PHYSICAL REVIEW VOLUME 95, NUMBER 5 SEPTEMBER 1, 1954

Photoprotons from Cobalt*

M. Elaine Toms† and William E. Stephens
University of Pennsylvania, Philadelphia, Pennsylvania

(Received May 26, 1954)

The charged particles ejected from a thin cobalt foil by the bremsstrahlung x-rays from a 24-Mev betatron have been observed in nuclear emulsions. Yields measured in units of 10^4 particles per mole per roentgen unit are: protons, 49 ± 10; deuterons, less than 1; alpha particles 1.6 ± 0.5 (corrected for absorption in cobalt foil). The angular distribution of the photoprotons could be fitted with a curve of the shape of $I(\theta)=71+8(\sin\theta+\sin\theta\cos\theta)^2$. The photoproton energy distribution can be accounted for mainly by evaporation from a compound nucleus, although 5 or 10 percent could be from a direct process. The relative absence of photodeuterons in cobalt, compared with the case of copper which has similar binding energies, suggests that the shell structure may be important in allowing photodeuteron emission.

INTRODUCTION

THE anomalous yield of photodeuterons from copper[1] has prompted further investigation to find additional information about photodeuteron emission. Cobalt has binding energies for deuterons, neutrons, protons, and alpha particles very close to those of copper and hence might be expected to photodisintegrate very similarly. Consequently, the photoemission of charged particles from a thin foil of cobalt irradiated with betatron x-rays was examined with the same technique as previously used on Mg,[2] Cu,[1] Ce, In, and Bi.[3] The yield[4] and angular distribution[5] of cobalt photoprotons has been measured previously with a scintillation detector. Our initial results, using nuclear emulsions were reported at the Washington meeting.[6]

EXPERIMENT

A collimated beam of bremsstrahlung x-rays from the University of Pennsylvania betatron operated at 24 Mev was used to irradiate a thin foil of cobalt of thickness 1.4 mil or 31.5 mg per cm². The foil was placed at an angle of 30° to the beam and 200-micron Ilford *E*-1 nuclear emulsion plates were placed at angles of 30°, 50°, 70°, and 90° to the beam on the left and 90°, 110°, 130°, and 150° on the right. The camera was evacuated and the foil was irradiated with 44 200-roentgen units of x-rays. The x-ray yield was calibrated against a Victoreen 100-r chamber in a 15-cm diameter Lucite cylinder. After development, about 0.44 cm² of each plate was scanned and the ranges of 4926 tracks in the correct direction were measured. About 150 tracks which left the emulsion were grain-counted to allow an estimation of the residual range. About sixty tracks below 150 microns in length were grain-counted to look for deuterons. The number of grains in the last forty microns of track scattered somewhat more than in faded *C*-2 emulsions, but there was no indication of a group of particles with a grain count distinctly above that of the recoil protons used as a check. 335 alpha particles were identified by their denser tracks. The observed proton ranges were increased by the equivalent half-foil thickness in the emulsion and the range-energy curve of Rotblat was used to convert to proton energy. Since the foil was thick enough to stop some of the alpha particles and since it seems likely that some of the low-energy alpha particles were missed in scanning, the observed alpha track distribution was not corrected for foil thickness, but the theoretical curve was corrected for absorption

