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Yield Measurements for ^{7}Be and ^{10}Be Productions from ^{nat}Cu, ^{nat}Ag and ^{197}Au by Bremsstrahlung Irradiation at E_0 = 200 MeV

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The yields of ^{7}Be and ^{10}Be produced by bremsstrahlung having a maximum energy (E_0) of 200 MeV in ^{nat}Cu, ^{nat}Ag and ^{197}Au targets were investigated by the AMS technique at MALT of the University of Tokyo. It was found that the yields at E_0 = 200 MeV were much lower than those at $E_0 \geqq 250$ MeV, obtained in our previous work. A change in the yields of the fragmentation component in the target-mass dependence was observed at E_0 = 200 MeV when compared with those at $E_0 \geqq 250$ MeV. However, the ratios of the fragmentation yield of ^{10}Be to that of ^{7}Be remained unchanged throughout the concerned E_0.

§ 1. Introduction

The formation of light nuclei, such as ^{7,10}Be and ^{22,24}Na, in high-energy nuclear reactions on medium-to-heavy-mass targets, called "fragmentation", is not yet clear concerning the reaction mechanisms. Therefore, no theoretical calculation code for nuclear reactions is able to satisfactorily reproduce the fragmentation. In order to provide experimental information about the fragmentation peculiarity, our group measured many yields of several light products (^{7,10}Be, ^{22,24}Na and ^{28}Mg) of bremsstrahlung-induced reactions from 23 targets ranging from ^{nat}B to ^{197}Au, the superscript (nat) being the natural isotopic abundance, at the maximum end-point energies (E_0) of 250 to 1200 MeV radiochemically in our

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previous works [1,2]. We successfully disentangled the contributions of photo-fragmentation from photospallation processes and found that the neutron-to-proton ratios of the targets strongly affect the formation of nuclei by fragmentation, as revealed by the yields of the isotopic pairs. In this work, the yields of the isotopic pairs of ^{7}Be and ^{10}Be from ^{nat}Cu, ^{nat}Ag and ^{197}Au at E_0 = 200 MeV (a lower energy than in the previous work) were measured in order to understand the effect of the difference in the photon energy of the initial interactions.

Although the amount of ^{7}Be produced in a target was determined by γ-ray spectrometry in the previous works, the measurements of both ^{7}Be and ^{10}Be yields were performed with the aid of AMS in this work, because it is expected that the yields of ^{7}Be from medium and heavy targets at E_0 = 200 MeV are much lower than those at $E_0 \geqq 250$ MeV. The advantage of AMS for ^{7}Be is not only high sensitivity, but also low background. Especially, it is very important that possible interference from spallation products having large yields in the γ-ray measurements at ~478 keV is avoidable in AMS.

§ 2. Experimental

Metallic plates of Cu, Ag and Au (1.7651, 2.1422, and 2.5871 g/cm^2, respectively) with a diameter of 10 mm were cut out for targets. The chemical purities of the Cu, Ag and Au plates were 99.99, 99.98 and 99.99 %, respectively. Each target was wrapped with a guard foil of the same material in order to avoid any recoil gains and/or losses of ^{7,10}Be from and/or into the surrounding materials, and stacked by sandwiching with two Al foils used as a beam flux monitor. Each stack was enclosed separately in a quartz tube evacuated by a rotary pump.

The irradiations were carried out in a water-cooled target holder with bremsstrahlung having E_0 = 200 MeV, obtained in 0.5 mm of a platinum converter at the 300 MeV electron linac of the Laboratory of Nuclear Sciences (LNS), Tohoku University. The durations of irradiation for Cu, Ag, and Au were 30, 40, and 50 minutes, respectively. The beam intensity was monitored by ^{27}Al(γ, 2pn)^{24}Na on two Al foils, as described in Ref. [3], and determined to be $(1.43\pm0.37)\times10^{12}$ for Cu, $(1.15\pm0.22)\times10^{12}$ for Ag, and $(1.76\pm0.72)\times10^{12}$ eq.q./s for Au.

