Isomer Ratios in ^{58}Co from the Photonuclear Reactions (γ,n) and (γ,np)†

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Isomer ratios in ^{58}Co have been measured for the photonuclear reactions ^{59}Co(γ,n)^{58}Co and ^{60}Ni(γ,np)^{58}Co. Their values [(ground-state yield)/(total yield)] are 0.43±0.03 and 0.68±0.03, respectively. Using the Huizenga-Vandenbosch formalism, a spin cutoff parameter $\sigma=4.4\pm0.6$ can be deduced if it is assumed that all the outgoing nucleons are evaporated. If direct processes are included, the spin cutoff parameter determined from the (γ,n) reaction will remain unchanged, whereas the one determined from the (γ,np) reaction will increase somewhat.

I. INTRODUCTION

THE work of Huizenga and Vandenbosch[1] has shown that isomer ratios, that is, the ratios of the rates of formation of a residual nucleus in its ground and metastable states, can be used for a determination of the dependence of the nuclear level density on the spin. This dependence is usually expressed by[2]

$$\rho(J)=\rho(0)(2J+1)\exp[-(J+\tfrac{1}{2})^2/2\sigma^2],$$

where $\rho(0)$ is the density of states with spin zero and σ is the spin cutoff parameter. σ is related to the nuclear moment of inertia and is the parameter which determines the relative level density.

Over the years a considerable number of isomer ratios produced in a variety of different ways have been measured.[3–12] Whereas particle bombardment and especially bombardment with heavy ions can impart great amounts of angular momentum to the nucleus (20 and more units of $\hbar$ are not unusual), photonuclear reactions involve only small changes in angular momentum because of the dipole character of the photon absorption. For this reason, the original Huizenga-Vandenbosch theory is adequate in photonuclear reactions, and it is not necessary to resort to some specific refinements[13] which are of considerable value for reactions involving large amounts of angular momentum.

According to Huizenga and Vandenbosch, the statistical model is used to calculate angular-momentum distributions after each of the following three steps of a compound nuclear reaction: the formation of the compound nucleus, the particle evaporation, and the γ de-excitation of the product nucleus. The isomer ratio then depends on the spin distribution of the compound nucleus, the angular momentum carried away by the emitted particles, the character of the γ cascade, and the spins of the isomeric states.

Since the photon absorption up to about 50 MeV is predominantly of electric dipole character, the spin distribution of the compound nucleus may be considered constant for different incident photon energies. Because of the narrow spread of possible spin states in the initial compound state, spin fractionation[4,5] should be unimportant, and therefore the influence of competing reactions on the isomer ratio is expected to be small. Furthermore, previous calculations[6] have shown that the dependence of the isomer ratio on the growing number of cascade γ rays with increasing excitation energy is relatively weak in (γ,n) reactions. Thus, for a given value of σ, the isomer ratio is not expected to vary strongly with incident photon energy.

In the present work, the ^{58}Co isomer ratios have been studied for the reactions ^{59}Co(γ,n)^{58}Co and ^{60}Ni(γ,np)^{58}Co. Statistical calculations of the Huizenga-Vandenbosch type[14] have been applied to the experimental ratios, and the corresponding values of σ have been obtained.

Tatarczuk and Medicus[6] have previously applied the Huizenga-Vandenbosch model in their study of ^{44}Sc isomer ratios, produced in (γ,n), (γ,np), and (n,$2n$) reactions. Since many of the data-reduction techniques and arguments are similar, this paper is kept short and the reader is referred to the earlier work.

