If atomic rather than nuclear masses are used to calculate the molecular moments of inertia, Eq. (18) may be rewritten[11,19]

$$\langle H^e \rangle = \frac{mc}{e} \sum_g \frac{G_{gg}\langle P_g^2 \rangle}{I_g}. \quad (19)$$

The fractional correction, owing to electronic precession, to the reciprocal moment of inertia I_g^{-1} is evidently $(mc/e)G_{gg}$. From an analysis of Zeeman observations, the three G_{gg}'s can be determined for the molecule considered, enabling one to calculate the electronic correction to the molecular rotational constants.

As an example of the order of magnitude of this correction, let us consider the molecule H_2O. The previously calculated values of $G_{gg'}$, Table IV, yield the following corrections to the rotational constants: A_0, 0.0049 cm^{-1}; B_0, 0.0028 cm^{-1}; C_0, 0.0017 cm^{-1}. It will be noted that these corrections are all approximately 0.02 percent, which is greater than, or of the same order of magnitude as the accuracy often assigned to rotational constants determined by microwave absorption methods.

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High Energy Gamma-Gamma Cross Section of In^{115}

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Several photonuclear reactions induced in indium by the x-rays from a 25-Mev betatron have been measured. Special attention has been given to the reaction $In^{115}(\gamma,\gamma')In^{115*}$. Applying proper corrections, it was found that this reaction has a shape similar to the shape found in the usual photonuclear reactions. This experiment shows that 1 in 7 de-excitations of an excited indium nucleus decays by γ-emission. The (γ,n) reaction in In^{115} has been measured and was found to have 0.42 Mev-barn for the integrated cross section, in good agreement with theoretical predictions. The ratio of the cross sections for production of the isomeric and ground states of In^{114} has also been studied. It was found that transitions to the isomeric state of In^{114} are highly favored, as would be expected from an analysis of the spin changes involved. The cross section for the reaction $In^{115}(\gamma,2n)In^{113*}$ has been measured and the ratio of this cross section to the (γ,n) reaction is compared with that predicted by statistical theory.

I. INTRODUCTION

An investigation of the reactions induced by photons in indium has the possibility of giving considerable information about the nature of the interaction of high energy photons with nuclei. A preliminary investigation of the activities induced in indium by an irradiation with a betatron[1] showed that it is possible to resolve the contributions from the following reactions:

	Reaction	Half-life
(a)	$In^{115}(\gamma,n)In^{114*}$	50 days
(b)	$In^{115}(\gamma,n)In^{114}$	72 sec
(c)	$In^{115}(\gamma,\gamma')In^{115*}$	4.5 hours
(d)	$In^{115}(\gamma,2n)In^{113*}$	1.7 hours

Besides these half-lives a strong activity from neutron capture in In^{115} (half-life = 54 min) was observed. Other activities which perhaps could be expected, such as $In^{113}(\gamma,np)Cd^{111}$—49-min half-life—and the end products of (γ,n) reactions in In^{113} have not been observed or could not be separated by counting; the first alternative is probably correct since In^{113} is only a 4.2 percent isotope.

A careful investigation of the activities listed above, as a function of the maximum energy of the betatron, can give information on four kinds of problems.

1. Characteristics of the (γ,n) processes in In^{115}.
2. Ratio of the cross section for production of the ground and isomeric states of In^{115}.
3. (γ,γ') reaction in In^{115} by production of the isomeric state in In^{115}.
4. The ratio between the $(\gamma,2n)$ and (γ,n) reactions in In^{115} and an analysis of this ratio in the light of statistical theory of nuclei.

The ratio of the cross sections for production of the ground and isomeric states is of special interest, since in the two cases previously investigated[2,3] the parent nucleus had small spin whereas in this case the parent nucleus In^{115} has a large spin (9/2). The spins of the ground and isomeric states of the residual nucleus are 1 and 5, respectively.

The (γ,γ') reaction in In^{115} which is studied by detection of the isomeric state in this isotope is of special interest since the excitation function for this

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[1] J. Almond, Engineering thesis, University of Saskatchewan, 1952 (unpublished).