After irradiation, each target was placed in a beaker containing 421 μg of Be^{2+} separately. The targets of Cu and Ag were dissolved with 16 M HNO_3, and Au with aqua regia. Copper was left in solution with excess NH_4OH. Silver was removed as AgCl with 6 M HCl. Gold was extracted into isopropyl ether after adjusting the solution to 8 M HCl. After a Fe^{3+} solution and NH_4OH were added, beryllium was collected as $Be(OH)_2$ with $Fe(OH)_3$. The precipitates free from target material were dissolved with 12 M HCl, and passed through an anion-exchange column filled with Dowex 1X8 (100-200 mesh) pretreated with 12 M HCl. The eluate with 12 M HCl was concentrated, and NH_4OH was added to the solution to precipitate $Be(OH)_2$. The precipitates were dissolved with 1 M HCl, and passed through a cation-exchange column filled with Dowex 50WX8 (100-200 mesh) pretreated with 1 M HCl. After $Be(OH)_2$ was precipitated with NH_4OH from the 1 M HCl eluate, the cation-exchange step was repeated. $Be(OH)_2$ was purified by repeated precipitations in a quartz beaker. The final beryllium solution was dried on a quartz beaker and ignited to BeO at 850℃. The BeO powder was mixed with niobium powder and pressed into a hole in an oxygen-free-copper cathode. The chemical recoveries were

about 60%.

The amounts of ^{7,10}Be were determined by AMS at MALT of the University of Tokyo. The measurement of ^{7}Be was carried out 108 days after irradiation. The ^{10}Be-AMS was performed by following the ^{7}Be-AMS. The details of the AMS for ^{7}Be at MALT are going to be reported by H. Nagai *et al.* and those for ^{10}Be were reported in [4-6]. The reproducibilities of standard samples in these measurements were ±5.8% for ^{7}Be and ±2.6% for ^{10}Be, respectively.

§ 3. Results and discussion

The measured yields of ^{7,10}Be in ^{nat}Cu, ^{nat}Ag and ^{197}Au at E_0 = 200 MeV obtained in this work are tabulated in Table 1. Those are essentially independent of the precursor decays. The half lives of ^{7}Be and ^{10}Be used for the data analysis are 53.29 d and 1.5×10^{6} y, respectively.

In Fig. 1, the yields of ^{7}Be (open squares) and ^{10}Be (closed squares) at E_0 = 200 MeV are plotted together with our previous data at $E_0 \geqq 250$ MeV (circles) as a function of E_0. It was found that all of the yields increased steeply around E_0 = 200 MeV and changed to a gradual increase at $E_0 \approx$ 250 MeV. This property confirms that the (3,3) resonance in complex nuclei has the peak cross section around a photon energy of $k \approx$ 300 MeV, while the threshold energy for the (3,3) resonance is ~140 MeV. This indicates

Table 1. Measured yields of ^{7}Be and ^{10}Be on ^{nat}Cu, ^{nat}Ag and ^{197}Au at E_0 = 200 MeV.

Target	Yields(μb/eq.q.)			
	^{7}Be		^{10}Be	
Cu	0.77	± 0.21	0.209	± 0.055
Ag	0.267	± 0.056	0.199	± 0.040
Au	0.052	± 0.023	0.147	± 0.061