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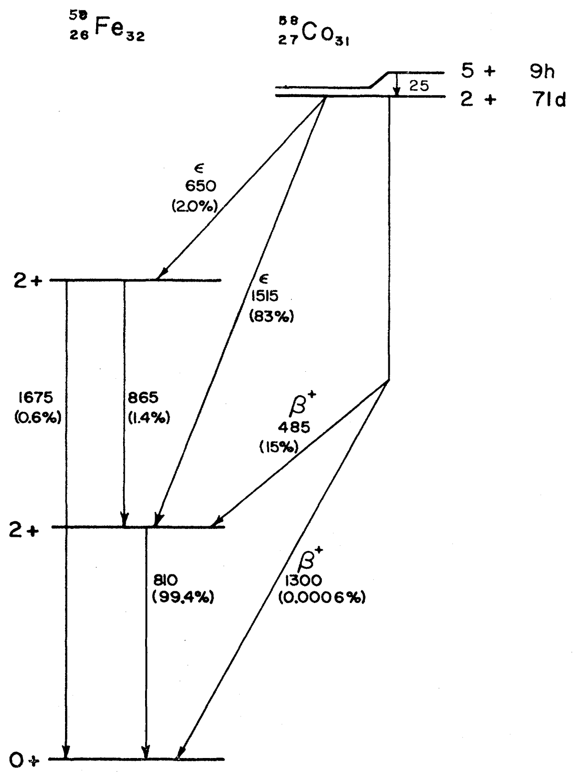

FIG. 1. Decay scheme of ^{58}Co. Energies in keV.

II. EXPERIMENTAL PROCEDURE AND DATA ANALYSIS

Samples of cobalt were irradiated at the Rensselaer Linac with bremsstrahlung of 48 MeV for 20 min in order to study the (γ,n) reaction. To obtain the ^{58}Co isomers through the (γ,np) reaction, a sample of the separated nickel-60 isotope was irradiated at the linac with a 48-MeV bremsstrahlung beam for 210 min. The residual γ activity of the samples was detected with a Princeton Gamma Tech-20 cm^3 lithium-drifted germanium counter connected to a multichannel pulse-height analyzer. The decay of all samples was observed for a period of several weeks. Counting times for each point were usually 40 min.

The decay scheme[15,16] of ^{58}Co (Fig. 1) shows that the decay of the ground state occurs by electron capture and positron emission. Essentially all of the ^{58}Co ground state decays into the 0.81-MeV level of ^{58}Fe. All of the decay of the metastable state, which has angular momentum 5+, leads to the ^{58}Co 2+ ground state. Thus the activities of the cobalt isomers can be obtained from the observation of the 0.81-MeV γ ray alone.

The decay of the 0.81-MeV line is shown in Fig. 2 for the (γ,np) reaction. The growth of the intensity of this

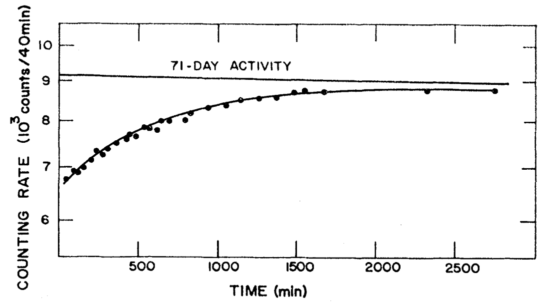

FIG. 2. Count rate for the 0.81-MeV γ line from ^{58}Co produced by the (γ,np) reaction. Irradiation time 210 min. End of irradiation at $t=0$. Semilogarithmic plot.

line, which also is observed in the (γ,n) measurements, corresponds to a half-life of the isomeric state of 9.3 ± 0.3 h. Earlier determinations[15] have yielded a period between 8.8 and 9.2 h.

If the bombardment time is short, the isomer ratio can be obtained from the ratio of the ground- and metastable-state activities at the time $t=0$. However, for a finite irradiation time, the actual ground- and metastable-state activities are obtained by the usual equations for radioactive growth and decay. For an irradiation time of 210 min, corrections amounting to about 10% must be applied to account for the decay of the metastable state during irradiation. Because electron-beam strengths were seen to be fairly constant during bombardment, no corrections were necessary for the small variations in reaction rates.