[2] Katz, Pease, and Moody, Can. J. Research 30, 476 (1952).
[3] Katz, Baker, and Montalbetti (to be published).

process can be measured and its cross section compared with that for the (γ,n) process. This can throw some light on the competition between γ-emission and neutron emission following the absorption of a photon of high energy by In^{115}. In particular this investigation can be compared to the results of the (γ,γ') reaction studied by Cameron and Katz[4] in the case of gold. In the investigation of Au, the cross section for the (γ,n) process was not known and the analysis of competition of (γ,γ') and (γ,n) was based on an assumed (γ,n) cross section. A recent measurement in this laboratory[5] showed that this cross section is somewhat greater than the assumed value (about 750 millibarns at peak position).

Finally, the measurement by the residual activity method of a $(\gamma,2n)$ process in addition to the (γ,n) process is possible only in a few cases. This measurement in In offers a simple way of testing one aspect of statistical theory of nuclei. The measurement of residual activities cannot separate the reaction $In^{115}(\gamma,2n)In^{113*}$ from $In^{113}(\gamma,\gamma')In^{113*}$. However, as a result of the large difference in isotopic abundance of In^{115} (95.8 percent) compared to In^{113} (4.2 percent), all the activity obtained can be attributed to a $(\gamma,2n)$ process.

II. EXPERIMENTAL PROCEDURE

Samples of In of about 1 inch diameter and 300 mg/cm^2 thick were enclosed in a cadmium box lined with In to reduce slow neutron capture and were exposed in the betatron beam of the University of Saskatchewan betatron at a distance of 27.7 cm from the target. The dose was measured by an ionization chamber calibrated against a Victoreen chamber inside a 4-cm Lucite block which is the usual procedure in this laboratory.[6]

The length of irradiation varied approximately from 10 min to 1 hour. After irradiation, 1 min was lost in transferring the sample to a counting system. The decay curve was followed for 10 min by an observer and later by an automatic counting system for a period of 24 hours. This allowed sufficient time for all the activities to decay to background except the 50-day activity. Measurements of this activity were carried out one week later.

To obtain good statistics the counting intervals were made sufficiently long to include at least 5000 counts. A standard source was used intermittently throughout this experiment to check the stability of the counting apparatus.

The decay curves obtained were analyzed, and the activities mentioned in the introduction were resolved. This separation of the decay curve into its components requires special care since some of the half-lives (54 min, 1.7 hr, and 4.5 hr) are not very different. A method of successive approximations was used starting from the longest half-life. More precisely the procedure used was as follows: first the natural background ($\sim$10 counts per minute) and the 50-day activity were subtracted; using the remaining data a 4.5-hour straight line was fitted to the points and the contribution of this activity was subtracted from the total. If the points of the 1.7-hour half-life fall in a straight line the procedure is carried again for the separation of the 54-min activity; if this does not occur another trial was made for the 4.5-hour activity, and so continued.

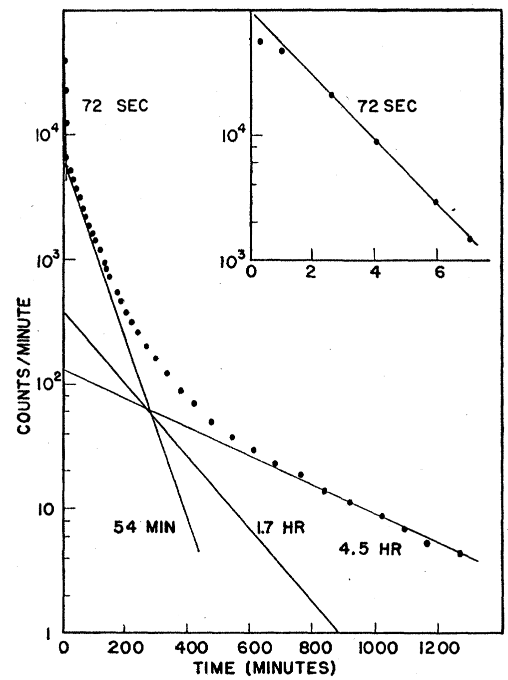

FIG. 1. A typical decay curve of In^{115} activated by betatron irradiation. The indicated lines correspond to the decay curves of the reactions: $In^{115}(\gamma,n)In^{114}$ (half-life 72 sec), $In^{115}(n,\gamma)In^{116}$ (54 min), $In^{115}(\gamma,2n)In^{113*}$ (1.7 hour), and $In^{115}(\gamma,\gamma')In^{115*}$ (4.5 hour). Background and 50 day activity from the reaction $In^{115}(\gamma,n)In^{114*}$ were subtracted. The 72 sec half-life is shown in detail in the insert.

