It thus appears that the production of the low-yield elements having charges two or more lower than the target element, especially at low energies, cannot at present be satisfactorily explained by the model used. If we confine ourselves to the two-stage model of nuclear reactions, we must conclude that the trouble most likely is in our ideas of what happens in the cascade stage—evaporation theory seems hardly likely to provide enough charged-particle emission to lead to these elements. The first nonequilibrium stage must lead to a larger charged-particle ejection than predicted by the calculations of Metropolis *et al.*

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Cross Section for the Reaction $C^{13}(\gamma,n)$ at 6.4 Mev

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Using radiation from the $F^{19}(p,\alpha\gamma)$ reaction at 874-kev proton energy, the cross section for the reaction $C^{13}(\gamma,n)$ was found to be 94.1 ± 10 microbarns. The neutrons emitted from a target enriched in C^{13} were detected by an arrangement of BF_3 counters embedded in wax to give a 4π geometry.

THE reaction $C^{13}(\gamma,n)$ has previously been investigated using betatron bremsstrahlung radiation by Cook *et al.*[1,2] The cross-section curve shows a plateau at 8 to 10 Mev and a peak at around 15 Mev.

C^{13} is in many respects similar to Be^9. Both can be considered as consisting of an alpha-particle core with an extra "orbital neutron," and it has been suggested[3] that the peak in cross section found immediately above threshold in $Be^9(\gamma,n)$ might also occur in $C^{13}(\gamma,n)$. The difficulty of performing bremsstrahlung experiments at these low energies would have precluded observing this in the experiments noted above. Accordingly, an attempt was made to measure the cross section using the approximately monochromatic radiation from the $F^{19}(p,\alpha\gamma)$ reaction.

The proton target consisted of a layer of calcium fluoride deposited by evaporating the water from a slurry of this material placed on a copper backing. The target was water cooled, and the proton beam from the 3-Mv Van de Graaff generator centered by observing the hot spot. A stainless steel target tube $1\frac{1}{2}$ inches in diameter was used and the beam was stopped down to less than $\frac{1}{2}$-inch diameter.

Carbon, in elementary powder form enriched in C^{13}, was contained in two thin-walled nickel cylinders, 2 cm in diameter and 6 cm long. These cylinders had been heated for a long period, until they were of constant mass, to drive off occluded water vapor. The carbon samples were analyzed by the ORNL chemists and shown to consist of 56.5% C^{13}. Two cylinders identical in shape and size to the C^{13} cylinders had equivalent quanties by weight of ordinary graphite (effectively C^{12}) enclosed, to act as blanks, and two more were filled with heavy water. The detector has been described by Johnson, Galonsky, and Ulrich.[4] It was a 4π detector consisting of eight BF_3 counters, 1 inch in diameter by 6 inches long, embedded in paraffin on a 4.4-inch diameter circle around the beam axis, and operated in parallel by a conventional stabilized power supply and linear amplifier. The paraffin moderator was a cadmium-covered cube 17 inches on a side, with a 2-inch layer of paraffin outside. The optimum conditions for gamma-ray discrimination[4] were used.

A four-inch cylinder of sodium iodide (*Tl*) attached to the usual photomultiplier counting setup was placed approximately three meters from the target in order to monitor the gamma radiation and eliminate uncertainties in the yield per proton arising from variations in target thickness.

In performing the experiment, three runs were required in order to obtain a single set of results: In the first run, the C^{13} cylinders were placed in a standard position as close to the target as possible. The proton beam was switched on, and counts recorded by the BF_3 counter and NaI counter in a given time, generally fifteen minutes. In the second run, the C^{13} was replaced by the similar C^{12} cylinders, and in the third run by the D_2O cylinders. In all, eighteen sets of results were obtained.

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The C^{13} cross section was determined as a ratio to the D cross section. Let $n_1=BF_3$ counts with D_2O sample for a given amount of irradiation, $n_2=BF_3$ counts with C^{13} sample for the same amount of irradiation, $n_3=BF_3$ counts with C^{12} sample for the same amount of irradiation, N_1=number of C^{13} atoms in the sample, N_2=number of D atoms in the sample, and $\sigma_D=D(\gamma,n)$ cross section at this gamma energy. Then

$$\sigma_{[C^{13}(\gamma,n)]}=(n_2-n_3)/(n_1-n_3)\times(N_2/N_1)\times\sigma_D.$$

However, two important corrections must be applied to this result:

1. The BF_3 counter setup is not uniform in its sensitivity to neutrons of all energies, and account must be taken of the energy difference of the neutrons emitted from D and from C^{13}. The D neutrons are of energy 1.99 Mev, whereas the C^{13} neutrons are of 1.154 Mev, assuming no transitions exist to excited states. The detector efficiency as a function of energy has been obtained by Johnson, Galonsky, and Ulrich[4] up to 0.7 Mev. A further calibration point at approximately 4.5 Mev was obtained for this work using a Pu-α-Be source. The calibration points were fitted using the curves of Wallace and Le Caine.[5] Although the absolute error in the points themselves may be quite high, ($\pm10\%$ for very low energies and at 4.5 Mev) nevertheless the error in comparing the neutrons from C^{13} and D is only about 7%. This assumes reasonably similar neutron angular distributions for the two sources. If one source should be highly anisotropic, the error would be considerably larger.

2. The absorption of gamma rays in the C^{13} and D_2O cylinders differed. A calculation based on the work of Heitler[6] indicated that the average intensity of radiation causing disintegrations in C^{13} was 1.03 times that for D_2O for the same proton target gamma-ray output, because of this absorption in the sample.

Several errors require mention:

(i) The gamma rays are not truly monochromatic.[7] For the 874 kev resonance in $F^{19}(p,\alpha\gamma)$ which was used, 65% of the radiation is of 6.13-Mev energy, 24% of 6.9-Mev energy and 11% of 7.1-Mev, a weighted average of 6.4-Mev.

(ii) An error arises in accepting a mean value for the $D(\gamma,n)p$ cross section for these gamma rays. Our estimated value[8,9] was $(21.2\pm3)\times10^{-28}cm^2$.

(iii) Considerable error comes in the estimation of the total mass of C^{13} used. This arises from two sources—in the estimates of the ratio of C^{13} to C^{12} in the sample, and in the amount of the absorbed water which was weighed with the sample. This error was estimated at 4%.

(iv) Errors can also arise from (a) not placing the D and C^{13} samples in the same position, (b) counting statistics, (c) the calculation of the difference of gamma-ray absorption by the two samples, and (d) the $(n,2n)$ reactions in the deuterium. All these last proved negligibly small.

The errors combine to give approximately 11% uncertainty in the cross section.

Taking account of all the above, our final result was

$$\sigma_{[C^{13}(\gamma,n)]}\text{ at 6.4 Mev}=94.1\pm10\text{ microbarns}$$

This result, taken together with the cross section curve of Cook *et al.*,[1] would not indicate a pronounced peak in cross section at the energy of the fluorine radiation. However, the cross section for this radiation does have approximately the same value as Guth *et al.*[10] have calculated on the basis of an orbital neutron.

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