transition was determined on the double-focusing spectrometer.

Photoelectric peaks from eight gamma rays were identified on the scintillation spectrometers. Two additional peaks have been interpreted as pair production peaks from the two highest-energy gamma rays. The gamma-ray energies are also shown in Table I.

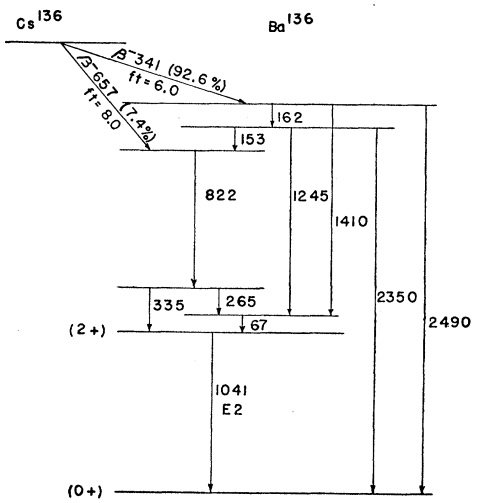

FIG. 1. Proposed decay scheme for Cs^{136}. Energy values are in kev.

No radiation was seen on the proportional counter besides the 67.2-kev transition, its xenon escape peak, and the K and L x-rays.

The decay scheme of Fig. 1 is proposed on the basis of gamma-ray intensities and gamma-gamma coincidence spectroscopy. The K-shell internal conversion coefficient for the 1.041-Mev gamma ray indicates an $E2$ transition, which leads to the assignment of a spin of two and even parity to the first excited state, as would be expected for an even-even nucleus.[7] A 1.041-Mev first excited state is consistent with other even-even nuclides in the region of mass 136. Work is continuing on the assignment of spins and parities to the other levels of Ba^{136}.

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Note added in proof.—Recent coincidence measurements show the 153-kev gamma ray to be in cascade with the 1245- and 162-kev gamma rays. This reverses the order of the 153–162 kev cascade from that shown in Fig. 1. The 153-kev transition is a crossover for a 65–88 kev cascade not shown in Fig. 1.

[7] M. Goldhaber and A. W. Sunyar, Phys. Rev. **83**, 917 (1951).

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Yield of Alpha Particles from Photonuclear Reactions at 23-Mev Bremsstrahlung

L. H. GREENBERG, J. G. V. TAYLOR, * AND R. N. H. HASLAM
University of Saskatchewan, Saskatoon, Saskatchewan, Canada

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The yield of alpha particles from (γ,α) reactions and other photoreactions involving alpha-particle emission from 9 elements up to atomic number 58 is given. Much of the data used have been previously published but further information has been obtained on the reactions in carbon, oxygen, and bromine. Original measurements have been made for the (γ,α) reactions in vanadium and silver. The yield is a maximum in the region of copper and drops rapidly with increasing atomic number. There is evidence that at high atomic numbers, reactions involving the emission of another particle as well as the alpha particle predominate over just single alpha-particle emission.

INTRODUCTION

THE study of the yield of neutrons and of protons from nuclei excited by photon absorption has received considerable attention. Sufficient data are now available for a preliminary examination of the dependence of alpha-particle yield on atomic number. The following is a report on the yield of alpha particles from the (γ,α) reaction produced by the bombardment of several medium weight nuclei with 23-Mev bremsstrahlung.

Figure 1 shows the (γ,α) yield points for betatron radiation having a maximum energy of 23 Mev. Some of the points shown are taken from previously described work, and some have been determined recently in this laboratory. A brief discussion of each point follows:

1. $C^{12}(\gamma,\alpha)Be^8$

This reaction has been examined by several workers,[1–4] some using bremsstrahlung and some using

* Now at McMaster University, Hamilton, Ontario.

