Isomer Ratio for the $Sn^{118}(\gamma,p)$ Reaction*

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The relative yields of In^{117} and In^{117m} from the $Sn^{118}(\gamma,p)$ reaction have been measured by gamma ray counting a sample of SnO_2 enriched in Sn^{118} that had been irradiated with 24-Mev bremsstrahlung. The measured ground to isomer yield ratio was 0.65 ± 0.15, and is consistent with predictions made on the basis of both the Wilkinson direct mechanism and the compound-nucleus mechanism. However, the values of the isomer ratios for the series of even-even tin isotopes (Sn^{118}, Sn^{120}, Sn^{122}, and Sn^{124}, the latter three from the work of Yuta and Morinaga) are not at all consistent with the predictions of the compound-nucleus mechanism but can be rationalized on the basis of the Wilkinson model, lending support for that theory for direct photoproton reactions.

I. INTRODUCTION

THE unexpectedly large yields for photoproton reactions in medium mass and heavy nuclei have been taken as evidence that these reactions are predominantly direct processes and do not involve compound-nucleus formation to any appreciable extent.[1–6] Additional evidence for the importance of direct processes has come from energy and angular distribution measurements on the emitted protons.[3,7] Wilkinson[8] has discussed the direct (γ,p) reactions in terms of his single-particle model for the nuclear photoeffect and has been quite successful in explaining many of the features of these reactions, particularly the magnitudes and mass number dependence of their yields. Although the number of detailed comparisons has been quite limited, Wilkinson's model also appears to account for the observed proton energy and angular distributions.

One of the features of his model is that the direct photoproton reactions are associated with specific single-particle proton transitions in the gamma-ray absorption process. The nucleon holes that result from these transitions define the distribution in angular momentum of the product nuclei. For product nuclei that have isomeric states, the relative cross sections for the production of the ground and isomeric states would be determined to a large extent by the details of the angular momentum distribution resulting from these single-particle transitions. Thus, the measurement of the relative cross sections for the production of isomeric pairs (so-called isomer ratios) may be a useful experimental approach to test the predictions of the Wilkinson model for photoproton reactions.

This paper reports the results of a measurement of the isomer ratio for the $Sn^{118}(\gamma,p)In^{117-117m}$ reaction. A yield measurement by Hirzel and Waffler[1] has previously indicated that this reaction is probably not a compound nucleus reaction because the observed yield for 17.2-Mev gamma rays is about a factor of fifty greater than that expected from evaporation theory.[6] Calculations by Wilkinson indicate that single-particle resonance direct processes can account for the observed yield. Since he has tabulated the important single-particle transitions that are involved in direct proton emission from isotopes of tin, this makes a convenient case to study the isomer ratio.

During the course of this work, the results of some similar studies by Yuta and Morinaga[9] were published. They measured the total yields and the isomer ratios for the (γ,p) reactions on the heavier even-even tin isotopes, Sn^{120}, Sn^{122}, and Sn^{124}. They indicated that the resulting total yields and isomer ratios for 25-Mev bremsstrahlung were consistent with the predictions of the Wilkinson model. Reference will be made to their results in the discussion of the $Sn^{118}(\gamma,p)$ data.

II. EXPERIMENTAL

The experiment involved determining the relative number of In^{117} and In^{117m} nuclei produced by irradiating a 64-mg sample of SnO_2 enriched in Sn^{118} for 90 min with 24-Mev bremsstrahlung from the University of Illinois betatron. The number of product nuclei was determined by gamma-ray counting the sample with a $1\frac{1}{2}$-in. diameter by $1\frac{1}{2}$-in. long NaI(Tl) scintillation crystal coupled to a 100-channel pulse-height analyzer. Preliminary experiments had shown that the use of a natural tin target resulted in a complex mixture of indium radioactivities which was virtually impossible to analyze satisfactorily. With the use of an enriched Sn^{118} target,[10] the product activities of interest could be determined by direct counting of the target material without the necessity of an intervening chemical separation to isolate an indium fraction. Because of the small amount of target material available, it was not considered

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[8] D. H. Wilkinson, Physica **22**, 1039 (1956).
[9] H. Yuta and H. Morinaga, Nuclear Phys. **16**, 119 (1960).
[10] The Sn^{118} sample was supplied by the Stable Isotopes Division of the Oak Ridge National Laboratory (operated by Union Carbide Nuclear Company). The isotopic composition of the tin was 112–0.05%, 114–0.04%, 115–0.1%, 116–0.4%, 117–0.8%, 118–95.6%, 119–1.4%, 120–1.3%, 122–0.1%, and 124–0.1%.