III. STATISTICAL MODEL CALCULATIONS

For photonuclear reactions, it is assumed that all of the γ-ray absorption is of electric dipole character. For a target nucleus of spin $I=0$, such as ^{60}Ni, the compound nucleus is formed with spin $J_c=1$. If the target nucleus has a nonzero ground-state spin, the spins of the compound nucleus are given by $J_c=I+1$, I, $I-1$, with probabilities proportional to their statistical weights: $2J_c+1$. In the present work, the spin J_c of the compound nucleus for the ^{60}Ni$(\gamma,np)^{58}$Co reaction is equal to 1. For the ^{59}Co$(\gamma,n)^{58}$Co reaction, the compound-nucleus spins are, with their respective fractions given in parentheses, $J_c=\frac{5}{2}$ (25%), $\frac{7}{2}$ (33%), and $\frac{9}{2}$ (42%).

The average energy of evaporated particles was used in the calculations. For a neutron, the average energy was taken as twice the nuclear temperature. This temperature is given by $T(E)=(E/a)^{1/2}$, where E is the average excitation after particle emission and a is the level-density parameter. The value of a was assumed as $0.1A$ MeV^{-1}. Estimates for the average proton energy were obtained from Beard and McLellan.[17]

The number of γ rays in the de-excitation cascade was taken as[5,18] $N_\gamma=\frac{1}{2}(aE)^{1/2}$. Only dipole transitions were considered in the cascade. Following Huizenga

[15] *Nuclear Data Sheets* compiled by K. Way *et al.* (U. S. Government Printing Office, National Academy of Sciences—National Research Council, Washington 25, D. C., 1960), NRC 60-5-12.

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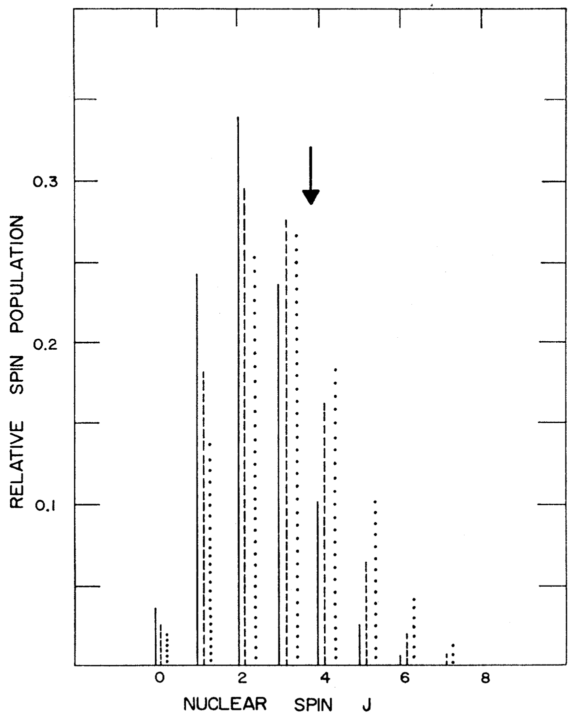

FIG. 3. The relative spin population in ^{58}Co for the case of the ^{60}Ni$(\gamma,np)^{58}$Co reaction, assuming a spin cutoff parameter $\sigma=4.4$. Solid line: after emission of the two nucleons; dashed line: after emission of the two nucleons and two γ rays; dotted line: after emission of the two nucleons and four γ rays. The arrow at $J=\frac{7}{2}$ indicates where the distribution is split to determine the relative populations of the ground and metastable states.

