleosynthesis and stellar evolution is a key factor. Knowledge of the quantitative abundance of the element ^{13}N in stars is extremely important, since this core is the starting point for the emergence of the cold and hot CNO cycle of hydrogen combustion in stellar nucleosynthesis through the reactions $^{12}C+p\rightarrow{}^{13}N^{*}(\beta^{+}\nu)\rightarrow{}^{13}C+p\rightarrow$(“cold” cycle) or, at higher temperatures, $^{12}C+p\rightarrow{}^{13}N+p\rightarrow{}^{14}O+p\rightarrow$ (“hot” cycle). With the complete combustion of hydrogen at later stages of stellar development, intense radiative capture of alpha particles by ^{12}C nuclei begins with the formation of oxygen. The ^{12}C nucleus is also an intermediate stage in the formation of the ^{13}C nucleus. In turn, the $^{13}C(\alpha,n)^{16}O$ reaction is the main source of neutrons for s and r - processes in AGB-branch stars and carbon-enriched weakly metallized stars. In addition, the $^{12}C(p,\gamma)^{13}N$ reaction is considered to be a source of low-energy solar neutrinos in massive stars, in addition to hydrogen being a necessary combustion component in the CNO cycle (GALLEX experiment). Therefore, knowledge of the energy dependence of the astrophysical S factors (S(E)) of the $^{12}C(p,\gamma)^{13}N$ reactions at ultra-low ($0\leq E\leq 50$ keV) and low energies ($E\leq 2.0$ MeV) is of great interest in nuclear astrophysics and Cosmology. Consequently, we need differential and total

cross sections for radiative capture, elastic scattering, and parameters of nuclear potentials extracted from their analysis.

Earlier research on this topic began in the 1950s in a number of papers. Currently, there are two sets of mutually consistent experimental data on S(E) for the reaction $^{12}C(p,\gamma)^{13}N$, measured in the range $327 \leq E \leq 980$ keV in the works of Rolfs C. (1974), Burtebaev N. et al. (2008), that is, in the region of the first resonance state of the ^{13}N nucleus ($E^*=2.365$ MeV;$1/2^-$), and the results of the mentioned works are more reliable (absolute error ~10%) compared to the experimental work of Tribble R.E. (2014), where the error is ≥15%). And the available experimental works by Angulo C. (1999) on the S(E) factor at E>980 keV, i.e. above the second resonant state of the ^{13}N core, $E^*=3.502$ MeV; $3/2^-$, contain large errors (≥40%). Also, a study carried out by Dufour M. and Descouvemont P. (1997) included an analysis of the S(E) factor of the reaction $^{12}C(p,\gamma)^{13}N$ at the microscopic level using different types of NN potentials. They found that the shape of these potentials had a significant impact on the results. One of the reasons for this sensitivity was that the calculations of SF for $^{12}C+p\rightarrow{}^{13}N$ were also influenced by the shape of the NN potential, as shown in the work of Timofeyuk N.K. (2013). In connection with the above, it is important to obtain new information about the spectroscopic factor SF value for $^{12}C+p\rightarrow{}^{13}N$ with a correct assessment of its accuracy.

The purpose of the dissertation is to determine reliable values of the reaction rates of the CNO cycle of hydrogen combustion $^{12}C(p,\gamma)^{13}N$ in the stellar temperature range ($0.1 \leq T_9(K) \leq 10$) using the values of the spectroscopic factor for the configuration $^{12}C+p\rightarrow{}^{13}N$ from the analysis of the proton transfer reaction $^{12}C(^{10}B,^{9}Be)^{13}N$, as well as conducting measurements of cross sections of radiation capture reactions in order to increase the accuracy of astrophysical S(E) factors.

Research objectives

To achieve these goals, the dissertation work sets the following tasks:

− perform new measurements of radiative capture cross sections (astrophysical S(E) factors) of the $^{12}C(p,\gamma)^{13}N$ reaction in the energy range E_{lab} = 1100 – 1400 keV;

− perform new measurements of the differential cross sections of elastic scattering $^{12}C(^{10}B,^{10}B)^{12}C$ and the proton transfer reaction $^{12}C(^{10}B,^{9}Be)^{13}N$ at an energy of 41.3 MeV;

− obtaining the parameters of optical potentials for elastic scattering of $^{12}C(^{10}B,^{10}B)^{12}C$ at an energy of 41.3 MeV and determining the energy dependence in a wide energy range.

− perform a theoretical analysis of the angular distributions of the DCS of proton transfer in the reaction $^{12}C(^{10}B,^{9}Be)^{13}N$ within the framework of DWBA and CRC using the FRESCO code and obtaining the SF for the $^{12}C+p\rightarrow{}^{13}N$ configurations;

− calculate and compare with the literature data the reaction rate of radiative capture of $^{12}C(p,\gamma)^{13}N$ at stellar temperatures $0.1 \leq T_9 \leq 10$ ($T_9=10^9$ K).

Object of study

The objects of the study are to determine the rates of radiative proton capture in the reaction $^{12}C(p,\gamma)^{13}N$, which are the initial and final stages in the CNO cycle of stellar hydrogen combustion at temperatures corresponding to the Gamow window. At such energies, when in the $^{12}C+p$ system the interaction is determined by the interference of direct and resonant proton capture with resonance at $E_r = 0.457$ keV, an accurate assessment of the contribution of direct proton capture, estimated through spectroscopic amplitudes (SA) for configurations $^{12}C+p\rightarrow{}^{13}N$.