As a test of this procedure the 72-sec half-life activity always appeared as a final curve with the correct slope.

A typical decay curve and its components are shown in Fig. 1.

Measurements and analysis of this kind were made for energies from 7 to 24 Mev.

The results obtained, when reduced to the same dose rate, gave the excitation functions for the reactions listed in the introduction.

Two corrections have to be applied before it is possible to analyze the excitation functions into cross sections:

(a) Correction for variations of the beam intensity over the sample surface.

(b) Normalization of the activation curve.

Correction (a)—The In samples subtended an angle of 5° at the electron target in the donut, whereas the

[4] A. G. W. Cameron and L. Katz, Phys. Rev. **84**, 608 (1952).
[5] R. Montalbetti, Ph.D. thesis, University of Saskatchewan, 1952 (unpublished).
[6] Johns, Katz, Douglas, and Haslam, Phys. Rev. **80**, 1062 (1950).

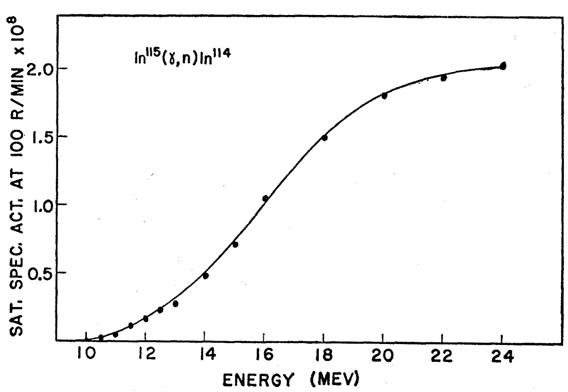

FIG. 2. Activation curve for the reaction $In^{115}(\gamma,n)In^{114}$. This curve has been normalized against copper and corrected for variations of the beam intensity over the sample surface.

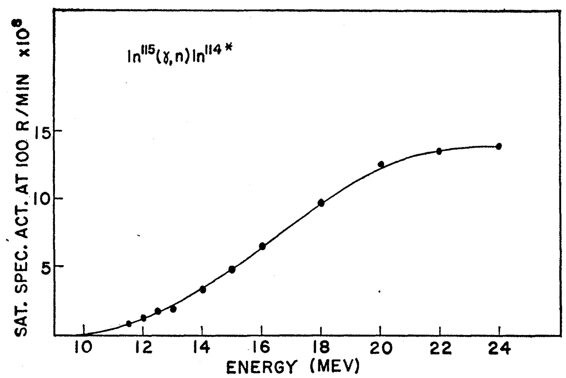

FIG. 3. Activation curve for the reaction $In^{115}(\gamma,n)In^{114*}$. This curve has been normalized against copper and corrected for variations of the beam intensity over the sample surface.

Victoreen used in the calibration subtended only an angle of 1°. The activities induced in the sample were proportional to the average intensity over the sample. On the other hand, the dose as seen by the Victoreen corresponded always only to that in the forward direction. If the angular distribution of the bremsstrahlung radiation were independent of betatron energy, then the activity would be proportional to the Victoreen reading. Since, as is well known,[7] the angular distribution is a strong function of the betatron energy, a correction needs to be applied.

The obvious solution of increasing the distance between sample and betatron target is not feasible because of the consequent reduction in intensity. The above correction has been carried out in the following way: two excitation functions have been measured for copper samples, of the same size as the In samples, at two distances from the target of the betatron; 27.7 cm (actual position used in In bombardment) and 111 cm. The activation curves obtained would be the same (correcting for inverse square law) if the intensity of the beam did not change with angle. The difference in the two curves must then be due to the effect mentioned above and this readily gives the required correction. This correction has been applied to all the measured curves.

Changes in spectral composition as a function of the angle between the incident electron and the emitted photons have been measured,[8] however these are small and are not expected to result in significant errors in the angle subtended by our detector.

Correction (b)—All the absolute determination of the activities were made with respect to copper, taking in account the disintegration schemes of the elements measured. To accomplish this identical samples of In and Cu were irradiated simultaneously in the betatron beam and measured alternatively in the same counter geometry.