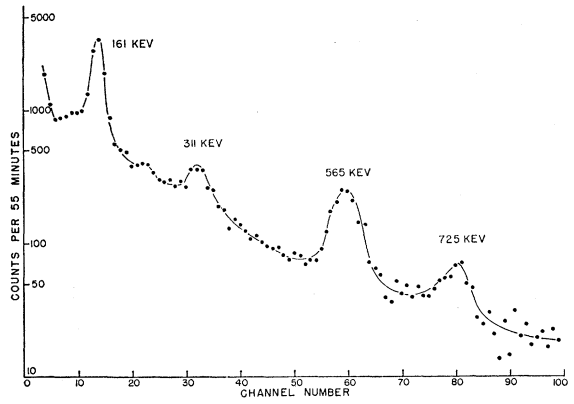

FIG. 1. Gamma-ray spectrum of the Sn^{118} sample after irradiation with 24-Mev bremsstrahlung.

feasible to determine a yield curve for this reaction. Also, no attempt was made to measure the absolute yield since this has been done previously by Hirzel and Waffler.[1]

The counting of the sample commenced immediately after the irradiation ended and continued over a twelve hour period in order to follow the decay of the various photopeaks. A typical gamma-ray spectrum is shown in Fig. 1. One notes that the main features are photopeaks at 161, 311, 565, and 725 kev. The origins of the various photopeaks can be seen by referring to the $In^{117-117m}$ decay scheme shown in Fig. 2. (This decay scheme is a modification of the decay scheme proposed by McGinnis.[11] The modifications are taken from the work by J. H. Wolfe.[12]) The decay of In^{117m} nuclei gives rise to the 311-kev peak and also contributes to the 161-kev peak. The decay of ground-state nuclei results in counts in the 161-, 565-, and 725-kev peaks. (The 725-kev photopeak is due to the coincidence summing of 161- and 565-kev photons in the ground-state decay.) The decay curves for the 161-, 565-, and 725-kev peaks were complex and could be resolved into 1.9-hr and 43-min components. The 311-kev peak decayed with a 1.9-hr half-life. These decay properties are consistent with the decay scheme and indicate that the observed photopeaks are indeed due to In^{117} and In^{117m}.

The relative number of ground state and isomer nuclei present at the end of the irradiation can be determined from the counting data in several different ways. For example, the number of 161-kev transitions in any two counts can be used along with decay and growth equations. Or, the 565-kev data can be treated in a similar manner. Or, the numbers of 161-kev (or 565 kev) and 311-kev transitions in any one count could be used. All of the approaches gave results consistent with each other, again indicating the absence of interfering activities. In the calculation of the relative numbers of

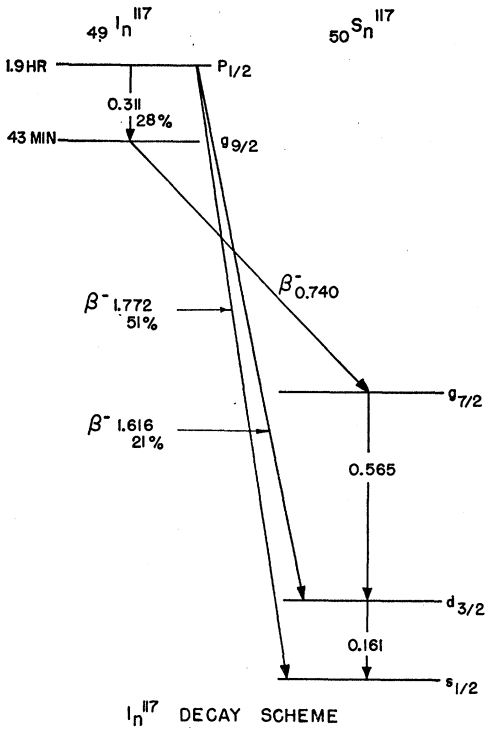

FIG. 2. Decay scheme of $In^{117-117m}$.

ground state and isomer nuclei from the number of counts in the various photopeaks, corrections were made for the crystal efficiency,[13,14] absorption in the crystal housing,[14] the abundances of the gamma rays in the decay schemes, and for the effects of the coincidence summing of 161- and 565-kev photons in the ground-state decay.[15]

The relative rates of production of the ground state and isomer in the (γ,p) reaction can be determined from the relative numbers of ground-state and isomer nuclei present at the end of the irradiation. In this calculation a correction must be made for the ground-state nuclei that grew in from decay of isomer nuclei during the irradiation in order to determine the direct nuclear reaction yield to the ground state. This correction involves the straightforward application of standard decay and growth relations.