[1] F. K. Goward and J. J. Wilkins, Proc. Roy. Soc. (London) **A217**, 357 (1953).
[2] Glättli, Seippel, and Stoll, Helv. Phys. Acta **25**, 491 (1952).
[3] M. Eder and V. L. Telegdi, Helv. Phys. Acta **25**, 55 (1952).
[4] H. Wäffler, and S. Younis, Helv. Phys. Acta **22**, 614 (1949).

lithium gamma rays to produce the reaction. The reported cross sections at an energy of 17.6 Mev varies over a fairly wide range, namely from 1.1 to 2.4×10^{-28} cm^2/atom. It was thought worth while to make a redetermination of the yield of this reaction.

The Be^8 nucleus resulting from the emission of an alpha particle from C^{12} may be in either the ground state or in an excited state. In either case the Be^8 is unstable and breaks into two alpha particles. If this has occurred in a nuclear emulsion, the event is seen as a three-pronged alpha-particle star which exhibits a momentum sum of practically zero.

A 100-micron Ilford E_1 emulsion was exposed to 196 r of 23-Mev bremsstrahlung from the University of Saskatchewan betatron and 1.3 cm^2 was searched. Of the stars located, 169 with three prongs showed the proper momentum balance. Correcting for the probable number whose tracks did not end in the emulsion there were 195 such events. The manufacturer's analysis gave 0.27 gram of carbon per cubic centimeter of emulsion. An analysis of these data gives 3570 events per mole of carbon per roentgen.

To compare this result with the results already published for 17.6-Mev radiation the cross section was calculated as a function of the photon energy. The energy of the photon which caused the event was assumed to be the sum of the energies of the three alpha particles and the binding energy of 7.15 Mev. On a series of plates (from which the above data were taken) exposed at betatron energies from 16 to 26.6 Mev the energy associated with 738 stars was calculated. Assuming a modified Schiff type bremsstrahlung spectrum as tabulated in the photon difference paper by Katz and Cameron,[5] the cross section curve was calculated. At 17.6 Mev the cross section was 1.7×10^{-28} cm^2/atom, which is in the range of the previously published values. The yield point at 23 Mev is therefore assumed to be not inconsistent with the other data on this reaction.

2. $N^{14}(\gamma,\alpha)B^{10}$

This yield point was taken directly from the data of Millar and Cameron[6] and is 580 events/mole r at 24-Mev bremsstrahlung. At 23-Mev bremsstrahlung one would expect no more than 400 events/mole r. This is based on only 8 events but does serve to verify the dip in the yield curve.

3. $O^{16}(\gamma,\alpha)C^{12}$

This point has been obtained by combining the results of Millar and Cameron[6,7] with more recent observations of the authors. The cross section curve of Millar and Cameron[7] multiplied by the appropriate Schiff bremsstrahlung spectrum[5] gave an activation point. The cross section curve of Millar and Cameron was obtained from the number of "recoil events" identified in a nuclear emulsion. The authors have repeated this and obtained only a slightly different value. However, the method is very uncertain for low-energy alphas. There is some evidence that the oxygen may be very strongly excited to the levels around 13 Mev, and then, on decay to the ground state of carbon, there is a release of about 6 Mev. The observed alpha-particle energy would be about 4.5 Mev with the remainder going to the recoiling carbon. This recoiling nucleus would have a track about a micron in length and would only slightly raise the alpha-particle energy as measured by the track length. A large number of the observed recoil events do fit this transition and there were also a large number classified as single alpha particles but which have an energy appropriate for this reaction. The method by which Cameron obtained the cross section for the reaction assumed that the kinetic energy of the alpha particle plus recoil nucleus and the binding energy was the total energy involved in the reaction. It is almost certain, however, that in many cases when the high-energy oxygen levels are excited the recoiling carbon nucleus is in an excited state. The oxygen point therefore has the greatest uncertainty of all shown on the graph.