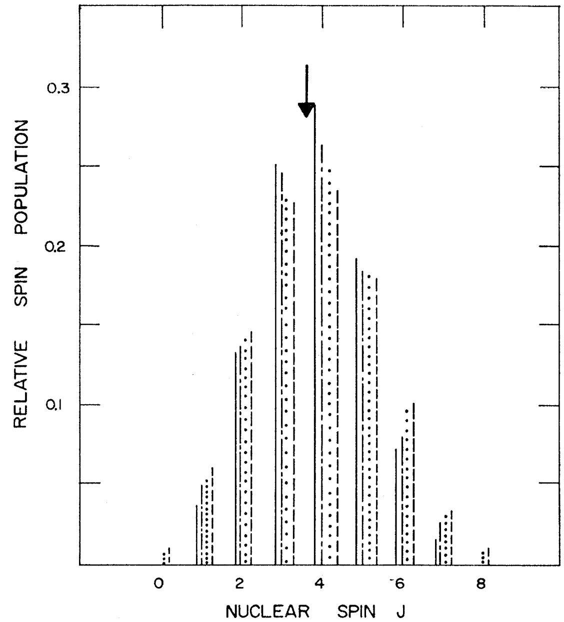

FIG. 4. The relative spin population in ^{58}Co for the case of the ^{59}Co$(\gamma,n)^{58}$Co reaction, assuming a spin cutoff parameter $\sigma=4.4$. Solid line: after emission of the neutron; dot-dash line: after emission of the neutron and one γ ray; dotted line: after emission of the neutron and two γ rays; dashed line: after emission of the neutron and three γ rays. The arrow at $J=\frac{7}{2}$ indicates where the distribution is split to determine the relative populations of the ground and metastable states.

and Vandenbosch, we assume that the final transition to the isomeric levels is that which involves the smaller spin change. In the photonuclear case, the calculations have previously been seen to be relatively independent of the initial γ-excitation energy.[6]

IV. RESULTS AND DISCUSSIONS

The experimental results are presented in Table I. The isomer ratio [(ground-state yield)/(sum of the ground- and metastable-state yields)] for the three measurements of the (γ,n) reaction between 35 and 54 MeV shows no change with energy. The determinations with 35- and 54-MeV bremsstrahlung energy have been made by Lichtblau and Goldmann[9] at the Darmstadt Linac.

TABLE I. ^{58}Co isomer ratios.

Reaction	Reference	Bremsstrahlung endpoint energy (MeV)	Experimental isomer yield (ground-state/total)
^{59}Co(γ,n)	7	30	0.56±0.02
	8	30	0.55±0.02
	9	35	0.43±0.02
	This work	48	0.43±0.03
	9	54	0.43±0.02
	10	68	0.38±0.02
^{60}Ni(γ,np)	This work	48	0.68±0.03

An example of the results of the statistical model calculations for the ^{60}Ni$(\gamma,np)^{58}$Co reaction is shown in Fig. 3. The solid lines show the relative spin population after the emission of the neutron and proton. The transmission coefficients used in the calculations are the ones from Moldauer[19] for neutrons and from Beard and McLellan[17] for protons. The dashed lines show the distribution after a cascade of two γ rays, while the dotted lines show the distribution after four γ rays. Figure 4 shows similar quantities for the (γ,n) reaction.

The dependence of the calculated isomer ratios on the spin cutoff parameter σ and on the number of dipole transitions in the γ-ray cascade (N_γ) is illustrated in Table II. The (γ,n) calculations are relatively independent of the number of γ rays in the cascade. Further, the (γ,n) calculations are quite insensitive to the energy of evaporated neutrons, the assumed excitation energy, the level-density parameter, and the quadrupole admixture in the γ cascade. For example, a change in the kinetic energy of the evaporated neutrons from 1.25 MeV, the value used in the computation of the first part of Table II, to 3.5 MeV changes the ratios for corresponding σ and N_γ by at most 0.004 (1%). In contrast, the (γ,np) calculations are as sensitive to the various model-dependent factors as they are to the spin cutoff

[19] P. A. Moldauer, Argonne National Laboratory Report No. ANL-6323, 1961 (unpublished).

TABLE II. ^{58}Co isomer ratio calculations for 48-MeV bremsstrahlung energy.

