JUN 19 1964

MASTER

C00-1195-12

Session 4d

Facsimile Price \$ 3.60

Microfilm Price \$ 1.13

PRODUCTION OF ^7Be FROM ^9Be , ^{12}C AND
 ^{16}O BY HIGH ENERGY PHOTONS*

Available from the
Office of Technical Services
Department of Commerce
Washington 25, D. C.

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Summary

The production of ^7Be from ^9Be , ^{12}C and ^{16}O by 45-275 MeV bremsstrahlung was measured by the residual activity method. The cross sections for the production of ^7Be from ^9Be and ^{12}C each have two maxima that are of comparable size. The first maximum occurs at the tail of the giant resonance and the second maximum close to meson threshold. The integrated cross sections from threshold to 275 MeV are 10 MeV-mb for ^9Be and 13 MeV-mb for ^{12}C . The production cross section for $^{16}\text{O} \rightarrow ^7\text{Be}$ is $\sigma_p = 0.03$ mb. The cross sections are normalized to the $^{12}\text{C}(\gamma, n)^{11}\text{C}$ cross section.

Introduction

In the course of another experiment⁽¹⁾ it was observed that high energy bremsstrahlung produced an appreciable amount of ^7Be in ^9Be and ^{12}C . The production cross section for the $(\gamma, 2n)$ reaction was an order of magnitude larger in ^9Be than in ^{12}C , ^{14}N , and ^{16}O , and the cross section of

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$^{12}\text{C}(\gamma, \alpha n) ^7\text{Be}$ was as high as 1/15 of $^{12}\text{C}(\gamma, n) ^{11}\text{C}$. To investigate this, we measured the excitation curves for the production of ^7Be from ^9Be and ^{12}C using the residual activity method. To obtain information on nuclear photon absorption in the little explored region just above meson-threshold, where nuclear structure is expected to manifest itself in the cross sections for various possible photo-disintegrations, we extended the measurements to 275 MeV photons. For comparison we measured some photo-disintegration processes in ^{27}Al . Since the magnitude of the cross section for the production of ^7Be , a 0.5 MeV gamma emitter with a half life of 53 days, is of interest in the design of the target area, beam stopper, etc., for high intensity electron accelerators, we irradiated also some water targets and measured the production of ^7Be . We measured the $^{12}\text{C}(\gamma, n) ^{11}\text{C}$ reaction to normalize our cross sections with those of Barber, et al. (2)

A summary of the reactions studies and their Q values is shown in Table I. Table II contains information about the radioactive nuclei that were measured. The interpretation of the measurements on aluminum is obscured by the fact that the ^{18}Ne , ^{22}Mg , and ^{24}Ne produced from ^{27}Al decays to ^{18}F , ^{22}Na , and ^{24}Na respectively before the counting is started and simulate a higher yield of the last three isotopes.

Experimental Method

Targets of beryllium pellets, anthracene powder, water, and aluminum pellets were irradiated with the bremsstrahlung beam of the Illinois betatron. Depending on the half life of the residual nucleus and the cross section of the reaction being investigated, the irradiations lasted up to 50 hours. The maximum energy of the betatron was varied between 45-275 MeV in steps of about 20 MeV. After the irradiation the targets were thoroughly shaken to homogeneously distribute the pellets in the counting container and thus circumvent corrections for the different angular distribution of the bremsstrahlung beam at different energies. The induced γ activity (including β^+ annihilation) was counted with the aid of a 4" x 3" sodium iodide crystal and a 256 channel pulse height analyzer. The activity in most of the samples was followed for over three months. The decay curves thus obtained were analyzed with the aid of a computer. The half lives of the various activities were the same as those appearing in the literature, within our experimental errors (1-5%). No spurious γ peaks were observed in our spectra, nor did we find extraneous half lives, except for a trace of 15-hour ^{24}Na in the beryllium. We estimate from this that the beryllium contained 0.1% aluminum impurity, as was listed by the manufacturer.

Results

Fig. 1 shows the production cross section as a function of peak bremsstrahlung energy for the reactions:

$^9\text{Be}(\gamma, ^7\text{Be})$, $^{12}\text{C}(\gamma, ^7\text{Be})$, $^{27}\text{Al} \rightarrow ^{18}\text{F}$, and $^{27}\text{Al} \rightarrow ^{24}\text{Na}$.