The activities corrected to the end of irradiation were compared as follows: According to a recent paper by Baker and Katz[9] the absolute disintegration rate of a substance is related to the activity measured by the following formula: (It is assumed that only β-rays are counted and that the sample is thick enough to give a cosine distribution.)

$$(c/m)=(d/m)(1-e^{-kt})/ktMDG(\theta), \qquad (1)$$

where (c/m) = counts per minute (corrected for external absorption and back-scattering); (d/m) = disintegrations/minute per mole of sample per roentgen/minute of irradiation; k = absorption coefficient of the β-rays in the sample material; M = number of moles in the sample; D = irradiation dose measured in roentgens per minute; and $G(\theta)$ = geometric efficiency of the counting system.

If instead of β-rays, conversion electrons are measured, a similar equation holds to a good approximation. We replace the correction for self-absorption $(1-e^{-kt})/kt$ by $R/2t$, where R is the range of the conversion electrons in the substance and t the thickness of the sample. This equation applies only for samples with t greater than R.

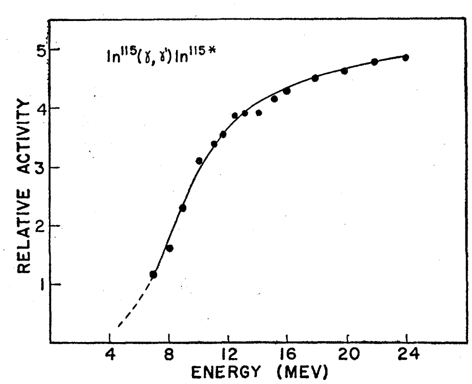

FIG. 4. Activation curve for the reaction $In^{115}(\gamma,\gamma')In^{115*}$, normalized against copper. The correction (a) has been applied.

[7] L. I. Schiff, Phys. Rev. **70**, 87 (1946).
[8] Goldemberg, Pieroni, Santos, and Silva, UNESCO Congress, July 1952, Rio de Janeiro, Brazil.
[9] R. G. Baker and L. Katz, Nucleonics **11**, No. 2, 14 (1953).

If α is the conversion coefficient of the electrons we have in place of (1) the equation

$$(c/m)=(d/m)(R/2t)MDG(\theta)\alpha/(\alpha+1). \quad (2)$$

In calculating the disintegration rate of In^{113*} an equation similar to (2) was written with decay constants from the National Bureau of Standards Circular 499 (Nuclear Data) and conversion electron range from the paper of Katz and Penfold.[10] Dividing Eq. (2) for In^{113*} by Eq. (1) for Cu the disintegration rate of In^{113*} is easily obtained.

For In^{115*} the measured activity is the sum of two terms: one for 6 percent β-rays of the form (1) and the other of the form (2) for the remaining disintegrations in which internal conversion occurs. The nuclear data used was taken from the National Bureau of Standards Circular 499.

The results presented were calculated using the experimental internal conversion coefficient $\alpha=0.33$. It must be observed that had we used the theoretical value $\alpha=1$, our results would have been lower by a factor of 2.

For In^{114} and In^{114*}, besides these equations, account must be taken of the fact that they are isomeric states and their activities are therefore related. We used the disintegration scheme of Johns *et al.*[11] and the appropriate expressions for this case from the papers of Katz, Baker, and Montalbetti[2] and Katz, Pease, and Moody.[3]

The normalized excitations functions are shown in Figs. 2, 3, and 4.

III. CROSS SECTIONS

All the activation curves obtained were analyzed to obtain cross sections for the corresponding reactions. In $In^{115}(\gamma,n)In^{114*}$, $In^{115}(\gamma,n)In^{114}$, and $In^{115}(\gamma,2n)In^{113*}$ we used the photon difference method of Katz and Cameron,[12] and for $In^{115}(\gamma,\gamma')In^{115*}$ we used the older method of analysis of Johns *et al.*[6] since the tables of Katz and Cameron start only at 8.25 Mev.

The results are shown in Figs. 5 and 6.

