THE MEASUREMENT OF EFFECTIVE CROSS SECTIONS OF ^{7}Be FORMATION AT IRRADIATION OF LIGHT NUCLEI BY FAST NEUTRONS IN SUBCRITICAL NUCLEAR SYSTEMS

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INTRODUCTION

The concepts of nuclear energy systems based on the synthesis of high-energy reactions of decay and fission of heavy nuclei (ADS) have been extensively developed the last years [1]. The basic feature of this technology is the use of subcritical systems (k_{eff}<1) driven by high energy proton accelerators (E_p~1…2 GeV). Such a approach supposes that high-energy protons interact with a neutron-producing target (*Pb, Bi, W and Pb-Bi*) and the neutrons, formed as a result of development of nucleon-meson cascade, are multiplied by the subcritical reactor system by a factor of $M=1/(1-k_{eff})\approx 50$. It is assumed that in such systems it is possible to achieve the density of neutron flux about $F \sim 10^{15}$ n/cm^2 ·c, which allows both the energy production, and largescale transmutation of long-lived fission products and minor actinides. There are approaches based on the usage of fluorides of light and heavy metals such as LiF, NaF, BeF2, ZnF2, NaF-ZnF2, Li-Pb to transfer heat as well as to produce energy [2].

The distinctive feature of ADS technology is the formation of neutrons in the wide energy range from one electron-volt up to several hundred megaelectron-volts. This leads to formation of a wider spectrum of radioactive nuclei with long half-life in comparison to that of critical systems due to spallation reactions. The formation of such isotopes results in an additional expousure of radioactivity, especially for molten salt systems. An example of these reactions, taking place on light nuclei, is the formation of a nucleus ^{7}Be ($T_{1/2}$=53,3 days). Its transition to the ground state is accompanied by γ-quantum emission (E_{γ}=477,6 keV).

In the experiments on measurements of the yield of neutrons from lead target irradiated by 900 MeV protons the cross section of ^{7}Be formation in the water was measured [3]. This work is the prolongation of a series of ADS technology experiments and is dedicated to experimental measurement of the cross-section of yield of ^{7}Be on light nuclei (C, O, F, Na, Cl, K). Table 1 shows the threshold energies of formations of ^{7}Be on nuclei ^{12}C, ^{16}O, ^{19}F, ^{23}Na, ^{35}Cl, ^{39}K. It should be noted that threshold energies change in a wide energy range from 15…27 MeV.

Table 1. Threshold energy T of ^{7}Be formation reactions at interaction of neutrons with carbon, oxygen, fluorine, sodium, potassium and chlorine nuclides

Reaction	T, MeV
${}^{1}_{0}n+{}^{12}_{6}C\rightarrow{}^{7}_{4}Be+{}^{6}_{2}He$	27,40
${}^{1}_{0}n+{}^{16}_{8}O\rightarrow{}^{7}_{4}Be+{}^{10}_{4}Be$	26,61
${}^{1}_{0}n+{}^{19}_{9}F\rightarrow{}^{7}_{4}Be+{}^{13}_{5}B$	27,10
${}^{1}_{0}n+{}^{23}_{11}Na\rightarrow{}^{7}_{4}Be+{}^{17}_{7}N$	26,19
${}^{1}_{0}n+{}^{35}_{17}Cl\rightarrow{}^{7}_{4}Be+{}^{29}_{13}Al$	19,03
${}^{1}_{0}n+{}^{39}_{19}K\rightarrow{}^{7}_{4}Be+{}^{33}_{15}P$	15,56

The measurement of the ^{7}Be yield cross section from light nuclei is also useful to understand the mechanism of nuclear reactions when heavy fragments are formed in the finite state because there is no logical theory to describe such reactions.

THE EXPERIMENT

The experiments were performed at the phasotron of the Nuclear Problems Laboratory of the JINR (Russia). The proton beam (E_p=660 MeV) stroke a cylindrical lead target 8 cm in diameter and 40 cm in length. The diameter of the proton beam was 3 cm. The protons fluence was equal to $5.5\cdot10^{13}$ after a 25-hour exposure. Irradiated H_2O, D_2O, CH_2, C, CF_2, NaCl, KCl targets were located on the lateral surface of the lead cylinder.

The monitoring of neutrons leakage, formed in fission reactions, was carried out by the following reactions: ^{209}Bi(n,3n)^{207}Bi, ^{209}Bi(n,4n)^{206}Bi, ^{209}Bi(n,5n)^{205}Bi, ^{209}Bi(n,6n)^{204}Bi and ^{209}Bi(n,7n)^{203}Bi, with thresholds of 14,44 MeV, 22,45 MeV, 29,62 MeV, 38,09 MeV, and 45,31 MeV, respectively. The density of the neutron flux F above the threshold energy was determined by activation method and the known cross sections of reactions ^{209}Bi(n, xn). The experimental values of threshold reaction rates on bismuth and density of the neutron flux agree well with the theoretical calculations by Monte Carlo method [4].

The irradiated substances were located at a height 10 cm above the detector. The time to register the activity was selected to be 1 to 3 days. To take into account the possible influence of the background on photopeak (E_{γ}=477,6 keV) in the similar conditions, we registered the γ-spectrum of non-irradiated substances.