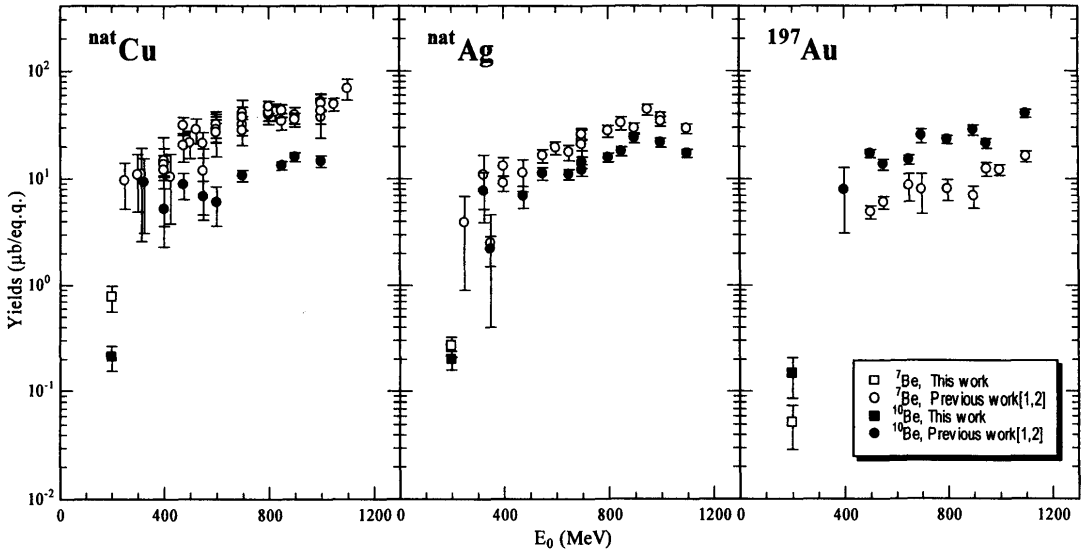

Fig.1. Yield variations for ^{7}Be and ^{10}Be productions from ^{nat}Cu, ^{nat}Ag and ^{197}Au as a function of E_0.

that the formation of beryllium nucleus is closely related to the process opened by the Δ-formation through the (3, 3) resonance.

In order to consider differences among targets at various E_0, the yield variations of ^{7}Be and ^{10}Be from E_0 = 200 to 1000 MeV in steps of 200 MeV are shown as a function of target mass (A_t) in Fig. 2. The lines from E_0 = 400 to 1000 MeV are the sum of two exponential components obtained by least-squares fits to the straight parts of the measured yield variation [1,2,7,8]. It was shown that the A_t-dependences of the yields were decomposed into spallation and fragmentation components [2]. The formation of ^{7,10}Be from the lighter targets was ascribed to spallation residues, and those from the heavier targets to fragmentation. The contribution to the yields of $^{7, 10}$Be from the spallation of ^{nat}Cu was estimated to be negligibly small by using the parameters of Rudstam's formula in Ref. [9]. The ^{7}Be yields at E_0 = 200 MeV obtained in the present work and shown by the open squares decrease with an increase in A_t more

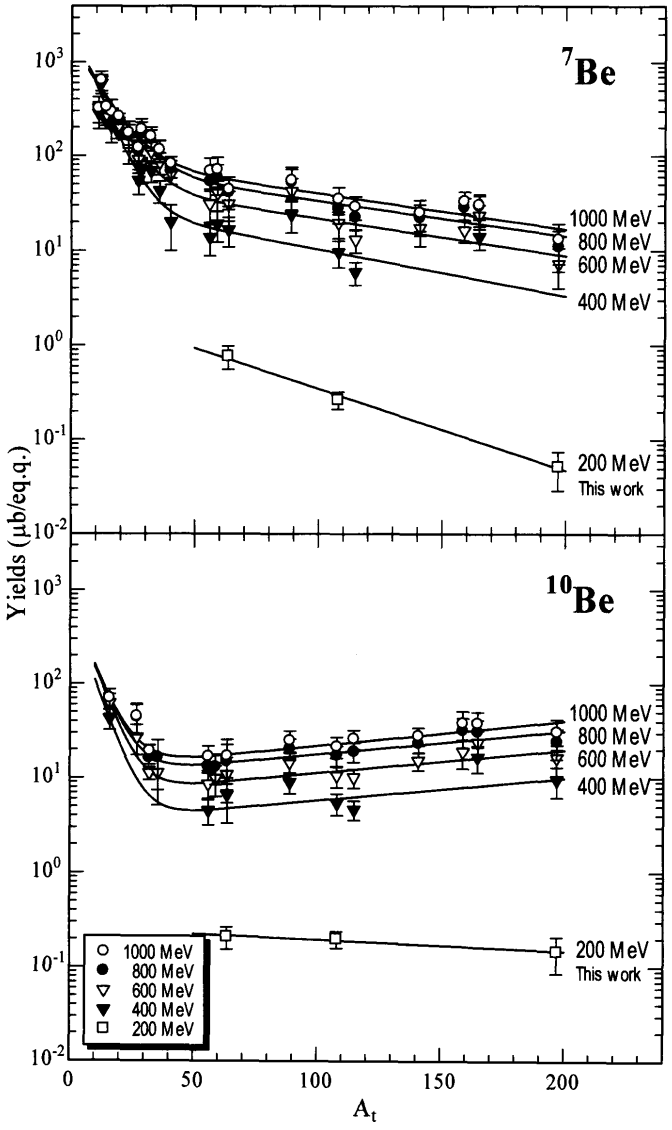

Fig.2. A_t-dependences of the yields of ^{7}Be and ^{10}Be at E_0 = 200, 400, 600, 800, and 1000 MeV.