Reaction	Spin cutoff parameter σ	Calculated isomer yield (ground-state/total) Number of dipole γ rays in the cascade $N_\gamma=1$	$N_\gamma=2$	$N_\gamma=3$	$N_\gamma=4$
^{59}Co(γ,n)	3.6	0.486	0.494	0.501	0.505
	4.0	0.455	0.458	0.459	0.460
	4.4	0.432	0.431	0.429	0.426
	4.8	0.415	0.411	0.406	0.401
	5.2	0.401	0.395	0.388	0.381
^{60}Ni(γ,np)	3.6	0.795	0.759	0.728	0.701
	4.0	0.770	0.730	0.694	0.664
	4.4	0.751	0.707	0.668	0.634
	4.8	0.736	0.689	0.647	0.611
	5.2	0.723	0.674	0.631	0.593

parameter. As seen in the second part of Table II, the variation with N_γ is about 0.035 (5%) on the average. Similar variations occur with a change of 1 MeV in the assumed kinetic energies of the evaporated particles. (The data in Table II are presented to three places only to show numerically the variations of the Huizenga-Vandenbosch model calculations with σ and N_r and not to suggest the over-all accuracy of the model.)

However, the present (γ,n) and (γ,np) isomer ratios are both consistent with a value of the spin cutoff parameter of 4.4 ± 0.6. The error cited here is a reflection of the experimental error in the isomer ratios. This is in close agreement with an earlier study of the ^{58}Co isomer by Weigold and Glover,[11] who reported a value of 4.0 ± 1.0, and with recent work on the ^{60}Co isomer ratios from neutron-induced reactions by Paulsen,[12] who obtained a value of 4.3 ± 0.3.

In the calculations, it was assumed that the emitted nucleons are evaporated. However, direct reactions play a role in photonuclear reactions and should also be taken into account. They tend to reduce the number of the emitted γ rays to a minimum and thus will in general change the isomer ratio. After emission of the neutron from the nucleus, the ratio of the spin population below the split at $J=\frac{7}{2}$ (as indicated in Fig. 4 by the arrow) to the spin population above this value remains essentially unchanged regardless of the number of emitted quanta. On the other hand, direct (γ,np) reactions (as, for example, in the quasideuteron model) in which the proton and the neutron share most of the available energy have a considerable effect on the isomer ratio, as the ground state of spin 2 would be greatly favored in a reaction proceeding from the ^{60}Ni initial state of spin 0. If it is assumed, for example, that in 10% of the (γ,np) processes neither the proton nor the neutron is evaporated, but both are directly emitted, then the computed spin cutoff parameter increases to 4.6. With a 20% contribution it becomes greater than 5.0.

The cause of this different behavior is easily seen. The angular-momentum distribution of the compound nucleus of the (γ,n) reaction has its maximum very near the critical spin value of $J=\frac{7}{2}$. This is in contrast to the situation with regard to the compound nucleus formed in the (γ,np) reaction. For the same reason, the computed isomer ratio of the (γ,n) reaction is relatively insensitive to the choice of any particular model, refinement, or formalism.

The cross section for the (γ,n) reaction peaks at approximately 18 MeV and has a full width at half-maximum of approximately 6 MeV. As the threshold of the reaction is 10.5 MeV, the excitation of the residual nucleus after the (γ,n) reaction is about 5 MeV. With regard to the (γ,np) reaction in ^{60}Ni, it can be assumed that the greater part of the cross section of the (γ,np) reaction, whose threshold is 20 MeV, resides in the region above 28 MeV. Thus, more than 8 MeV is available for the kinetic energies of the neutron and proton, and for the excitation of the residual nucleus. The above comments are based on the ^{59}Co photonuclear cross-section work of Fultz *et al.*[20] and the photodisintegration of nickel work of Carver and Turchinetz.[21] Therefore, because of the energetics of the giant resonance, statistical model calculations should be justified in the above photonuclear reactions.

The ^{58}Co isomer ratio depends on the reaction which produces it and on the initial target nuclear spin. The fact that consistent values of the spin cutoff parameter are obtained for different reactions also provides some justification for the statistical calculations.

In general, very close agreement should not be expected because many approximations must be made in the calculations. It is significant, however, that the different isomer ratios in ^{58}Co for the two reactions considered here result in a spin cutoff parameter between 4 and 5.

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