EXPERIMENTAL CROSS-SECTION EVALUATION DATA FOR ^{7}Be PHOTOPRODUCTION BY ^{12}C, ^{14}N, ^{16}O NUCLEI IN THE ENERGY RANGE BETWEEN 40…90 MeV

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The ^{7}Be isotope produced in the upper atmosphere under the action of cosmic radiation is an important factor in population radiation load. A correct determination of the radiation dose coming from this isotope calls for consideration of the photonuclear mechanism of ^{7}Be production by the nuclei of oxygen and nitrogen. The paper gives the experimental yields from A(γ, X)^{7}Be nuclear reactions in the bremsstrahlung beam versus the end-point energies of electrons (from 40 to 90 MeV). The mathematical model approach with the GEANT4 class library was used to calculate the spectra of bremsstrahlung incident on the targets. Based on the experimental results, we have calculated the A(γ, X)^{7}Be reaction cross-sections for oxygen, nitrogen and carbon. Calculated values of photonuclear reaction cross-sections for ^{7}Be production by ^{12}C, ^{14}N, ^{16}O nuclei were obtained with the use of the TALYS package. Agreement between experimental and calculated results only for ^{12}C and ^{14}N is shown.

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INTRODUCTION

At present, the monitoring of radionuclides content in the air-ground interface suggests the conclusion that the radioactivity of ground air is essentially contributed by a short-lived isotope ^{7}Be of cosmic origin. The ^{7}Be isotope presents interest not only from the standpoint of its radioactive effect on biological systems, but also because it can serve as an indicator of the build-up of air-supplied pollutants by natural environments [1]. The last-mentioned property may be conveniently used for estimating a possible atmospheric pollution and air exchange in the environment. Therefore, the investigation into the mechanisms and regularities of the processes of ^{7}Be generation, transport and migration in the ecosphere objects and at their interfaces appears rather urgent. It is considered that the main reactions leading to beryllium isotope generation in the terrestrial atmosphere take place at interaction of cosmic rays with nitrogen and oxygen nuclei [2], which are the principal constituents of the atmospheric air: $_7N^{14}(p, X)\,_4Be^7$, $_8O^{16}(p, X)\,_4Be^7$, $_7N^{14}(n, X)\,_4Be^7$ and $_8O^{16}(n, X)\,_4Be^7$. Another possible mechanism of ^{7}Be generation in the upper atmosphere may lie in photonuclear reactions.

The literature comprises scarce data on the reactions of multiparticle photodisintegration of nuclei. For example, details for the $_6C^{12}(\gamma, n\alpha)\,_4Be^7$ reaction cross-section can be found in ref. [3], whereas no data on the reactions $_7N^{14}(n, X)\,_4Be^7$ and $_8O^{16}(n, X)\,_4Be^7$ are available in the literature. Since the mentioned nuclei are the basic components of atmospheric air, it is just these reactions are of particular interest for the analysis of the photonuclear mechanism of ^{7}Be production in the atmosphere.

1. EXPERIMENT

To determine the ^{7}Be photoproduction cross-section in the A(γ, X)$_4$Be^7 reaction, experiments were made to expose a set of targets comprising oxygen, nitrogen and carbon to bremsstrahlung at the electron linear accelerator LUE-40 [7]. The energy of accelerated electrons was varied with a 10 MeV step from 40 to 90 MeV, the current being about 4.2 μA. In total, six target irradiation sessions were carried out. The time of exposure was varied in order to attain the same dose (charge) in all the sessions, namely, 12.5 μA·h. The design of the target assembly is presented in Fig. 1.

The target beam is incident on the converter consisting of 4 tantalum plates, 4 mm in total thickness, with air gaps in-between to improve heat removal.

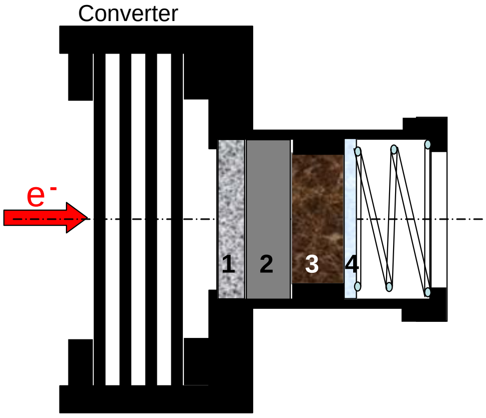

Fig. 1. Target assembly for exposure at the accelerator

Immediately behind the converter there were the targets comprising the nuclei under study: 1-^{16}O, 2-^{12}C, 3-^{14}N, and the molybdenum target 4-Mo used as a check test piece.