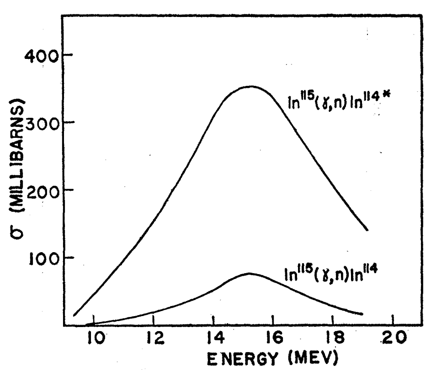

FIG. 5. Cross sections for the reactions $In^{115}(\gamma,n)In^{114}$ (72-sec half-life) and $In^{115}(\gamma,n)In^{114*}$ (50 day).

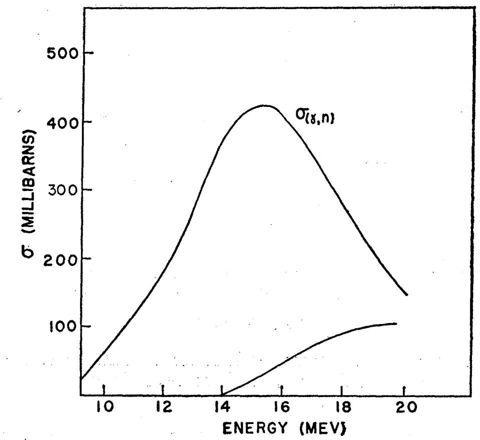

FIG. 6. Total cross sections for the photoneutron reactions in In^{115} and the cross section for the reaction $In^{115}(\gamma,2n)In^{113*}$ plus $In^{113}(\gamma,\gamma')In^{113*}$. The total photoneutron cross section is the sum of the two cross sections shown in Fig. 5.

IV. DISCUSSION OF RESULTS

(γ,n) Reaction in In^{115}

The characteristics of the (γ,n) reactions in In^{115} are listed in Table I.

The experimental value for the total integrated cross section, 2.7 Mev-barn, is in good agreement with that calculated from the Levinger-Bethe[13] formula using $x=0.55$ for the fraction of exchange force between nucleons. This value of x was obtained from np interaction experiments[14] and seems to be a reasonable choice as shown by Eyges.[15]

The number of neutrons emitted at 18 Mev, considering only (γ,n) processes, is a little higher than the value interpolated from the data of Price and Kerst[16] and about twice the value obtained for In by Montalbetti.[5] The discrepancy between our experiment, and that of Montalbetti using direct neutron detection, may be explained by the fact that In is a strong absorber of slow neutrons and in his set-up the sample itself acts as a neutron sink.

TABLE I. Characteristics of (γ,n) reactions in In^{115}.

	Peak energy (Mev)	Width at half-maximum (Mev)	Maximum cross section (barns)	$\int\sigma dE$ (Mev-barns)
50-day isomer	15	5.5	0.35	2.2
72-sec isomer	15	4.5	0.07	0.5
Total	15	5.5	0.42	2.7

[10] L. Katz and A. S. Penfold, Revs. Modern Phys. **24**, 28 (1952).
[11] Johns, Cox, Donelly, and McMullen, Phys. Rev. **87**, 1134 (1952).
[12] L. Katz and A. G. W. Cameron, Can. J. Research **29**, 518 (1951).
[13] J. S. Levinger and A. H. Bethe, Phys. Rev. **78**, 115 (1950).
[14] Hadley, Kelley, Leith, Segre, Wiegand, and York, Phys. Rev. **75**, 351 (1949).
[15] L. Eyges, Phys. Rev. **86**, 325 (1952).
[16] G. A. Price and D. W. Kerst, Phys. Rev. **77**, 806 (1950).

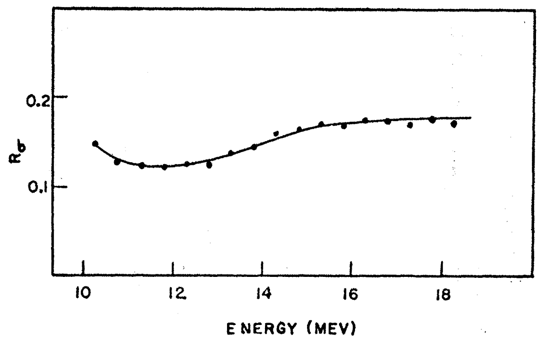

FIG. 7. Ratio R_σ of the cross sections for transitions of In^{115} to the ground and isomeric states in In^{114}.