4. $V^{51}(\gamma,\alpha)Sc^{47}$

A yield point for 23-Mev bremsstrahlung was obtained for the (γ,α) reaction in V^{51} by the method of residual activity. A mass of 15.6 grams of sodium orthovanadate ($Na_3VO_4\cdot16H_2O$) was irradiated in the geometry used in the (γ,α) reaction in copper.[8] The sample

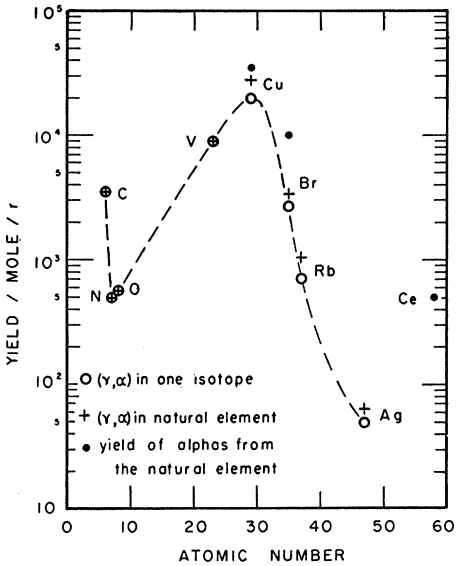

FIG. 1. The yield of alpha particles from photonuclear reactions as a function of atomic number. The (γ,α) yield from the heavy isotope, where one exists, as well as the yield corrected for the natural element is given. In cases where it has been measured the total yield of alpha particles from all reactions is also shown.

[5] L. Katz and A. G. W. Cameron, Can. J. Phys. **29**, 518 (1951).
[6] C. H. Millar and A. G. W. Cameron, Phys. Rev. **78**, 78 (1950).
[7] C. H. Millar and A. G. W. Cameron, Can. J. Phys. **31**, 723 (1953).
[8] Haslam, Smith, and Taylor, Phys. Rev. **84**, 840 (1951).

was dissolved in 100 ml of water with about 10-mg Sc^{+++} carrier and 2-mg Fe^{+++} carrier. An excess of NaOH was added to precipitate Sc and Fe as hydroxides. The solution was filtered through No. 40 filter paper. The precipitate was dried and counted between two RCL end-window counting tubes.

Counting corrections were based on the assumption of a 0.6-Mev beta.[9] The dose received by the sample was 46 400 roentgens in 40 minutes and was measured by the activity induced in tantalum strips irradiated simultaneously with the sodium orthovanadate. The activity of the sample was followed for 31 days, previous trial irradiations having shown a pure 72-day activity after this time. Subtraction of the 72-day titanium activity caused by the (n,p) reactions left the activity caused by 3.43-day Sc^{47} and a small amount due to 15-hour Na^{24}. The decay curves are shown in Fig. 2.

Correcting for attenuation of the beam in the sample, counting losses, etc., the yield was determined to be 9×10^3 disintegrations/mole r for 23-Mev bremsstrahlung. Natural vanadium is practically 100 percent V^{51} so there is no correction for the naturally occurring element.

5. $Cu^{65}(\gamma,\alpha)Co^{61}$ and $Cu(\gamma,\alpha)Co$

The yield point for the $Cu^{65}(\gamma,\alpha)Co^{61}$ reaction was taken from the published data of Haslam, Smith, and Taylor[8] and is 2.0×10^4 events/mole r of Cu^{65}. The yield from Cu^{63} was estimated from this on the basis of the statistical theory of nuclear reactions. By using the result of this calculation and correcting for isotopic abundance, the yield from naturally occurring copper was estimated to be 2.8×10^4 events/mole r.

Byerly and Stephens[10] made a measurement of the yield of alpha particles emitted from a copper sample irradiated at 24-Mev bremsstrahlung. Corrected to 23 Mev by the use of an approximate yield curve their data give 3.5×10^4 events/mole r. Because their method involved the detection of emitted alpha particles, reactions involving the emission of a neutron or proton as well as an alpha particle were included. The method used by Haslam, Smith, and Taylor detected only the events in which an alpha and no other particle was emitted. The yield point of Byerly and Stephens is expected to be higher than that of Haslam and the agreement is therefore excellent.