To ensure thermal resistance in the process of exposure, the following materials were used as targets: corundum (Al_2O_3), high-purity graphite (C) and a highly compressed aluminum nitride powder (AlN). The design of the target assembly has made it possible to dispense with water cooling, using instead air blast cooling, which provided prompt access to the targets before and after their irradiation.

The activity of each target after its irradiation was measured using the spectrometer complex CANBERRA InSpector 2000 with an energy resolution of 1.74 keV in the 1332 keV line and a relative activity measurement error no more than 6%.

2. CALCULATION AND SIMULATION RESULTS

To calculate the cross-section for isotope ^{7}Be photoproduction, it is necessary to know the flux density of bremsstrahlung photons at the site of target location. For this purpose, a computational modeling was performed to describe the passage of primary electrons of energies ranging from 40 to 90 MeV with a 10 MeV step through the target assembly model having the parameters, which correspond to the parameters of the experimental target assembly. For computation purposes, a computer program "KIPT" has been developed. The program is written in the C++ language in OC Linux with the use of the Geant 4 class library, version 9.4. The electron beam diameter was set to be 10 mm, the electron beam distribution was determined using class G4UniformRand.

The parameters of the target assembly model were described with the use of the methods of class G4DetectorConstruction (defined were the component parts of the target assembly model, in particular, the geometrical parameters and materials, visualization parameters, etc.). In the description of visualization options we have put to be visible only tantalum plates (turquoise blue), alumina (red), carbon (orange), and aluminum nitride (violet) (Fig. 2).

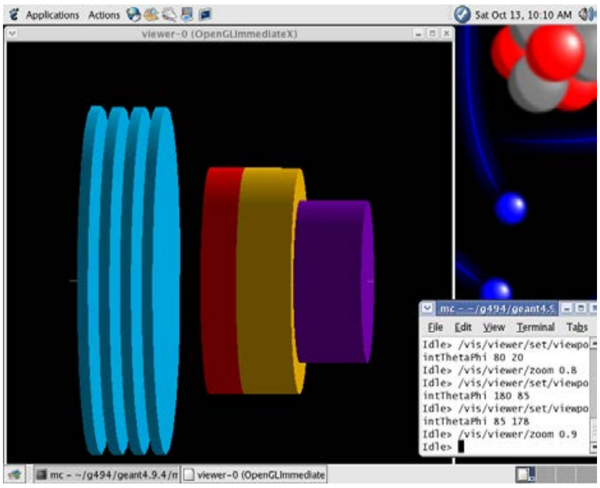

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Fig. 2. OpenGL-visualization of the facility fragment (theta=85°, phi=178°)

For the description of physical processes, the low-energy electromagnetic process model "Livermore" was used. In modeling, the gamma-quanta that have passed through the Al_2O_3, C and AlN targets were traced.

Fig. 3 shows typical computed energy spectra of gamma-quanta of energies between 18 and 40 MeV, which have passed through different targets. The primary electron energy was E_e = 40 MeV, the number of primary electrons amounted to N_{events}= 6.24·10^6. Similar spectra have been computed for energies 50, 60, 70, 80 and 90 MeV. Later on, these results were used to calculate cross-sections for ^{7}Be photoproduction by the nuclei under study using the "photon-difference" method.

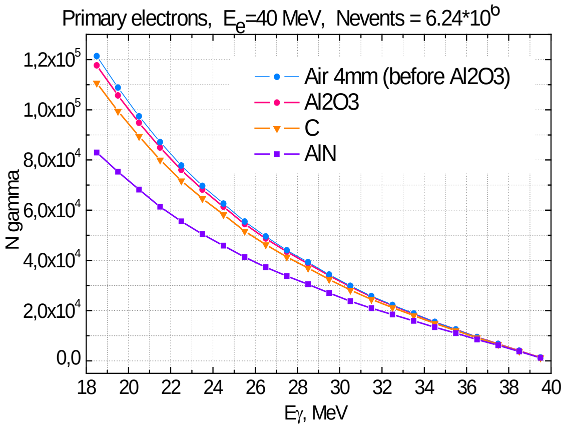

Fig. 3. Energy spectra of bremsstrahlung gamma-quanta for E_{e-} = 40 MeV

3. RESULTS AND DISCUSSION

On the basis of target activity measurements, the ^{7}Be yield curves were plotted as functions of electron beam energy for all the targets under study (Figs. 4-7).