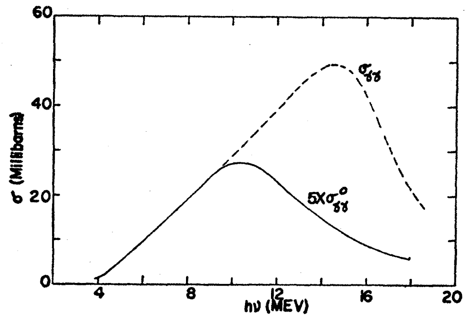

FIG. 8. Cross sections for the (γ,γ') process in In^{115}. Solid line—cross section obtained experimentally ($\sigma_{\gamma\gamma}^0$). Dotted line—cross section ($\sigma_{\gamma\gamma}$) after application of corrections (A) and (B).

The ratio $R_\sigma=\sigma_g(\gamma,n)/\sigma_i(\gamma,n)$ is plotted in Fig. 7, where $\sigma_g(\gamma,n)$ = cross section for transitions to the ground state, and $\sigma_i(\gamma,n)$ = cross section for transitions to the isomeric state.

It will be seen that the ratio is less than unity. This means that more transitions go to the isomeric state than to the ground state, and can be understood if we remember that the isomeric state in In^{114} has a spin of 5 and the ground state a spin of 1. Dipole photon absorption by In^{115} and s or p type neutron emission will result in excited levels of In^{114} which are predominantly of high spin. Cascades from these excited levels may therefore be expected to favor the isomeric state (see reference 2).

As in the case of molybdenum,[3] the ratio R_σ passes through a shallow minimum near threshold and assumes a constant value at about 6 Mev from this threshold. This behavior can be understood if the assumption is made, as in the case of bromine and molybdenum,[2,3] that transitions of small spin change are increasingly favored as threshold is approached from the high energy side. In the case of bromine and molybdenum the target nucleus has small spin, and therefore transitions to the level of lower spin in the isomeric pair is favored as threshold is approached (see reference 2). In our case the target nucleus In^{115} has high spin and transitions of small spin change will favor the isomeric state, so that in approaching the threshold from the high energy side the ratio R_σ is depressed and passes through a shallow minimum.

The available data on the ratio of production of the ground and isomeric states of In^{114} by other reactions is very incomplete and is not sufficient to define a unique set of cascade branching ratios consistent with the experimental results.

(γ,γ') Reaction in In^{115}

The characteristics obtained for the (γ,γ') reaction in this experiment are as follows: Integrated cross section = 0.034 Mev-barn. Width at half-maximum = 9 Mev. Maximum cross section = 4.4 mb. Energy at peak cross section = 9 Mev.

The experimental curve ($\sigma_{\gamma\gamma}^0$) is shown in Fig. 8, solid line. Measurements below 6 Mev were not possible because of the low activities obtained at these energies. Recently Touschek[17] has estimated the position of the first level of a nucleus excited by dipole transitions. For In this estimate gives $E_T<2.1$ Mev. This is not inconsistent with our measurement.

This cross section indicates only those transitions which go to the isomeric state of In^{115}. Actually, if one visualizes an excited level above the (γ,n) threshold, generally two types of processes will be important: neutron de-excitation and γ-de-excitation, proton emission being strongly suppressed by the Coulomb barrier. However, not all the initial γ-de-excitations are seen in our experiment: (A) Some of them go to the ground state in In^{115}, and (B) others are followed by neutron emission when the emitted γ-rays have very low energy. Corrections have to be applied for both these effects. The cross section (Fig. 8—solid line) $\sigma_{\gamma\gamma}^0$ is then a minimum value and will be altered both in magnitude and shape by these corrections.

(A) From results on measurements of Br^{80},[2] Mo^{91},[3]

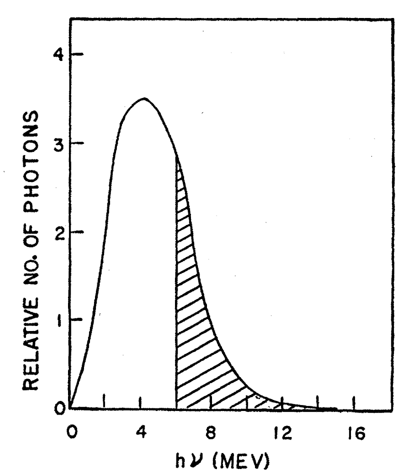

FIG. 9. Energy distribution of photons emitted by an In^{115} nucleus excited at 15 Mev. The shaded area indicates those emitted photons which cannot be followed by neutron emission.