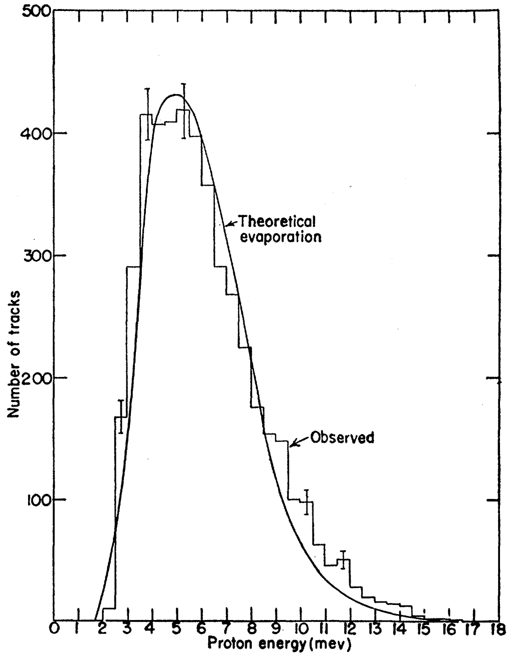

Fig. 1. The number of observed proton tracks from cobalt as a function of proton energy is shown in the histogram. The theoretical curve is calculated as proton evaporation from a statistical model nucleus and corrected for absorption in the cobalt foil.

---

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

† Now at Naval Research Laboratory, Washington, D. C.

[1] P. R. Byerly, Jr., and W. E. Stephens, Phys. Rev. **83**, 54 (1951).

[2] M. E. Toms and W. E. Stephens Phys. Rev. **82**, 709 (1951).,

[3] M. E. Toms and W. E. Stephens, Phys. Rev. **92**, 362 (1953).

[4] A. K. Mann and J. Halpern, Phys. Rev. **82**, 733 (1951).

[5] Mann, Halpern and Rothman, Phys. Rev. **87**, 146 (1952).

[6] Toms, Gerardo, and Stephens, Phys. Rev. **95**, 629(A) (1954).

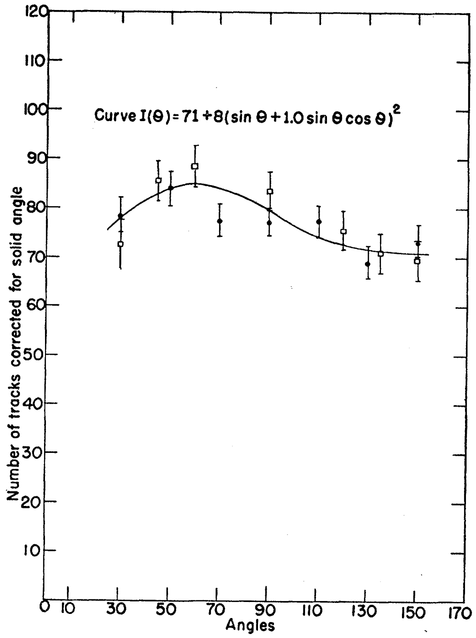

FIG. 2. The observed angular distribution of photoprotons from cobalt. The dots are the present work; the squares are from the scintillation detector work of Mann and Halpern. The curve is described by $I(\theta)=71+8(\sin\theta+\sin\theta\cos\theta)^2$.

in the foil. The background determined in a manner similar to previous work[3] is negligible.

The energy distribution of the observed photoprotons is shown by the histogram of Fig. 1. The angular distribution of these protons is shown for all energies in Fig. 2, and in Fig. 3 for various energy groups of protons. The alpha-particle energy and angular distributions are shown in Figs. 4 and 5. Figure 5 shows the number of alphas per unit solid angle of range greater than 20 microns as a function of angle with the beam.

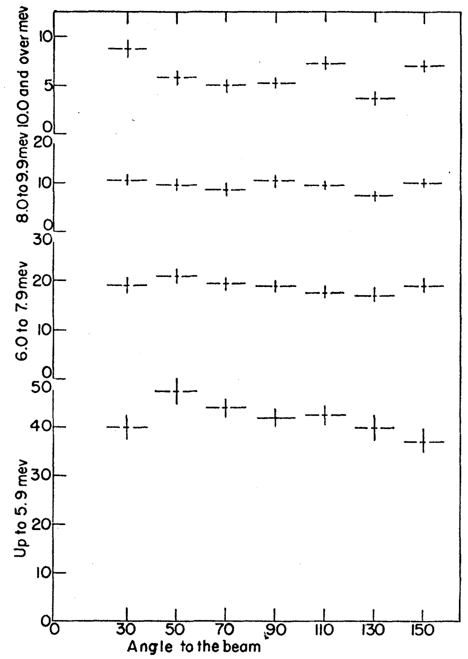

FIG. 3. Observed angular distribution of various energy photoprotons from cobalt.