III. RESULTS AND DISCUSSION

The measured ratio of the direct rate of production of the ground state to the rate of production of the isomer is 0.65 ± 0.15 for 24-Mev bremsstrahlung. The quoted uncertainty includes a contribution that arises from the uncertainty in the branching ratios in the decay scheme for In^{117m}.

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[14] L. T. Dillman, Ph.D. thesis, University of Illinois, Urbana, Illinois, 1958 (unpublished).
[15] N. H. Lazar and E. D. Klema, Phys. Rev. **98**, 710 (1955).

According to the Wilkinson theory for photonuclear reactions,[8] the absorption of a photon by a nucleus is associated with a single-particle transition in which a nucleon is elevated from a closed shell to a higher single-particle state where it either interacts with the rest of the nucleus to form an ordinary compound nucleus or is directly emitted from the nucleus without sharing its energy with other nucleons. (The relative probability of the latter process, direct emission, depends on the barrier penetrability of the emitted nucleon.) In the case of a target nucleus of fairly high atomic number, the compound nuclei that are formed would be expected to decay mostly by neutron emission. Thus, the emission of photoprotons from tin would be mostly due to direct emission after absorption by a single-particle proton transition.

Wilkinson has calculated the expected yield of protons due to direct emission processes for 23-Mev bremsstrahlung incident on tin nuclei and has tabulated the results in terms of the single-particle transitions involved. This information is given in Table I where the important proton transitions are listed along with their values and proton yields. (The value of a transition is defined as the percentage of all absorption processes in proton shells that takes place by that transition. The proton yield is the percentage of all absorption processes in proton shells that leads to direct proton emission via the stated transition.) The nucleon hole distribution following direct proton emission can be obtained from the data in Table I and is given in Table II. Most of the resulting configurations represent states with little or no excitation energy. The transitions that give rise to $g_{9/2}$ holes are direct transitions to the ground state of the product (In^{117}). Those giving rise to $p_{\frac{1}{2}}$ holes are direct transitions to the isomeric state, In^{117m}. The other transitions leave the product nuclei in higher excited states that will de-excite to either the ground state or the isomer by one or, at most, two gamma transitions. The branching of these higher energy states to the isomer and ground state was estimated by considering the possible gamma-ray transitions and applying selection rules to obtain the relative intensities of competing transitions.[16] These considerations indicated that 14% of the $f_{\frac{5}{2}}$ holes, 4% of the $p_{\frac{3}{2}}$ holes, and 100% of the $f_{7/2}$ holes result in eventual production of the ground state. Thus, the hole distribution given in Table II would lead to a value of 0.31 for the predicted ground to isomer yield ratio. This value is less than that observed experimentally (0.65 ± 0.15).

TABLE I. Proton transitions in the nuclear photoeffect in tin (from Wilkinson, reference 8).

Transition	Value (%)	Proton yield (%)
$1f_{5/2}$ to $1g_{7/2}$	26.1	0.41
to $2d_{5/2}$	0.1	0.00
to $2d_{3/2}$	1.9	0.16
$1f_{7/2}$ to $2d_{5/2}$	2.7	0.22
$2p_{3/2}$ to $2d_{5/2}$	10.5	0.81
to $2d_{3/2}$	2.1	0.16
to $3s_{1/2}$	2.4	0.31
$2p_{1/2}$ to $2d_{3/2}$	5.8	0.44
to $3s_{1/2}$	1.2	0.16
$1g_{9/2}$ to $1h_{11/2}$	45.0	0.28
to $1h_{9/2}$	1.0	0.00
to $2f_{7/2}$	1.2	0.09
Total	100.0	3.04

However, the calculation of the proton yields for the various transitions given in Table I depends quite sensitively on the energies that are assumed for the positions of the various single-particle states. This is particularly true for those states that give rise to protons of low kinetic energy and high values of orbital angular momentum because then one has a very rapid dependence of the barrier penetrability on the proton's kinetic energy.[17] One notes that an increase in the number of $f_{7/2}$ holes by a factor of about four would give agreement between the predicted and experimental ground to isomer ratios. Since the $f_{7/2}$ states are deepest in the well and give rise to protons having fairly high orbital angular momentum, they could easily be affected to this extent. Thus, small changes in the parameters used in the calculations could easily change the nucleon hole distribution enough to give agreement. One concludes from this discussion that unless the positions of the various nucleon states are known quite accurately, the calculated isomer ratio would have a rather large uncertainty associated with it. This means that the measurement of a single isomer ratio may not be a very restrictive test of the reaction mechanism.

