Experimental Results on Cross Sections for $^7$Be Photoproduction on $^{12}$C, $^{14}$N, and $^{16}$O Nuclei in the Energy Range of 40–90 MeV

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Abstract—The yields of $A(\gamma, X)^7$Be reactions induced by bremsstrahlung photons were measured at the endpoint electron energies of 40, 50, 60, 70, 80, and 90 MeV. The spectra of bremsstrahlung incident to the targets used were calculated via a simulation based on the GEANT 4 code passage. The cross sections for the $A(\gamma, X)^7$Be reactions on $^{12}$C, $^{14}$N, and $^{16}$O nuclei were evaluated on the basis of the measured reaction yields and the calculated bremsstrahlung spectra. The experimental cross sections for the photonuclear reactions of $^7$Be production were compared with their counterparts calculated on the basis of the TALYS 1.4 package. Agreement of the experimental and evaluated results was demonstrated for $^{12}$C nuclei and partly for $^{14}$N nuclei.

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1. INTRODUCTION

Reactions induced by electromagnetic interaction stand out among a wide variety of nuclear reactions. The interaction of low- and intermediate-energy photons are widely used in various realms of science and technologies—from nuclear physics to medicine and materials sciences. In recent years, cross sections for photonuclear reactions have found application in the field of monitoring the content of radionuclides in the near-Earth layer of the atmosphere [1, 2].

To date, it has been found that the radioactivity of air receives a significant contribution from the short-lived isotope $^7$Be of cosmogenic origin. It is commonly believed that dominant reactions leading to the production of beryllium isotopes in the Earth’s atmosphere are induced by the interaction of cosmic rays (protons and neutrons) with nitrogen and oxygen nuclei [3, 4], which are the main component of atmospheric air. The results obtained in [1, 2] reveal that photonuclear reactions may be yet another possible mechanism of the production of the beryllium isotope $^7$Be in the upper atmosphere, making a contribution that is commensurate with the contribution of the proton and neutron mechanisms.

In the literature, there are only few data on reactions involving the multiparticle photodissociation of nuclei. For example, the interested reader can find a detailed investigation of the cross section for the reaction $^{12}$C$_6(\gamma, n\alpha)^7$Be$_4$ in [5], but there are virtually no data on the reactions $^{14}$N$_7(\gamma, X)^7$Be$_4$ and $^{16}$O$_8(\gamma, X)^7$Be$_4$ in the literature. Since nitrogen and oxygen nuclei form a dominant component of atmospheric air, these are reactions that are of particular interest for an analysis of the photonuclear mechanism of $^7$Be production in the atmosphere. In contrast to what was done in the previous studies of our group [1, 2], the energy dependence of the yields of $A(\gamma, X)^7$Be reactions induced by bremsstrahlung photons of energy in the range between 40 and 90 MeV is measured in the present study, and the cross sections for these reactions on $^{12}$C, $^{14}$N, and $^{16}$O nuclei are thereupon determined on the basis of the results of these measurements by the photon-difference method.

2. DESCRIPTION OF OUR EXPERIMENT

In order to determine the cross section for $^7$Be photoproduction in $A(\gamma, X)^7$Be$_4$ reactions, we performed an experiment at the LUE-40 linear electron accelerator [6]. A set of targets containing oxygen, nitrogen, and carbon was irradiated with...
bremsstrahlung photons. The energy of accelerated electrons was changed from 40 to 90 MeV with a step of 10 MeV at a current of about 4.2 μA. Six irradiation runs at the endpoint electron energies of 40, 50, 60, 70, 80, and 90 MeV were performed. In all of these runs, the charge of electrons incident to the target had the same value of 12.5 μA. The design of the target assembly is shown in Fig. 1.

An electron beam was incident to a converter consisting of four tantalum plates of total thickness 4 mm that were separated by air gaps intended for improving heat removal. Targets containing (1) 16O, (2) 12C, and (3) 14N, which were nuclei under study, and (4) a molybdenum target, which was used as a reference target, were positioned immediately downstream of the converter.

In order to ensure thermal stability in the course of irradiation, corundum (Al₂O₃), high-purity graphite (C), and aluminum-nitride powder (AlN) were used as targets. This design of the target assembly made it possible to abandon cooling with water in favor of cooling with a fast air flow, and this provided an easy access to targets prior to and after irradiation. The activity of each target after irradiation was measured with the aid of a CANBERRA InSpector 2000 spectrometer, whose energy resolution is 1.74 keV for the 1332 keV line and whose relative error in determining activities is not greater than 6%.

3. EVALUATION AND SIMULATION

In order to evaluate the cross section for the photoproduction of the isotope ⁷Be, it is necessary to know the bremsstrahlung-photon-flux density at the target locus. In order to determine it, we performed a computer simulation of the propagation of primary electrons with energies changing from 40 to 90 MeV with a step of 10 MeV through a target-assembly model that has parameters identical to the parameters of the experimental target assembly. The respective calculations relied on a computer code called KIPT and developed in the C++ language within the Linux operating system by using the GEANT 4, version 9.4, library. The electron-beam diameter was set to 10 mm, and the distribution of the electron beam was determined with the aid of the G4UniformRand generator.

The parameters of the target-assembly model were described by means of methods of the G4DetectorConstruction class (ingredients of the target-assembly model, including geometric parameters, materials, and parameters of visualization, were determined). The Livermore low-energy electromagnetic model was used as a basis for describing physics processes. In our simulation, we traced photons that traversed the Al₂O₃ (corundum), C (carbon), and AlN (aluminum nitride) targets. Figure 2 shows the calculated energy spectra of photons for the electron endpoint energy of 40 MeV that traversed the targets used. The energy of primary electrons is $E = 40$ MeV, and their number is $N_{\text{events}} = 6.24 \times 10^6$. The analogous spectra were also calculated for the energies of 50, 60, 70, 80, and 90 MeV. In the following, the bremsstrahlung spectra calculated for all values of the endpoint electron energy were thereupon used in evaluating, by the photon-difference method, the reaction yields for a comparison with respective experimental values.