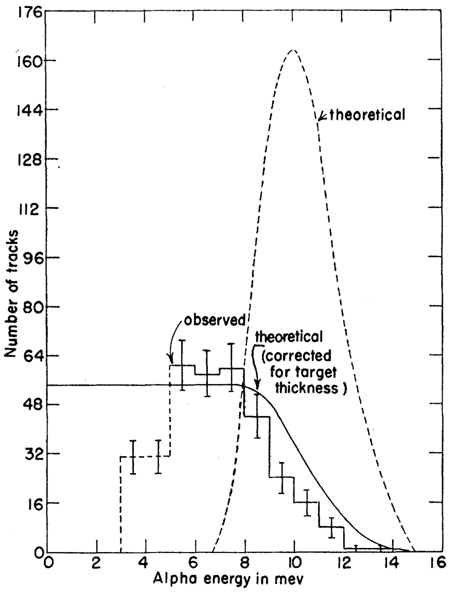

FIG. 4. Energy distribution of photo alpha particles from cobalt. The histogram shows the observed alpha tracks. The dotted curve is the evaporated calculation distribution. The solid curve is the evaporated distribution corrected for cobalt foil thickness.

The observed photoparticle yields corrected for angular distribution are given in Table I. The alpha yield is also corrected for absorption in the foil and for missed short-range tracks.

DISCUSSION

The observed energy distribution of the protons in Fig. 1 can be compared with a curve calculated on the basis of evaporation from a statistical-model nucleus. This calculation is based on the (γ,n) cross-section

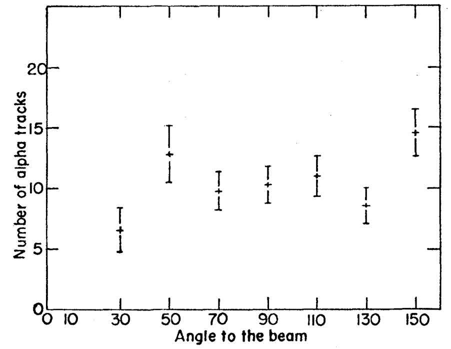

FIG. 5. Angular distribution of the cobalt photo alpha particles of range greater than 20 microns.

curve of Nathans and Halpern,[7] the bremsstrahlung photon distribution curve, Weisskopf's level density and penetrability values,[8] and the binding energies of Table I. This theoretical curve has been approximately corrected to take account of the broadening of the curve due to foil thickness. Most of the photoprotons have an energy distribution consistent with evaporation. However, about 5 percent of the protons have energies slightly higher than expected. This difference may be due either to the use of an incorrect level density or to the occurrence of a direct photoeffect. As much as 10 percent of a direct effect in addition to the evaporated protons would be consistent with the observed energy distribution.

The yield of 49×10^4 protons per mole-roentgen is in agreement with the 37×10^4 reported by Mann and Halpern[4] from their scintillation detector survey using 23-Mev bremsstrahlung. The agreement with the theoretical calculated value from evaporation, 75×10^4 protons per mole-roentgen, is also reasonable. The ratio of proton yield to neutron yield is observed to be 0.21 in good agreement with the value, 0.2, calculated from Weisskopf's[8] F ratios.