TABLE II. Nucleon hole distribution following direct photoproton emission from tin derived from Table I. The states are arranged according to increasing excitation energy.

$1g_{9/2}$ (ground state)	$2p_{1/2}$ (isomer)	$1f_{5/2}$	$2p_{3/2}$	$1f_{7/2}$
12.2%	19.7%	18.7%	42.2%	7.2%

Although the measurement of a single isomer ratio may not tell us much about the reaction mechanism, the determination of a series of related isomer ratios may be of some help. The results of the measurements by Yuta and Morinaga[9] of the isomer ratios for the (γ,p) reactions in Sn^{120}, Sn^{122}, and Sn^{124} along with the $Sn^{118}(\gamma,p)$ result from this work are given in Table III. (In all the cases listed in Table III, the ground state of the product is thought to be a $g_{9/2}$ state, and the isomer is believed to be a $p_{\frac{1}{2}}$ state.) One notes that the relative yield of the ground state (the higher spin state) decreases markedly with an increase in the target mass number. This large change in the isomer ratio over this series of target nuclei is consistent with what one would expect on the

[16] M. G. Mayer and J. H. D. Jensen, *Elementary Theory of Nuclear Shell Structure* (John Wiley & Sons, Inc., New York, 1955), Chaps. 4 and 12.

[17] H. Feshbach, M. M. Shapiro, and V. F. Weisskopf, Atomic Energy Commission Report NYO-3077, 1953 (unpublished).

basis of the Wilkinson model. One notes that the thresholds for these reactions increase with mass number[18]; they are also given in Table III. Increasing the reaction threshold has the effect of decreasing the kinetic energies of the emerging protons. This would result in decreased barrier penetrabilities for all protons, but the effect would be much greater for those having large orbital angular momenta.[17] This would decrease the relative importance of the transitions that lead to the ground state, thus decreasing the ground to isomer ratio. It is difficult to make accurate numerical predictions of the effect because of the sensitivity of the calculations to the detailed positions of the various single-particle states, but an effect of the magnitude seen in Table III is reasonable.

Although the yield measurements for these reactions indicate that they probably are not compound nucleus reactions, it is of interest to see what one expects for the isomer ratios for a compound nucleus mechanism. Huizenga and Vandenbosch[19,20] have recently discussed the theoretical aspects of the calculation of isomer ratios for compound nucleus processes, so the details will not be repeated here. Of direct application here are their calculations for several (γ,n) reactions leading to isomeric pairs. In these calculations the spin distribution is computed for each step of the process These steps are the primary gamma-ray absorption to give the compound nucleus, the evaporation of the proton, and the gamma-ray cascade that eventually leads to either the ground state or the isomeric state of the product. Following the methods of Huizenga and Vandenbosch, one predicts a value of 0.72 for the ground-to-isomer yield ratio in the $Sn^{118}(\gamma,p)$ reaction. This is in agreement with the experimental value. However, the compound nucleus calculations give only a small variation of the isomer ratio over the series of target nuclei listed in Table III, predicting, for example, a ratio of 0.66 for the $Sn^{124}(\gamma,p)$ reaction, a value that is much larger than the observed ratio.

Thus, the isomer ratio for the $Sn^{118}(\gamma,p)$ reaction does not by itself give much information about the reaction mechanism except that it is probably not inconsistent with the predictions of the Wilkinson model. However, the behavior of the isomer ratios for the series of the heavy even-even tin isotopes does lend some support to the proposed model by Wilkinson for direct photoproton reactions.

TABLE III. Ground state to isomer yield ratios and thresholds for the (γ,p) reactions on Sn^{118} (this work) and Sn^{120}, Sn^{122}, and Sn^{124} (Yuta and Morinaga).

Reaction	Ground state to isomer yield ratio	Threshold (Mev)
$Sn^{118}(\gamma,p)In^{117}$	0.65 ±0.15	9.9
$Sn^{120}(\gamma,p)In^{119}$	0.32 ±0.10	10.9
$Sn^{122}(\gamma,p)In^{121}$	0.17 ±0.06	11.3
$Sn^{124}(\gamma,p)In^{123}$	0.075±0.04	12.0

[18] The thresholds were calculated from the mass data given in A. H. Wapstra, *Handbuch der Physik*, edited by S. Flügge (Springer-Verlag, Berlin, 1958), Vol. 38, Part 1, p. 1.

[19] J. R. Huizenga and R. Vandenbosch, Phys. Rev. **120**, 1305 (1960).

[20] R. Vandenbosch and J. R. Huizenga, Phys. Rev. **120**, 1313 (1960).