The production cross section is defined as $\sigma_p = A/NQ$ where A is the number of reactions induced, Q is the number of incident effective quanta, and N is the target thickness in atoms/cm². The "arbitrary units" used in Fig. 1 and 2 are actually cm² multiplied by a factor that is close to one. This factor depends on the detection efficiency. Besides the reactions shown in Fig. 1 we measured also the production of ^7Be from ^{16}O and ^{22}Na from ^{27}Al . Table III shows the production cross sections up to 275 MeV bremsstrahlung.

Even though our measurement of the production cross section was taken only at 20 MeV intervals, we performed a Penfold-Leiss analysis to obtain the gross features of the cross section. This analysis was done on the curves drawn by eye through the measured points as indicated in Fig. 1. The results for the beryllium and carbon targets are shown in Fig. 2. The integrated cross sections between threshold and 275 MeV are:

for ${}^9\text{Be}(\gamma, {}^7\text{Be})$	10 ± 3	MeV-mb
${}^{12}\text{C}(\gamma, {}^7\text{Be})$	13 ± 3	MeV-mb
${}^{27}\text{Al} \rightarrow {}^{18}\text{F}$	13 ± 2	MeV-mb
${}^{27}\text{Al} \rightarrow {}^{24}\text{Na}$	28 ± 4	MeV-mb

Discussion

A. Below 100 MeV

The cross section curves of Fig. 2 show clearly a peak at about 35 MeV for both the ${}^9\text{Be}(\gamma, {}^7\text{Be})$ and the ${}^{12}\text{C}(\gamma, {}^7\text{Be})$ reactions. The accuracy of the experiment does not allow us to make any precise estimate about the width or position of the peaks: either an isochromat or a 20 MeV wide peak could be accommodated by our present data.

However, the existence of the peaks is certain. The peak in beryllium is produced by the reaction ${}^9\text{Be}(\gamma, 2n){}^7\text{Be}$.

The peak in carbon below 47 MeV is produced by ${}^{12}\text{C}(\gamma, \alpha n){}^7\text{Be}$.

For photon energies higher than 47 MeV a four- or more-body break-up of ${}^{12}\text{C} \rightarrow {}^7\text{Be}$ is possible due to the break-up of the α particle.

Most of the cross section for nuclear photon absorption below meson-threshold is concentrated in the giant resonance and appears as (γ, n) and (γ, p) reactions. The closer the threshold for a reaction like $(\gamma, 2n)$ lies to the peak of the giant resonance, the larger its cross section is likely to be. From this point of view, it is not surprising that the $(\gamma, 2n)$ reaction in ${}^9\text{Be}$ is much larger than in ${}^{12}\text{C}$,

because the $(\gamma, 2n)$ reaction threshold is about 11 MeV closer to the peak of the giant resonance in ^9Be than it is in ^{12}C .

The $(\gamma, 2n)$ reaction in ^9Be could be described by the following model: The incoming gamma ray interacts with an α cluster in ^9Be and a neutron is emitted from this cluster, similar to the photodisintegration of helium. The branching ratio of the decay channels of the resulting system is governed by the usual selection rules of spin, isotopic spin (T) and parity. For example, the decay of a $T = 1$ state into two α particles is forbidden even though this would be the most favorable channel from the point of view of phase space. The explanation of a primary interaction with an α cluster seems reasonable for the ^9Be nucleus (where no shell model calculations of the giant resonance are available). One is tempted to apply a similar model for the $(\gamma, 2n)$ reactions in ^{12}C and ^{16}O . These two nuclei are very similar in the α cluster model and their spin, isotopic spin and parity are identical. The Q values for the $(\gamma, \alpha n)$ reactions in ^{12}C and ^{16}O are also similar, namely 26 MeV. We would then expect a similar behavior for the $(\gamma, \alpha n)$ reactions in both nuclei, with an eventual favoring of the one in ^{16}O because the number of excited states in ^{11}C leading to the ground state