The numbers of alpha particles observed were increased by those estimated from the theoretical curve of Fig. 4 to have been absorbed in the foil or missed in the emulsion because of short length. The resultant yield, 1.6×10^4 α particles per mole-roentgen, is not much greater than that expected from evaporation, considering that there is some uncertainty in the alpha binding energy which is known only from the mass formula. The observed alpha energy distribution is most easily compared to a calculated curve approximately corrected for foil absorption. As shown in Fig. 4, a number of short alpha particles (below 20 microns) must have been missed in scanning. In order to be sure that none of the observed alpha particles was due to radioactive contamination in the cobalt, we exposed the foil directly on a nuclear emulsion but found no appreciable alpha activity.

The observed proton angular distribution is shown in Fig. 2 together with the scintillation detector measurements of Mann and Halpern. The agreement is reasonable despite the difference in the proton spectrum observed. (The foil thickness in the scintillation detector measurements was 113 mg/cm^2 plus 11 mg/cm^2 of additional absorption in the scattering chamber which favored the higher-energy protons.)

Figure 4 suggests that the anisotropic protons are primarily in the 3–7 Mev region. The proton energy distribution calculated for direct effect protons has its peak at 5 to 6 Mev proton energy. Consequently the anisotropy can still be ascribed to the presence of a few percent of direct effect protons.

The alpha-particle angular distribution (Fig. 5) does not depart from isotropy significantly in comparison with the statistical uncertainty although the 30° and 150° values are somewhat off.

The absence of photodeuterons was surprising in view of the fact that cobalt has binding energies for the last deuteron, proton, neutron, or alpha particle which are very close to those of copper where considerable photodeuterons were observed.

A possibly significant difference between cobalt and copper may be the shell structure associated with the ground state. In copper, the last proton is considered to be in a $p_{3/2}$ shell[10] while the last neutrons occupy $p_{3/2}$ and $f_{5/2}$ shells close together. Cobalt on the other hand has an almost closed shell of $f_{7/2}$ protons and four neutrons in a $p_{3/2}$ shell. It may therefore be more difficult in cobalt to assemble a neutron and proton with similar angular momentum and spin to make a deuteron either in a pickup process or in direct emission. These conjectures are made more reasonable by the single-particle model of the giant resonance proposed by Dr. D. H. Wilkinson to whom we are grateful for enlightening discussions of these ideas.

TABLE I. Binding energies and photo yields for cobalt.

Particle	Binding energy (Mev)	Observed yield	Calculated evaporated yield[g]
		(10^4 particles per mole-roentgen)	
neutron	10.25±0.2[a]	235,[d] 228[e]	...
proton	7.17±0.2[b]	49±10, 37±7[f]	75
deuteron	14.87[c]	<1	0.03
alpha	6.03[c]	1.6±0.5 (corrected for absorption)	0.6
yield ratios (γ_p/γ_n)		observed	calculated evaporation[f]
		0.21	0.2

[a] Sher, Halpern, and Mann, Phys. Rev. **84**, 387 (1951).
[b] Calculated from Co^{58} β^+ energy and reference a.
[c] N. Metropolis and G. G. Reitwiesner, U. S. Atomic Energy Commission Report NP-1980, 1950 (unpublished).
[d] G. A. Price and D. W. Kerst, Phys. Rev. **77**, 806 (1950).
[e] R. Nathans and J. Halpern, Phys. Rev. **93**, 437 (1954).
[f] A. K. Mann and J. Halpern, Phys. Rev. **82**, 733 (1951).
[g] Calculated using $r_0=1.5\times10^{-13}$ cm.

CONCLUSION

The cobalt photoemission seems consistent with simple evaporation of particles plus 10 percent of protons showing anisotropic angular distributions from a more direct process. The absence of photodeuterons from cobalt and their appearance from copper suggest the possibility that photodeuteron emission may be affected by the nuclear structure.

We wish to acknowledge the help of Henry Gerardo in scanning part of the nuclear emulsion plates.

---

[7] R. Nathans and J. Halpern, Phys. Rev. **93**, 437 (1954).

[8] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952), pp. 352 and 372.

[10] P. F. A. Klinkenberg, Revs. Modern Phys. **24**, 63 (1952).