[17] B. F. Touschek, Phil. Mag. 41, 849 (1950).

and In^{114} (above), one can estimate that only 1 in 5 transitions go to the isomeric state which we observe. This results from the following reasoning: the ground state of In^{115} has a spin of 9/2 and the isomeric state has a spin of $\frac{1}{2}$; dipole photon absorption ($l=1$) by the ground state will result in excited levels of spin 7/2 (0.267), 9/2 (0.336), and 11/2 (0.400), where the statistical weight of each level according to its multiplicity is indicated in parentheses. From an examination of these spins it can be easily seen that cascading to the ground state will be strongly favored. In the case of Br^{80} such favoring is in the ratio of 2:1, in the case of Mo^{91} it is 5:1, and in the case of In^{114} it is also 5:1. For this reason we assume that in In^{115} this ratio is of the order of 4:1.

We must then raise the values obtained for $\sigma_{\gamma\gamma}{}^0$ by a factor ($R_{\sigma\gamma}$) of 5 to correct for transitions to the ground state. This correction is insensitive to the nuclear excitation energy except very close to the threshold.

The peak cross section is now 22 mb for the (γ,γ') process and the integrated cross section is 0.17 Mev-barn.

(B) In order to obtain an approximate correction for initial transitions which are followed by neutron emission, we carried out the following calculations: the energy distribution of the initial photons emitted by an excited nucleus is peaked at low energies as can be seen from Fig. 9, where this distribution has been plotted for the case of In at an excitation of 15 Mev.[18] If a photon is emitted with an energy less than 6 Mev, the remaining nucleus has sufficient energy to emit a neutron instead of a γ-ray; this adds to the observed (γ,n) cross section and reduces the (γ,γ') cross section. Obviously all transitions where the photon carries more than 6 Mev cannot be followed by neutron emission. Thus as a first approximation the fraction of the area under the curve above 6 Mev represents the fraction of initial γ-de-excitation which go to the isomeric and ground state.

The correct cross section for inelastic γ-scattering can thus be written, to a first approximation:

$$\sigma_{\gamma\gamma}{}' = \sigma_{\gamma\gamma}{}^0 R_{\sigma\gamma} (\Gamma_\gamma)_1 / (\Gamma_>)_1, \qquad (3)$$

where $R_{\sigma\gamma}$ is the correction factor calculated above. $(\Gamma_\gamma)_1$ and $(\Gamma_>)_1$ are the total area, and the area above 6 Mev under the curve of Fig. 9.

However, some of the nuclei left in energy states corresponding to the area below 6 Mev in Fig. 9 can decay by further γ-emission. This gives a second approximation to the $\sigma_{\gamma\gamma}$ cross section,

$$\sigma_{\gamma\gamma}{}'' = \sigma_{\gamma\gamma}{}^0 R_{\sigma\gamma} \frac{(\Gamma_\gamma)_1}{(\Gamma_>)_1 + (\Gamma_<)_1 (\sigma_{\gamma\gamma}{}'/\sigma_{\gamma n})(\Gamma_\gamma)_2/(\Gamma_>)_2}, \qquad (4)$$

where $(\Gamma_<)_1$ is the area under the curve of Fig. 9 below 6 Mev, and the other quantities are as previously defined except the subscript 2 refers to calculations at the energy where the distribution of photons of Fig. 9 has a maximum. Similar extensions of this equation to higher approximations can obviously be carried out. This was done at energies where the contributions from high approximations were not negligible. The final cross section so obtained will be represented by $\sigma_{\gamma\gamma}$.

[18] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952), p. 649.

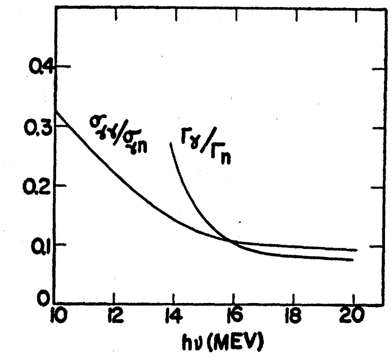

FIG. 10. Ratios of $\sigma_{\gamma\gamma}/\sigma_{\gamma n}$ and Γ_γ/Γ_n.