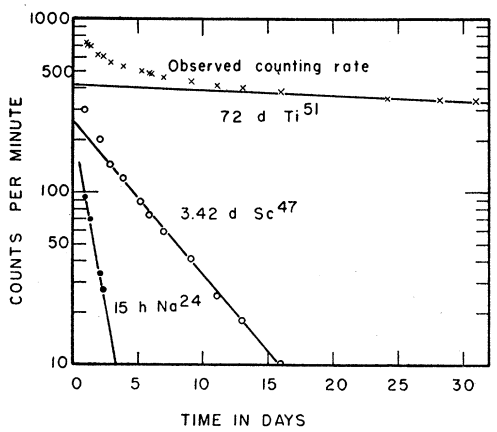

FIG. 2. The decay curve of the scandium separated from irradiated vanadium. Some 72-day Ti and 15-hour Na were also present but could be subtracted out.

6. $Br^{81}(\gamma,\alpha)As^{77}$ and $Br(\gamma,\alpha)As$

The yield for the reaction $Br^{81}(\gamma,\alpha)As^{77}$ was taken from the paper of Taylor and Haslam.[11] As for copper, a correction was made in order to obtain the yield from Br^{79} and the natural element. Taylor and Haslam had carried out a similar calculation at 17.6 Mev to compare their results with those obtained by Nabholtz *et al.*[12] using lithium gamma rays. The agreement at 17.6 Mev was good.

The yield at 23 Mev was 2.7×10^3 events/mole r in Br^{81} and 3.4×10^3 events/mole r in natural bromine.

The total yield of alpha particles from natural bromine can be estimated from the work of Haslam *et al.*[13] with nuclear emulsions. One may assume that the alpha particles in their high-energy peak were caused practically entirely by the reaction in bromine rather than both in bromine and silver as they assumed. Using their data and also more recent data of the authors, which are in excellent agreement, the yield of alpha particles from natural bromine was calculated to be 1.0×10^4 alphas/mole r. This would include many reactions in which other particles were also emitted and is, as expected, considerably higher than the yield measured by Taylor.

7. $Rb^{87}(\gamma,\alpha)Br^{83}$ and $Rb(\gamma,\alpha)Br$

The yield point for $Rb^{87}(\gamma,\alpha)Br^{83}$ was obtained by Haslam and Skarsgard[14] and was 7×10^2 events/mole r for 23-Mev bremsstrahlung. Correcting for the natural element one obtains 10.3×10^2 events/mole r.

8. $Ag^{109}(\gamma,\alpha)Rh^{105}$ and $Ag(\gamma,\alpha)Rh$

This reaction was of special interest because of the presence of Ag in a nuclear emulsion. The contribution of the silver atoms to the particle tracks observed in a nuclear emulsion bombarded with x- or gamma rays could be definitely established only by direct measurement of the cross section for the reaction.

The reaction $Ag^{109}(\gamma,\alpha)Rh^{105}$ may be detected by irradiating silver in the betatron beam and examining it for 37-hour Rh^{105} beta activity. Because of the high

[9] N. L. Krisberg and M. L. Pool, Phys. Rev. **75**, 1693 (1949).
[10] P. R. Byerly, Jr., and W. E. Stephens, Phys. Rev. **83**, 54 (1951).
[11] J. G. V. Taylor and R. N. H. Haslam, Phys. Rev. **87**, 1138 (1952).
[12] Nabholtz, Stoll, and Wäffler, Phys. Rev. **86**, 1043 (1952).
[13] Haslam, Cameron, Cooke, and Crosby, Can. J. Phys. **30**, 349 (1952).
[14] R. N. H. Haslam and H. M. Skarsgard, Phys. Rev. **81**, 479 (1951).

Coulomb barrier for alpha-particle emission, the cross sections for emission of neutrons or protons are much higher than the cross section for alpha emission. Reactions other than the (γ,α) would then lead to large interfering activities which would mask the low activity of the Rh^{105}. Also, to count the rhodium-105 it would be necessary to obtain a concentrated sample to avoid large self-absorption effects and poor geometry. For these two reasons it was necessary to separate the rhodium from the irradiated silver sample by a chemical method. The literature contains no method to separate small amounts of rhodium from large amounts of silver and a great deal of time was spent in developing a process.

