EVIDENCE FOR PHOTOFISSION OF IRON*

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Studies of proton-induced reactions in the GeV energy region[1,2] have given evidence that fission occurs in nuclei at least as light as silver. It has been pointed out that any nucleus can be made to undergo fission provided it is supplied with sufficient excitation energy.[3,4] In this note we present evidence of photofission in iron foils that were bombarded with high-energy electrons.

In a study[5] of residual radioactivity produced in targets exposed to electrons in the GeV energy region, radionuclides were identified over a wide range of mass number. It was demonstrated that the residual nuclei are produced predominantly by photonuclear reactions that are induced by the electron bremsstrahlung photons.

The experiments are done by exposing targets to monitored beams of electrons at the Cambridge Electron Accelerator and subsequently measuring the gamma spectra from the exposed targets with a Ge(Li) gamma spectrometer. Radionuclides are identified by gamma energy and half-life.

The yields of radionuclides identified in iron foils exposed to electron beams are plotted in Fig. 1 as a function of the number of nucleons removed from the target nucleus. The yield of $^{32}P + ^{33}P$, which are pure beta emitters, was identified by radiochemistry. (Analysis of the decay curve indicates that the two isotopes are produced with about equal intensity.) All of the other nuclides were identified in gamma spectra obtained by the Ge(Li) spectrometer. Additional identifications of ^{24}Na and ^{43}K were made by radiochemistry.

In the mass region $A \geq 43$ in Fig. 1 the yield of radionuclides exhibits an exponential decrease with the number of nucleons emitted from the target nucleus. The yields of ^{24}Na and $^{32}P + ^{33}P$ are, however, much larger than would be expected, unless the mechanism for production of these nuclei is different from that of the nuclides with $A \geq 43$.

In spectra obtained from aluminum targets that were bombarded with 3-GeV electrons an appreciable yield of ^{7}Be was observed.[5] Careful examination of the gamma spectra obtained from the iron targets yielded no evidence for ^{7}Be. A radiochemical separation also yielded no evidence for ^{7}Be in an iron foil that was bombarded with 3-GeV electrons. Studies of proton- and alpha-induced reactions[6] have shown that emission of ^{7}Be is enhanced by rotational motion of the compound nucleus. Photon-induced reactions produce little rotational motion of the target nucleus.

The curve of Fig. 1 is an exponential drawn through a plot of calculated cross sections for production of residual nuclei by nucleon-induced reactions. The cross sections were calculat-

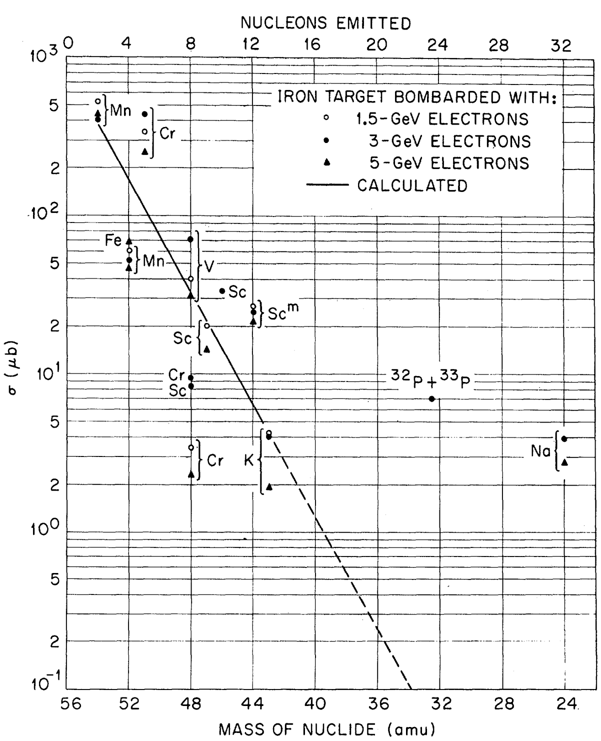

FIG. 1. Yields of radionuclides identified in iron samples that were exposed to a beam of 3-GeV electrons. The values of σ are based on the integrated electron beam intensity.