is larger than in ${}^7\text{Be}$. Comparing the experimental results of the present work for ${}^{12}\text{C}$ and the measurements of Bishop et al. (3) for ${}^{16}\text{O}$ one sees that the cross section for $(\gamma, \alpha n)$ in ${}^{12}\text{C}$ has a peak between 30-40 MeV that is 5-10 times bigger than the $(\gamma, \alpha n)$ cross section in ${}^{16}\text{O}$. In the region of 70-80 MeV photon energy the cross section for ${}^{12}\text{C} \rightarrow {}^7\text{Be}$ is lower than for ${}^{16}\text{O} \rightarrow {}^{11}\text{C}$. We conclude that the actual behavior of the reactions ${}^{12}\text{C}(\gamma, \alpha n)$ and ${}^{16}\text{O}(\gamma, \alpha n)$ are quite different and it seems impossible to explain this by the naive α cluster model.

The shell model calculations of the giant resonance offer better possibilities for explaining the difference between the $(\gamma, \alpha n)$ cross section in ${}^{12}\text{C}$ and ${}^{16}\text{O}$: A sizable fraction of the giant resonance dipole strength in ${}^{12}\text{C}$ is thought to be in the state $\left| (1s)^{-1} 1p_{1/2} \right\rangle$ at $\sim 34-37$ MeV. (4) No such state is present in ${}^{16}\text{O}$. Attempts are being made to calculate this.

We have not yet made the cross section calculation for the reactions ${}^{27}\text{Al} \rightarrow {}^{24}\text{Na}$ and ${}^{27}\text{Al} \rightarrow {}^{18}\text{F}$, but we can conclude from the yield curves of Fig. 1 that the $(\gamma, \alpha n)$ cross section is very small in ${}^{27}\text{Al}$. From Table III we conclude that the $(\gamma, 2\alpha n)$ cross section is small in ${}^{16}\text{O}$ also.

B. Above 100 MeV

The curves of Fig. 2 show an increase in cross section around meson-threshold for the ${}^9\text{Be}(\gamma, {}^7\text{Be})$ and ${}^{12}\text{C}(\gamma, {}^7\text{Be})$ reactions.

One expects an increase in the nuclear photon absorption cross section because of mesonic effects. This region--in contrast to the giant resonance--is poorly investigated. The experimentally observed cross section for the photopion production on complex nuclei is proportional to $A^{2/3}$, where A is the atomic number.⁽⁵⁾ Several models, such as the optical model and the Wilson model, have been used to explain this $A^{2/3}$ behavior on the assumption that the nuclear photon absorption cross section σ_A is proportional to A . To a good approximation $\sigma_A = CA\sigma_\pi$ where σ_π is the total pion production cross section on a free nucleon and C is a factor that takes into account the Pauli principle. Emulsion data⁽⁶⁾ indicates that $C \sim 0.7$. The integrated cross section for total pion production between threshold and 400 MeV on a free proton is about 80 MeV-mb. For a free neutron this is about 90 MeV-mb. This gives $\int_{140}^{400} \sigma_A dk \simeq 60$ MeV-mb per nucleon. For comparison we note that the total integrated nuclear photon absorption cross section up to 140 MeV is $(1 + x)15$ MeV-mb per nucleon where x is experimentally determined to be about 0.8 for light nuclei.⁽⁷⁾

Our results do not allow us to make a detailed description of the cross section for the photoproduction of ^7Be from ^9Be and ^{12}C , but it seems to us that there is enough evidence to draw the following conclusions from the data:

- A) The second maximum starts below meson threshold.
- B) The peak in the reaction $^9\text{Be}(\gamma, ^7\text{Be})$ is at a photon energy 20-60 MeV below the peak in $^{12}\text{C}(\gamma, ^7\text{Be})$.
- C) The cross sections for the production of ^7Be from ^9Be and ^{12}C do not rise like the pion production cross section rises, at least up to 275 MeV. (The maximum for the photopion production on free nucleons is at about 330 MeV.)

For comparison we mention that the production of ^{18}F and ^{24}Na from ^{27}Al , shown in Fig. 1, seems to go more nearly like the pion production on free nuclei.

The Wilson model gives a qualitative explanation for the increased cross section below meson threshold similar to the case of the photodisintegration of the deuteron: (8) The incoming gamma ray interacts with a single nucleon, producing a pion that is reabsorbed by a 2-nucleon pair, one of which is the parent nucleon.