Subject of study

Experiments to measure the energy spectra of the products of nuclear reactions of proton transfer $^{12}C(^{10}B,^{9}Be)^{13}N$ and elastic scattering $^{10}B+^{12}C$ at near barrier energies of ^{10}B ions are planned to be carried out on the extracted beam of the U-200P AVF cyclotrons of the Heavy Ion Laboratory of the University of Warsaw using a registration and identification system types of particles based on the ΔE-E technique, as well as measurement of differential cross sections of $^{12}C(p,\gamma)^{13}N$ at low energies at the UKP-2-1 linear accelerator of the Institute of Nuclear Physics of the Ministry of Energy of the Republic of Kazakhstan;

Research methods

Literature review, experimental and theoretical study of nuclear reactions for astrophysical applications, methods of theoretical nuclear physics.

The main provisions for the defense:

1. New experimental angular distributions of elastic scattering $^{12}C(^{10}B,^{10}B)^{12}C$ and proton transfer reaction $^{12}C(^{10}B,^{9}Be)^{13}N$ at energy E_{10B}~41.3 MeV, and the results of their analysis within the framework of the Distorted Wave Born Approximation (DWBA) and Coupled Reaction Channels (CRC) method make it possible to reliably calculate the reaction rates $^{12}C(p,\gamma)^{13}N$;

2. The established value of the spectroscopic factor for the configuration $^{10}B+d\rightarrow{}^{12}C$ (SA=1.375) correctly reproduces the rise in elastic scattering cross sections by taking into account the contribution of the process of elastic transfer of the d-cluster at reverse angles and justifies their cluster structure;

3. The spectroscopic amplitude SA = 0.650 for $^{12}C+p\rightarrow{}^{13}N$, established from the analysis of the DCS reaction of $^{12}C(^{10}B,^{9}Be)^{13}N$, was used to evaluate the astrophysical S(E) factor and the reaction rate of radiation capture of protons, revealing that the average reaction rate at energies $E\leq200$ keV or $T_9\leq0.35$K 1.1 times higher than recommended in the NACRE II review.

The scientific novelty of the study is as follows:

– new differential cross sections for the reaction $^{12}C(p,\gamma)^{13}N$ in the energy range $E_{p,\,lab.}$ = 1100 – 1400 keV at 0^0 for radiative capture of protons by ^{12}C nuclei to the ground state ^{13}N;

– new differential cross sections for elastic scattering $^{10}B+^{12}C$ and the proton transfer reaction $^{12}C(^{10}B,^{9}Be)^{13}N$ were obtained at a beam energy of 41.3 MeV;

– the values of the total astrophysical S(E) factors and their errors were determined for the reactions $^{12}C(p,\gamma)^{13}N_{(g.s.)}$ in the energy range $350\leq E\leq1390$ keV,

as well as the reaction rates in the range $0.01 \leq T_9 \leq 10$ and the value of the radiation γ-width of the first resonant excited state of the ^{13}N nucleus (2.365 MeV; $1/2^-$);

– The results obtained made it possible to replenish the international nuclear database EXFOR (IAEA) to establish the rate of the $^{12}C(p,\gamma)^{13}N_{(g.s.)}$ reaction occurring in the interior of the Sun and in massive stars.

Scientific and practical value of the work

Using the created asymptotic theory and the new precision experimental data obtained, they will be used to obtain the main result of the dissertation - a reliable calculation of the reaction rates of $^{12}C(p,\gamma)^{13}N$. Practical significance - they will allow us to establish the degree of reliability and accuracy of calculations within the framework of the Distorted Wave Born Approximation (DWBA) approach for near-barrier peripheral reactions of charged particle transfer.

The relationship of this work with other research works

The dissertation work was carried out as part of the research work on the topic: "Study of radiative capture of protons and peripheral nuclear transfer reactions at energies near the Coulomb barrier caused by heavy ions for astrophysical and thermonuclear applications" grant No. AP05132062. This research was funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan for 2018-2020.

Personal contribution of the author

The experimental results presented in the dissertation were obtained by the author together with employees of the HIL University of Warsaw (Warsaw, Poland) and the laboratory of low-energy nuclear reactions of the Institute of Nuclear Physics (Almaty, Kazakhstan). The work on theoretical analysis was carried out as a result of joint work of scientists, such as the Institute of Nuclear Physics of the Academy of Sciences of the Republic of Uzbekistan (Tashkent) and is reflected in joint publications. The author's personal contribution consists of participating in the work at all stages of the experiments, setting research objectives, planning, processing experimental data and carrying out theoretical calculations.

Approbation of work

Published 12 publications (7 articles and 5 theses) in various journals and conferences in the field of dissertation research. 6 articles in journals included in the Thomson Reuters (Web of Knowledge) and Scopus (Elsevier) databases and 1 article in journals recommended by the Committee for Quality Assurance in Education and Science of the Ministry of Education and Science of the Republic of Kazakhstan, 5 theses were published at international scientific conferences held in Kazakhstan.

The structure and scope of the dissertation

The dissertation consists of an introduction, five sections, a conclusion and a list of used sources of 137 titles. The total volume of work is 106 pages of text, including 10 tables and 55 figures.