The irradiated samples consisted of 50 g of $AgNO_3$. After irradiation they were dissolved in 150 ml of H_2O, and a rhodium carrier in the form of $RhCl_3$ solution was added. 20 mg of KCl as a 1-mg/ml solution was added, and the solution boiled for 3 minutes. The addition of concentrated NH_4OH to the hot solution yielded a heavy precipitate. On addition of excess concentrated NH_4OH, the major part of the precipitate dissolved, leaving a small amount of dark brown precipitate. The solution was then filtered in a Büchner funnel onto a 1-inch diameter filter paper. The precipitate was washed with NH_4OH and alcohol, dried, and counted between two end-window RCL counting tubes which gave a geometry factor of 0.6. The samples exhibited the 37-hour Rh^{105} activity with small amounts of 8-day Ag^{106} and 14-hour Pd^{109} in some samples.

The yield of the rhodium extraction was assumed to be 100 percent. It could not be measured because the composition of the precipitate was not known. However, the yield of precipitate was proportional within 5 percent to the amount of rhodium carrier added. It was then not illogical to assume that practically all of the rhodium was precipitated.

Samples were irradiated at 22 and 24 Mev. The radiation time for each was approximately one-half hour and the dosages up to 50 000 roentgens.

The dosage given to each sample was determined by measuring the activity induced in tantalum disks inserted in the end of the $AgNO_3$ sample holder. The conversion to roentgens was done in the same manner as outlined in the paper on the (γ,α) reaction in copper.[8] Appropriate corrections were also made for inverse square attenuation and absorption of the x-rays in the sample. The mean of the 22- and 24-Mev values was used to obtain the yield at 23 Mev which was 50 disintegrations/mole r. This is not the general procedure to obtain a yield point at 23 Mev but the 22- and 24-Mev yield points were part of an attempt to obtain a complete yield curve for the reaction.

Correcting for the isotopic abundance and the expected yield from the lighter isotope, natural silver would give 67 events/mole r. The errors are very large, and the correction is insignificant.

9. $Ce(\gamma,\alpha)Ba$

Toms and Stephens[15] measured the yield of alpha particles from a cerium sample bombarded with bremsstrahlung of 24-Mev maximum energy. The yield at 23 Mev would be lower by a factor of 0.7 to 0.9. The emitted alpha particles were observed and hence reactions other than those in which just a single alpha particle was emitted were included. For 24-Mev bremsstrahlung Toms and Stephens report a yield of 800 alphas/mole r from cerium. At 23 Mev this could be as low as 500 alphas/mole r.

This point as shown on the graph (Fig. 1) does not verify the downward trend toward higher atomic number. It could be either that, for the higher elements, reactions in which a neutron is also emitted are more predominant, or that a mechanism such as the direct photoelectric effect becomes more important.

DISCUSSION

This is only a preliminary survey to indicate the approximate value of the yield from the (γ,α) reactions in the various elements. The shape of the yield curve is similar to that of the curve for the proton yield as a function of atomic number presented by Mann and Halpern.[16] The alpha-particle yield is lower by a factor varying from 10^2 to 10^4.

It is obvious that more points at higher atomic number are required. The work of Toms and Stephens suggests that the downward trend may not continue as steeply becuase they calculate that from bismuth there would be 100 alphas/mole r. The absorption cross section for gamma rays increases with increasing atomic number, the potential barrier increases, and the photoelectric effect is expected to increase. The relative effects of these factors must be determined by further experiments.

It must also be pointed out that a yield curve such as this does not give the relative integrated cross sections for the reactions. The yield is a strong function of the energy at the resonance peak in the cross-section curve as well as the area under the curve.

ACKNOWLEDGMENT

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[15] M. E. Toms and W. E. Stephens, Phys. Rev. **92**, 362 (1953).
[16] A. K. Mann and J. Halpern, Phys. Rev. **82**, 733 (1951).