Nuclear Instruments and Methods in Physics Research A 825 (2016) 17–23

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

A Modified activation method for reaction total cross section and yield measurements at low astrophysically relevant energies

S.V. Artemov [a,*], S.B. Igamov [a], A.A. Karakhodjaev [a], G.A. Radyuk [a], O.R. Tojiboyev [a], U.S. Salikhbaev [a], F.Kh. Ergashev [a], I.V. Nam [a], M.K. Aliev [b], I. Kholbaev [b], R.F. Rumi [b], R.I. Khalikov [b], Sh.Kh. Eshkobilov [b], T.M. Muminov [b]

[a] Institute of Nuclear Physics of Uzbekistan Academy of Sciences, Tashkent, Uzbekistan
[b] Research Institute of Applied Physics, National University of Uzbekistan, Tashkent, Uzbekistan

ARTICLE INFO

Article history:
Received 26 November 2015
Received in revised form
6 April 2016
Accepted 7 April 2016
Available online 8 April 2016

Keywords:
Nuclear astrophysics
Activation method
Reaction yield
Annihilation γγ- coincidence
Stopping power

ABSTRACT

The activation method is proposed for collection of the sufficient statistics during the investigation of the nuclear astrophysical reactions at low energies with the short-living residual nuclei formation. The main feature is a multiple cyclical irradiation of a target by an ion beam and measurement of the radioactivity decay curve. The method was tested by the yield measurement of the $^{12}C(p,\gamma)^{13}N$ reaction with detecting the annihilation γγ- coincidences from $^{13}N(\beta^+\nu)^{13}C$ decay at the two-arm scintillation spectrometer.

1. Introduction

Accurate simulation of the evolution and observable characteristics of stars as well as the processes at the early stages of the universe requires a thorough knowledge of the rates of many reactions involving stable and radioactive nuclei [1–3]. As a rule, before being extrapolated to very low astrophysical relevant energies, these rates are calculated from the respective reaction total cross sections (astrophysical *S*-factors) or the reaction yields.

Presently a great attention is drawn to renew the existing experimental database on the low-energy nuclear reactions of astrophysical importance with more precise values of astrophysical *S*-factors and reaction rates. In a number of cases, the data with absolute experimental errors not higher than 4–5% are required for verification of astrophysical models. For reactions with charged particles, the major experimental constraint is related to the exponential decay of the cross section with decreasing energy which results in impetuous increase of experimental errors. Therefore, the statistical validity of measurements is a serious problem when the new relevant data are obtained. Moreover, uncontrolled systematic errors frequently arise in the analysis of available experimental data. For example, in two series of experimental data on the $\{\alpha+{}^3He\rightarrow{}^7Be+\gamma\}$ reaction obtained recently by different approaches [4,5], the average cross section values extrapolated to low energies showed sufficiently larger difference than the errors in each separate experiment. Therefore, it is desirable to apply different improved experimental methods for obtaining the same data [6,7].

The following methods are usually used for the direct experimental studies of the astrophysically important processes at very low energies [8–14]:

- detection of products formed directly in a reaction (commonly, measurement of the “prompt” γ-quanta) – see, for example, [12];
- off-line mass-spectrometric separation of nuclei – final products of reaction (recoil separators and other techniques – see, for example, [13]
- activation methods (often supplemented by chemical extraction of the radioactive reaction products – see, for example, [14]).

Each of these methods has a number of advantages and imperfections.

The activation method is advantageous at measuring very low cross sections because it allows for the geometry of measurements close to 4π. Using this method one can detect beta-particles, gamma-quanta or γγ-coincidences (in the case of β^+-radioactive residual nucleus) in the event counting mode with large detection efficiency instead of applying the precise gamma-ray spectrometry

* Corresponding author.
E-mail address: artemov@inp.uz (S.V. Artemov).

http://dx.doi.org/10.1016/j.nima.2016.04.021
0168-9002/

with smaller efficiency. It automatically provides the total cross section or the yield of the reaction and does not depend on details of the γ-ray decay scheme and on the form of the γ-ray angular distributions. However, in practice the applicability of this technique is limited to the radioactive nuclei formation reactions with the half life longer than ~ten seconds. Another disadvantage of the commonly used methods is the inefficiency in usage of the accelerator beam associated with the time spent to move the irradiated target into the different position required for measurements. Besides, this procedure must be repeated if the accumulated statistics is not satisfactory. In addition, the activation method has some requirements. Firstly, it is necessary to identify the nucleus – product of the reaction at the time when beta-particles or annihilation quanta are detected. Secondly, one should take into account a possibility of the concurrent reactions resulting in formation of the final nucleus.

The paper describes the original version of the activation method and the corresponding multidetector setup which was assembled and installed into the ion line of the electrostatic accelerator EG-2 at the Research Institute of Applied Physics of National University of Uzbekistan (RIAP NUU RUz). The method can be applied to studies of several reactions of astrophysical importance with formation of relatively short-living radioactive nuclei. This version of the method is peculiar with multiple iterations of the irradiation/measurement procedure (without moving the target or detector) and summation of the recorded events to accumulate sufficient statistics. Application of fast software-controlled counters allows one to record the beam intensity with small discrete steps within the irradiation period and to trace the decrease of the intensity of β-particles and/or annihilation γ-quanta accompanying β^+-decay of the formed nuclei during the measuring period. To maintain the optimal ratio of accumulated "useful" and background events, a special emphasis is made on the measurement mode selection.