RESULTS OF EXPERIMENT

We measured the value of specific activity A of ^{7}Be in the chemical substance at the end of the irradiation

$$A = \frac{S}{m\varepsilon p \exp(-\lambda t_s)[1-\exp(-\lambda t_m)]/\lambda}, \quad (1)$$

where S is the number of countdowns in the analytical peak, m – mass of substance, ε is the efficiency of registration of γ-quantum (E_γ = 477,6 keV) taking into account self-absorption, p is the number of γ-quantum per one decay of ^{7}Be, t_s is the time of the substance's endurance (delay), and t_m is the time of measurement.

ANALYSIS OF RESULTS

The rate of the reaction of ^{7}Be formation

$$I = \int_T^{E^{max}} \sigma(E)\varphi(E)dE \quad (2)$$

is connected with specific activity A_0, which is determined by the following ratio

$$A_0 = \frac{N_A}{M}[1-\exp(-\lambda t_a)]I. \quad (3)$$

The value we are looking for, is the cross section averaged on neutron spectrum, $<\sigma(E)>$ is calculated as

$$\langle\sigma(E)\rangle = \frac{I}{F}, \quad (4)$$

where F is the neutron flux density above the threshold energy T (Table 2). As it has been shown in [5], the shape of nuclear reactions' cross sections does not depend significantly on the mass number of the target nucleus. Therefore the densities of neutron flux F above the threshold energies of ^{7}Be formation were determined by the interpolation of flux densities values for threshold reactions on bismuth with close energies.

In this work, the results were interpreted according to the following model. We assume that when a fast neutron with energy E, exceeding the threshold by ~10 MeV, interacts with the nucleus (A, Z), the section of ^{7}Be formation can be represented as

$$\sigma_i(A,E) = \pi R^2 \eta_i, \quad (5)$$

where R is the radius of nucleus, and η_i is the probability of the reaction along channel i. The probability η_i was expressed in a form analogous to [6]

$$\eta_i = c_i D(R, \mu_i, z_i, Z, E). \quad (6)$$

In this formula $D(...)$ is the penetrability of the effective potential barrier of the nucleus (A, Z) for ^{7}Be with a charge z_i = 4 and reduced mass μ_i, c_i is the probability of formation the compound nucleus in i-configuration. The averaged ^{7}Be formation cross section for fast neutron spectrum of versus the irradiated elements is shown in Table 2.

Table 2. The averaged ^{7}Be formation cross section on fast neutrons spectrum for carbon, oxygen, fluorine, sodium, chlorine and potassium.

№	Substance	Cross sections of reaction, b; (Relative error, %)
1	$C(CH_2)$	$1{,}0\cdot10^{-2}$ (23)
2	C	$6{,}4\cdot10^{-3}$ (23)
3	O (H_2O)	$2{,}0\cdot10^{-3}$ (25)
4	O (D_2O)	$1{,}9\cdot10^{-3}$ (25)
5	F (CF_2)	$1{,}4\cdot10^{-3}$ (27)
6	Na (NaCl)	* $1{,}5\cdot10^{-3}$ (30)
7	Cl (NaCl, KCl)	* $1{,}5\cdot10^{-4}$ (30)
8	K (KCl)	* $5{,}7\cdot10^{-5}$ (30)

Note. The reaction cross sections calculated by the formulas (5) - (6) are marked with an asterisk (*). Specific activities for the substances NaCl and KCl were determined in the experiment.

CONCLUSION

The averaged on fast neutrons spectrum cross section of ^{7}Be formation on carbon, oxygen, fluorine, sodium, chlorine and potassium (Table 2) decrease as the mass number of the target nucleus increases. The reaction rate of ^{7}Be formation in the ~10% error do not depend on the presence of deuterium or tritium in water. Similarly, the presence of hydrogen in polyethylene within the measurement's errors does not affect on the rate of ^{7}Be formation at the interaction of fast neutrons with carbon. When we compare the value of the cross section of ^{7}Be formation on oxygen obtained in this work and equals 0,0020±0,0005 b at the energy of protons E_p =660 MeV with cross section at E_p=900 MeV (σ=0,0015±0,0003 b), we can see that they are equal within the error. This conclusion was confirmed by the Monte Carlo calculations of neutron spectra at the irradiation by the protons of different energies. The calculated spectra, normalized per one neutron, are practically the same. This means that the averaged on fast neutron spectrum cross sections of ^{7}Be formation must be close for different proton energies.

REFERENCES

1. Accelerator driven systems: Energy generation and transmutation of nuclear waste. Statua report. IAEA-TECDOC-985. November, 1997.
2. K. Furukawa, S.Chigrinov, Y.Kato,K. Mitachi , ICENES'93 ,1993, p. 429- 433.
3. V.S.Butstev, G.L.Butsteva, S.Yu.Dudarev etc. JINR P1-2001-167. Dubna, 2001.
4. J.F.Briesmeister. MCNP-4B. Report LA-12625-M. Los Alamos National Laboratory, 1997.
5. V.S. Barashenkov. Cross sections of interaction of the particles and nuclei with nuclei. Dubna, JINR, 1993, 346 p.
6. A.S. Davydov. Theory of atomic nuclei. Gosizdat, fiz-mat. lit. M., 1958, 611 p.