rapidly than those at higher E_0. The fragmentation component of the ^{10}Be yields at E_0 = 200 MeV also decreases slightly with an increase in A_t in coutract to gradual increase at higher energies. What these tendencies mean is still an open question. It is considered to be a problem that needs a further study. However, it is interesting to note that the fragmentation yield ratios for the isotopic pair of ^{10}Be/^{7}Be at E_0 = 200 and 1000 MeV are quite similar to each other, as shown in Fig. 3, where the yield ratios are plotted as a function of the neutron-to-proton ratio of the target ($(N/Z)_t$). The effects on the relative production between ^{7}Be and ^{10}Be due to a difference in the energy for the initial interaction were uncertain. It was pointed out that the production ratio of ^{10}Be to ^{7}Be exceeded unity around ^{141}Pr with $(N/Z)_t$ = 1.39 and the neutron-deficient ^{7}Be (N/Z = 0.75) appeared to be formed preferably even in a

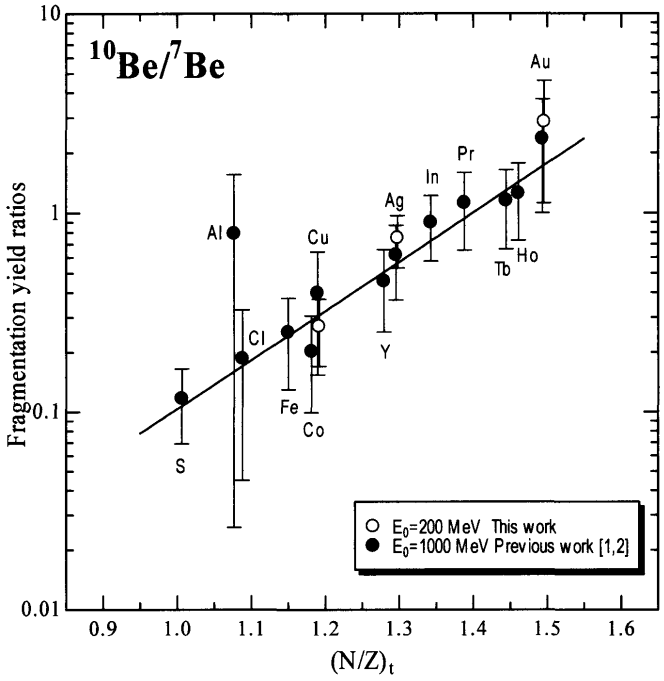

Fig.3. Fragmentation yield ratios of ^{10}Be/^{7}Be at E_0 = 200 and 1000 MeV as a function of $(N/Z)_t$.

nucleus of $(N/Z)_t$ = 1.00-1.39 compared with ^{10}Be very rich in neutron as high as N/Z = 1.50 [2]. The $(N/Z)_t$ values at which ^{24}Na/^{22}Na and ^{28}Mg/^{22}Na exceed unity are also closer to the N/Z values of ^{24}Na and ^{28}Mg, respectively. The overwhelming production of ^{7}Be and ^{22}Na from the targets with $(N/Z)_t$ larger than N/Z of these nuclides suggests that the production of these neutron-deficient nuclei occurs after some neutron emissions from the excited targets. The present study has shown that the same mechanism holds even at E_0 = 200 MeV. However further measurements for ^{7,10}Be are necessary, as well as for other light nuclei, at $E_0 \leqq 200$ MeV where the quasi-deuteron resonance or giant-resonance is effective in the photon-nucleus interactions. It was shown in the present work that the AMS technique is a powerful tool for measuring very low yields of ^{7}Be and ^{10}Be in nuclear reaction study.

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