Schematically the sequence is as follows:

where the square brackets indicate the intermediate virtual state. We note that the following facts promote the above reaction: A) The π^- photoproduction in ^9Be is known experimentally to be unusually large.⁽⁵⁾ B) The π^- absorption in complex nuclei occurs predominately by a neutron-proton pair resulting in the emission of two fast neutrons.⁽⁹⁾ This model thus predicts an increase in the cross section for $^9\text{Be}(\gamma, ^7\text{Be})$ below meson threshold due to virtual meson production and subsequent absorption. The observed decrease in cross section above meson threshold is not readily explained by the model and indicates that the production of ^7Be is no longer enhanced when emission of pions becomes competitive.

Similar arguments can be drawn for carbon, but a more sophisticated analysis that includes the detailed structure of the nuclei involved is necessary to explain the difference between the cross sections of the reactions $^9\text{Be}(\gamma, ^7\text{Be})$ and $^{12}\text{C}(\gamma, ^7\text{Be})$.

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*Supported in part by the U. S. Atomic Energy Commission and the Office of Naval Research.

TABLE I

<u>Reaction</u>	<u>-Q in MeV</u>
${}^9\text{Be}(\gamma, 2n){}^7\text{Be}$	21
${}^9\text{Be}(\gamma, 2n\pi^0){}^7\text{Be}$ etc.	156
${}^{12}\text{C}(\gamma, \alpha n){}^7\text{Be}$	26
${}^{12}\text{C}(\gamma, 2p3n){}^7\text{Be}$	55
${}^{12}\text{C}(\gamma, \alpha n\pi^0){}^7\text{Be}$ etc.	161
${}^{16}\text{O}(\gamma, 2\alpha n){}^7\text{Be}$	33
${}^{27}\text{Al}(\gamma, 2pn){}^{24}\text{Na}$	31
${}^{27}\text{Al}(\gamma, 2\alpha n){}^{18}\text{F}$	31

TABLE II

<u>Nucleus</u>	<u>Half Life</u>	<u>Mode of Decay</u>
${}^7\text{Be}$	53 days	K (90%); γ 0.48 MeV (10%)
${}^{18}\text{F}$	111 min.	β^+ 0.63 MeV
${}^{22}\text{Na}$	2.58 years	β^+ 0.54 MeV; γ 1.27 MeV
${}^{24}\text{Na}$	14.97 hours	β^- 1.39 MeV; γ_1 1.37 MeV; γ_2 2.75 MeV
${}^{18}\text{Ne} \xrightarrow{\beta^+} {}^{18}\text{F}$	1.6 sec.	
${}^{22}\text{Mg} \xrightarrow{\beta^+} {}^{22}\text{Na}$	<4 sec	
${}^{24}\text{Ne} \xrightarrow{\beta^-} {}^{24}\text{Na}$	3.4 min.	

TABLE III

<u>Energy</u>	<u>$^{16}\text{O} \rightarrow \text{Be}^7$</u>	<u>$^{27}\text{Al} \rightarrow \text{Na}^{22}$</u>
75 MeV	3 μb	18 μb
140 MeV	18 μb	21 μb
275 MeV	26 μb	32 μb

Figure Captions

- Fig. 1 Production Cross Section as Function of Peak
bremsstrahlung energy for the reactions
 ${}^9\text{Be}(\gamma, {}^7\text{Be})$, ${}^{12}\text{C}(\gamma, {}^7\text{Be})$, ${}^{27}\text{Al} \rightarrow {}^{18}\text{F}$ and
 ${}^{27}\text{Al} \rightarrow {}^{24}\text{Na}$.
- Fig. 2 Cross Section for the Reaction ${}^9\text{Be}(\gamma, {}^7\text{Be})$ and
 ${}^{12}\text{C}(\gamma, {}^7\text{Be})$.

Table Captions

- Table I List of Reactions Studies and Their Q Values.
- Table II Half Life and Decay Products of the Nuclei
Used in This Experiment.
- Table III Production Cross Section for the Reactions
 ${}^{16}\text{O} \rightarrow {}^7\text{Be}$ and ${}^{27}\text{Al} \rightarrow {}^{22}\text{Na}$.