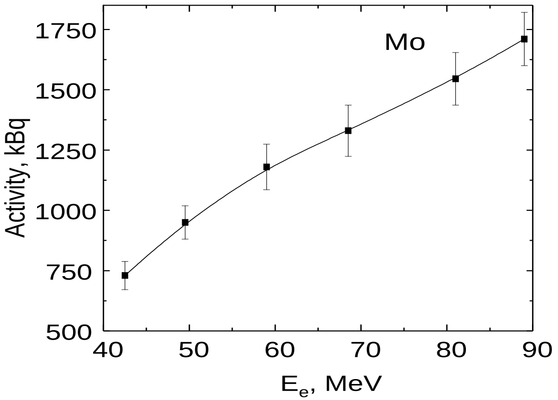

Fig. 4. ^{99}Mo activity (yield) in the check test target versus electron energy

The simulated bremsstrahlung spectrum was convolved with the known experimental cross-section for the ^{100}Mo(γ, n) ^{99}Mo reaction [6] and with the cross-section, obtained using the program TALYS-1.4, with the result that the calculated values of ^{99}Mo activity in the check test target were obtained. The difference between the measured ^{99}Mo activity value (see Fig. 4) and the simulated result does not exceed 5…8 %. This confirms the adequacy of the technique applied.

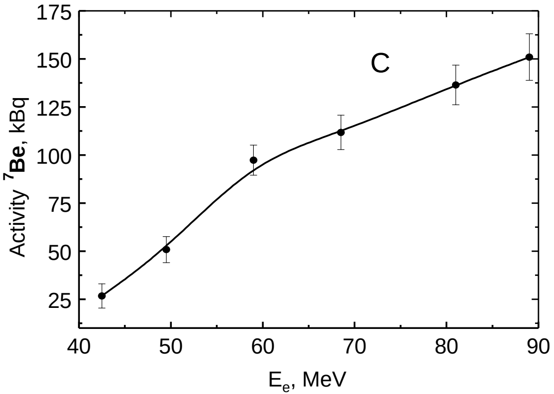

Fig. 5. ^{7}Be activity in ^{12}C-target vs electron energy

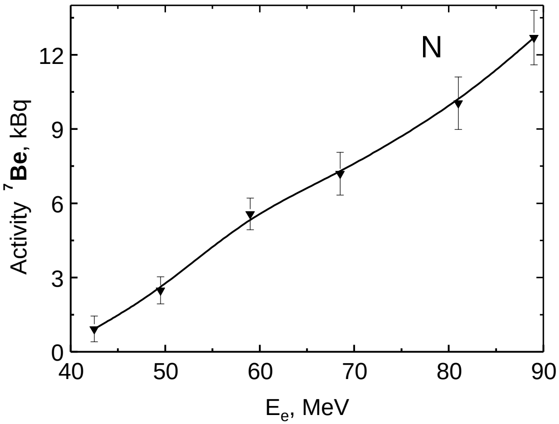

Fig. 6. ^{7}Be activity in ^{14}N-target vs electron energy

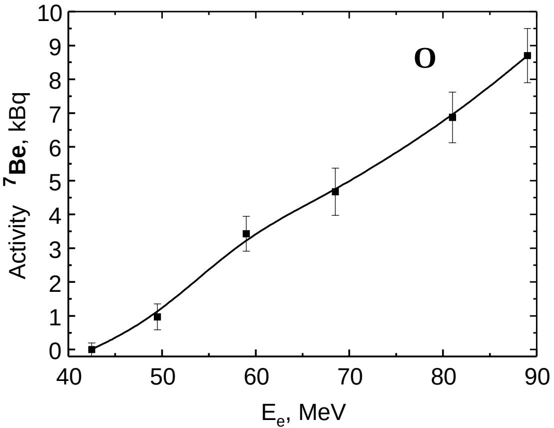

Fig. 7. ^{7}Be activity in ^{16}O-target vs electron energy

The experimental data on ^{7}Be activity in the C, N, O targets were corrected for the ^{99}Mo yield. In this way the errors due to nonidentical conditions of different irradiation sessions were reduced in the determination of the cross-section for ^{7}Be production.