ed from the cascade-evaporation results of Bertini.[7] Calculations were made at 50-MeV invervals between 50 and 400 MeV; the cross sections thus obtained were multiplied by the intensity of the bremsstrahlung spectrum[8] at each energy. These products were summed for each mass number to yield the plot through which the curve of Fig. 1 was drawn. This curve was then normalized to the experimental data, for mass 43 and larger, in Fig. 1. The calculations included ^{43}K and residual nuclei of larger mass. Although the absolute magnitude of the calculated cross section for nucleon-induced reactions is almost three orders of magnitude larger than that of the measured cross sections in Fig. 1, the fall-off of cross section with intensity is in reasonable agreement with that of the data down to mass 43.

The yield of ^{24}Na is a factor of between 10^3 and 10^4 larger than would be expected from extrapolation of the cascade-evaporation theory. The yield of $^{32}P+{}^{33}P$ is also much higher than would be predicted by the theory. Apparently another reaction mechanism is responsible for the yield of ^{24}Na that is observed.

A spectrochemical analysis of a piece of the iron foil that was used for the bombardments indicated the presence of impurities that can account for less than 1% of the ^{24}Na production, if it is assumed that the impurities, near mass 24, have cross sections for production of ^{24}Na that are about the same as that of aluminum.[5] It was also observed that the yield of ^{24}Na in a thick target varies with depth in the material in the same manner as other radionuclides.

One may attempt to attribute the relatively large yield of ^{24}Na to nuclear fragmentation, i.e., the emission of fragments of mass 5-10. Emission of several fragments would be required, and this process would not yield similar amounts of ^{24}Na and ^{32}P.

The most reasonable explanation for the relatively large yields of ^{24}Na and ^{32}P appears to be that photofission of iron nuclei is induced by high-energy bremsstrahlung photons. The Q value for this reaction is −28 MeV and the Coulomb barrier is ~22 MeV, therefore the fission barrier is ~50 MeV.[9] Many of the photons in the bremsstrahlung spectrum from 3-GeV electrons have enough energy to produce fission in iron.

One would expect that photofission of iron would result in production of other residual nuclei in the same mass region. A small yield of ^{22}Na was observed. Many of the radioactive nuclei in the mass region between 24 and 32 have half-lives that are too long or too short to be identified in the experiment reported here and in Ref. 5. Some evidence of ^{28}Mg was observed; however, it has a beta decay chain length of two, compared with one for ^{24}Na and ^{32}P, and thus the yield of ^{28}Mg would be appreciably lower than that of ^{28}Al or ^{28}Si.

Fission is energetically favored over other reaction mechanisms such as multiple-nucleon (32 for production of ^{24}Na in ^{56}Fe) or alpha-particle emission. Both cascade-evaporation theory[7] and nuclear evaporation theory[10] predict much lower relative yields of ^{24}Na than is observed. Any mechanism other than fission would result in a much lower yield of ^{24}Na than of ^{32}P, whereas the experimentally observed yields are approximately equal.

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[1]A. A. Caretto, J. Hudis, and G. Friedlander, Phys. Rev. 110, 1130 (1958).

[2]E. W. Baker and S. Katcoff, Phys. Rev. 123, 641 (1961).

[3]J. M. Miller and J. Hudis, Ann. Rev. Nucl. Sci. 9, 159 (1959).

[4]R. W. Spence and G. P. Ford, Ann. Rev. Nucl. Sci. 2, 411 (1953).

[5]C. B. Fulmer, I. R. Williams, G. F. Dell, and L. N. Blumberg, Bull. Am. Phys. Soc. 12, 499 (1967); and to be published.

[6]R. H. Lindsay, Phys. Rev. 147, 782 (1966).

[7]H. W. Bertini, Phys. Rev. 131, 801 (1963); 138, AB2(E) (1965). Also Oak Ridge National Laboratory Report No. ORNL-TM-1225, 10 September 1965 (unpublished).

[8]Y. S. Tsai and Van Whitis, Phys. Rev. 148, 124 (1966).

[9]W. D. Myers and W. J. Swiatecki, Nucl. Phys. 81, 1 (1966).

[10]I. Dostrovsky, Z. Frankel, and G. Friedlander, Phys. Rev. 116, 683 (1959).