The ^{12}C(p,γ)^{13}N reaction was chosen as a testing ground to validate the proposed method. The reaction was well-studied by means of several experimental methods in the broad energy range near and above the astrophysically important energies. Two earlier works [15,16] were performed using the conventional activation method with detection of β+-particles produced in the ^{13}N decay for the reaction yield extraction in the energy ranges of 88–128 keV and 125–200 keV, correspondingly. In [17] the yield of the reaction was measured in the energy range of 0.4–2.5 MeV by detecting the annihilation γ-quanta with scintillation detector using a thick graphite target. Earlier, the energy dependence of the total cross section was studied by the "prompt" γ-quanta detection [12,18–22].

This paper describes the main characteristics of the experimental setup (Part 2), the proposed measurement procedure (Part 3) as well as the experimental data treatment and obtaining the yields of the studied reaction (Part 4).

2. Experimental setup

A proton beam of the electrostatic accelerator EG-2 "SOKOL" of the RIAP NUU RUz [23] is used for experimental testing of the method. It covers the energy range of approximately 150–1500 keV with the ^{1}H$^+$ ions external beam intensity of about 20 μA at the energy spread (FWHM) of ~2.5 keV. Fig. 1 displays the part of the ion guide behind the separating magnet (1), which discriminates the beam impurities, and elements of the setup. The energy stability is provided by the feedback system, which tracks out an equality of beam current values on the right and left plates of the slit collimator (2). The stability of the magnetic field is monitored by the nuclear magnetic resonance system.

Right behind the slit collimator, there is a software-controlled beam chopper with the Faraday cup (3) designed for integration of the beam current hitting the target. The surface of the tantalum diaphragm with diameter of 9 mm (5), which defines a size of the beam spot on the target surface, is surrounded by phosphor (4) allowing one to observe a beam hitting the diaphragm surface through the viewing window. The guard ring is placed in front of the entry to the insulated flange coupling (see (7)) the ion guide assembled with the target chamber (9). It is biased to −300 V to prevent escape of the emitted electrons from the insulated target chamber and their escape into the chamber from the diaphragm. The chamber is made of stainless steel and has the T-shaped tubular configuration with three flanges on the edges of the tubes with the inner diameter of 40 mm. In front of the target chamber the liquid nitrogen trap (8) made of copper tube with the inner diameter of 15 mm and length ~300 mm is mounted for preventing the carbon buildup on a target surface. The target (11) is mounted on the water-cooled holder (12,13) embedded into the upper flange of the chamber. The target plane is positioned at 45° to the beam axis (10) when the semiconductor detector is enabled. Electrically insulated part of the ion line and the target chamber serve as a Faraday cup.

Detector assembly consists of the semiconductor Si - detector (16) located under the target inside the chamber, two scintillation NaI(Tl)-detectors and HPGe - detector (see insertion in Fig. 1). The Si-detector has the sensitive zone thickness of approximately 700 μm and the entrance window diameter of 24 mm. It can be used for β-particles detection and is mounted on the lower flange of the chamber at a distance of 25 mm from the target. Its electric outlets including the ground connection are insulated from the

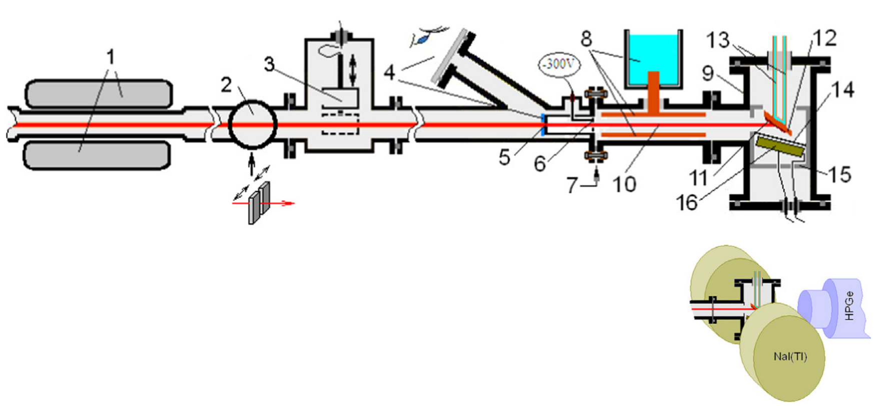

Fig. 1. The beam transportation system and experimental setup. 1-separating magnet, 2 – slit collimator, 3 – beam chopper, 4-viewing window, 5 – beam shaping diaphragm, 6 – guard ring, 7 – insulating flange coupling, 8 – liquid nitrogen trap, 9 – target chamber, 10 – beam trajectory, 11 – target, 12 – water-cooled target holder, 13 – water cooling system, 14-screening foil, 15 – lead positron converter, 16-silicon detector. In the insertion below the scintillation NaI(Tl) crystals and HPGe detector are schematically shown.