The averaged cross-sections for the ^{7}Be isotope production from different targets were calculated by the following formula:

$$\sigma = \frac{A_0 \cdot A_m}{\Phi_0 \cdot m \cdot N_{AV} \cdot \left(1 - e^{-\lambda \cdot t_{\text{íàë}}}\right) \cdot 10^{-24}}, \qquad (1)$$

where

σ – is the cross-section (b);

Φ_0 – is the γ-quantum flux density (1/cm^2·s);

A_0 – is the target activity (Bq);

A_m – is the atomic weight of the target isotope;

N_{Av} – is the Avogadro number;

m – is the isotopic mass in the target (g);

λ – is the decay constant of ^{7}Be.

The density of nuclear-active bremsstrahlung gamma-quantum flux was calculated for each energy interval (10 MeV) by subtracting simulated brems-strahlung spectras for nearby end-point energy value of electron. The activity difference for boundary energies of each interval was calculated in a similar way. The resulting reaction cross-sections σ(E) for ^{7}Be production present the values averaged over the 10 MeV interval.

It should be noted that the application of the classical technique of spectrum subtraction, i.e., the photon-difference method, permits one to obtain a more monochromatic spectrum as compared to the initial bremsstrahlung photon spectrum. A substantial thickness of the tantalum converter brings up problems concerning the low-energy part of the difference spectrum, namely, it ceases to be zero and introduces a significant error into the cross-section evaluation. So, the determination of the reaction cross-section σ(E) from the experimental yield (target activity) actually provides information on the evaluative cross-section

$$\sigma^o(E) = \int F'(E_i E)\sigma(E)dE\,, \qquad (2)$$

that essentially differs from the sought-for cross-section σ(E) by the value, by which the difference spectrum F′(Ei, E) differs from the Schiff residue in the limit of the δ-function [4].

It is obvious that to estimate the validity of the obtained results, it is necessary to have an independent method of evaluating cross-sections for the reactions under study. The program TALYS [5] has been used to plot ^{7}Be production cross-sections as functions of the photon energy for carbon, nitrogen and oxygen nuclear targets (solid curves in Figs. 8-10).

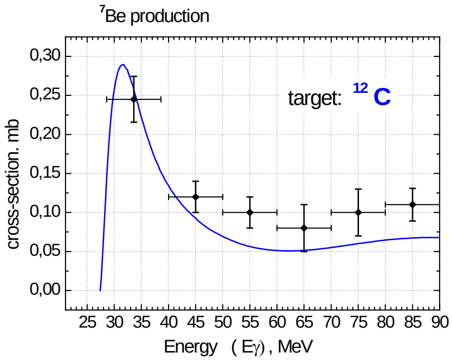

Fig. 8. Cross-section for ^{7}Be production by ^{12}C nuclei

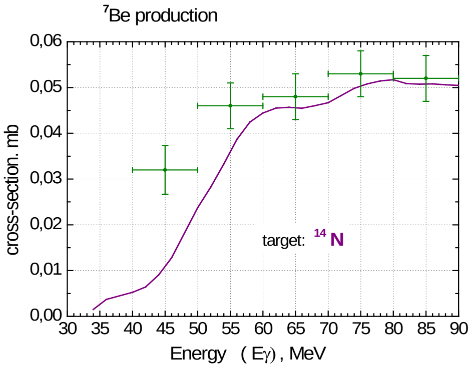

Fig. 9. Cross-section for ^{7}Be production by ^{14}N nuclei

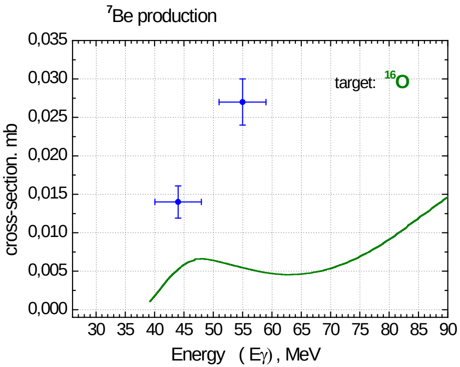

Fig. 10. Cross-section for ^{7}Be production by ^{16}O nuclei

The points in the plots show the calculated values of the evaluative cross-section σ(E).

For the ^{12}C nuclei the cross-section σ(E) for the ^{7}Be production reactions is in satisfactory agreement with the cross-section calculated by the TALYS program and with data [3]. However, for the ^{14}N nuclei (below 60 MeV) and ^{16}O nuclei (in the whole energy range), it appeared impossible to attain a satisfactory agreement even with the use of the yield-curve smoothing procedure. Ishkhanov et al. have described [5] the technique of reconstructing the Ta photodisintegration reaction yield with the use of the cross-sections calculated by the TALYS code. In our case with the use of this technique for reconstructing the yields from the reactions $_7N^{14}(\gamma, X)\ _4Be^7$, $_8O^{16}(\gamma, X)\ _4Be^7$, the reaction yields (and hence, the TALYS cross-section) turn out to be essentially lower than the experimental reaction yields (σ(E) values, accordingly). The reasons for this discrepancy may be attributed to both the experimental and calculation procedure errors, namely, no consideration was given to the cluster structure of the emitted reaction products and to TALYS working peculiarities at escape of a great amount of nucleons [5].

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ЭКСПЕРИМЕНТАЛЬНЫЕ РЕЗУЛЬТАТЫ ОПРЕДЕЛЕНИЯ СЕЧЕНИЯ ФОТОРОЖДЕНИЯ ^{7}Be НА ЯДРАХ ^{12}C, ^{14}N,^{16}O В ДИАПАЗОНЕ ЭНЕРГИЙ 40…90 МэВ

А.Н. Довбня, А.С. Деев, В.А. Кушнир, В.С. Малышевский, Т.В. Малыхина, В.В. Митроченко, С.А. Пережогин, А.В. Торговкин, Г.В. Фомин, Б.И. Шраменко

Изотоп ^{7}Be, образующийся в верхних слоях атмосферы под действием космического излучения, является важным фактором радиационной нагрузки на человека. Для правильного определения дозы облучения от этого изотопа необходим учет фотоядерного механизма образования ^{7}Be на ядрах кислорода и азота. Приведены экспериментальные зависимости выходов ядерных реакций A(γ, X) ^{7}Be на пучке тормозного излучения для следующих граничных энергий электронов: 40, 50, 60, 70, 80, 90 МэВ. Методом математического моделирования с использованием библиотеки классов GEANT4 рассчитаны спектры тормозного излучения, падающего на мишени, по результатам эксперимента были вычислены сечения реакций A(γ, X) ^{7}Be на кислороде, азоте и углероде. При помощи пакета TALYS получены расчетные зависимости сечения фотоядерных реакций образования ^{7}Be на ядрах ^{12}C, ^{14}N, ^{16}O. Показано частично удовлетворительное согласие экспериментальных и расчетных результатов.

ЕКСПЕРИМЕНТАЛЬНІ РЕЗУЛЬТАТИ ВИЗНАЧЕННЯ ПЕРЕРІЗІВ ФОТОУТВОРЕННЯ ^{7}Be НА ЯДРАХ ^{12}C, ^{14}N, ^{16}O В ДІАПАЗОНІ ЕНЕРГІЙ 40…90 МеВ

А.М. Довбня, О.С. Деєв, В.А. Кушнір, В.С. Малишевський, Т.В. Малихіна, В.В. Митроченко, С.О. Пережогін, О.В. Торговкін, Г.В. Фомін, Б.І. Шраменко

Ізотоп ^{7}Be, що утворюється у верхніх шарах атмосфери під впливом космічного випромінювання, є важливим чинником радіаційного навантаження на людину. Для правильного визначення дози опромінення від цього ізотопу потрібно ураховувати фотоядерний механізм утворення ^{7}Be на ядрах кисню та азоту. Наведено експериментальні залежності виходів ядерних реакцій A(γ, X) Be^7 на пучку гальмівного випромінювання для наступних граничних енергій електронів: 40, 50, 60, 70, 80, 90 МеВ. Методом математичного моделювання з використанням GEANT4 розраховані спектри гальмівного випромінювання, що падає на мішені, за результатами експерименту були обчислені перерізи реакцій A(γ, X) ^{7}Be на кисні, азоті і вуглеці. За допомогою пакету TALYS отримані розрахункові залежності перерізів фотоядерних реакцій утворення ^{7}Be на ядрах ^{12}C, ^{14}N, ^{16}O. Показано частково задовільне узгодження експериментальних та розрахункових результатів.