The correct cross section curve $\sigma_{\gamma\gamma}$, both in magnitude and shape is shown by the dotted line of Fig. 8. Its maximum is at around 15 Mev and peak cross section is 50 mb.

Some computations have been made to test these results. The probability for neutron emission from an excited nucleus in terms of the half-width for de-excitation by various processes is given by $\Gamma_n/\sum_x \Gamma_x$, where Γ_x is the half-width for the emission of x. Similarly the probability for gamma-emission is $\Gamma_\gamma/\sum_x \Gamma_x$, and the ratio between γ and neutron emission is Γ_γ/Γ_n. The half-width for gamma-emission was calculated from a formula by Blatt and Weisskopf[18] and neutron emission from a formula by Ewing and Weisskopf.[19] The ratio of Γ_γ/Γ_n calculated with these equations is shown in Fig. 10.

It can be readily shown from statistical theory that

$$\sigma_{\gamma\gamma}/\sigma_{\gamma n} = \Gamma_\gamma/\Gamma_n. \qquad (5)$$

The ratio $\sigma_{\gamma\gamma}/\sigma_{\gamma n}$ is also plotted in Fig. 10. At high energies the two curves are in fair agreement.

The ratio of $\sigma_{\gamma\gamma}/\sigma_{\gamma n}$ shows that in a highly excited indium nucleus the decay can proceed by initial γ-emission in as many as 1/7 of the de-excitations. The previous estimate of this ratio for gold[4] based on an assumed (γ,n) cross section of 500 mb indicated

TABLE II. Comparison of the experimental ratio $\sigma(\gamma,2n)/\sigma(\gamma,n)$ with theory. [The measured values of $\sigma(\gamma,2n)$ were multiplied by 3. See text.]

Energy Mev	$\frac{\sigma(\gamma,2n)}{\sigma(\gamma,n)}$ experimental	$\frac{\sigma(\gamma,2n)}{\sigma(\gamma,n)}$ theoretical
17	0.66	0.12
18	0.90	0.35

[19] V. F. Weisskopf and D. H. Ewing, Phys. Rev. **57**, 472 (1940).

that $\frac{1}{3}$ of the excited gold nuclei decay by initial γ-emission. Using the measured value of the (γ,n) cross section in gold[6] the above ratio becomes $\frac{1}{5}$.[20]

Recently, the cross section for the reaction $Rh^{103}(\gamma,\gamma')Rh^{103*}$ has been measured by del Río and Telegdi.[21] A comparison of their results and those for In^{115} shows that the absolute values are in good agreement to within experimental accuracy.

Some further remarks should be added about this (γ,γ') experiment. The excitation of the isomeric state of In^{115} has been achieved by several means, including excitation by low energy x-rays[22] and inelastic neutron scattering.[23] For this reason considerable attention should be given to the importance of neutron contamination of the betatron beam and to the presence of the large amount of soft x-rays in the spectrum of the bremmstrahlung radiation.

The last possibility of contributing to the observed (γ,γ') activation can be discarded because of the fact that the samples received the same dose of radiation at all energies in our activation curve. This normalization procedure means that there are less soft x-rays incident on the indium samples at high energies. If the photon absorption were due to a low energy region only, our activation curve for the reaction $In^{115}(\gamma,\gamma')In^{115*}$ would decrease with increasing betatron energy. This is contrary to the experimental results (Fig. 6).

The presence of fast neutrons in the betatron beam is more serious, and tests have been carried out to check their possible influence.

An In foil was placed behind a lead block 7 cm thick and irradiated in the betatron beam at 24 Mev for 15 min. The lead block absorbs practically all the x-radiation but is very ineffective in absorbing and slowing down fast neutrons. Furthermore, (γ,n) reactions in it will give rise to a large neutron flux. The decay curve of the indium sample so irradiated was measured. About 5 percent of the previously measured activities from In^{114} and In^{114*}, and a strong 54-min neutron absorption activity were found, but there was no detectable activity arising from In^{115*}. The large amount of 54-min activity resulting from neutron absorption indicated that at least as many neutrons were present in this experiment as in the usual irradiation. If the observed 4.5-hour activity were due to inelastic neutron scattering, it should have been easily detected.

Furthermore, the neutron background in our experiments results predominantly from (γ,n) reactions in the lead shield and copper coils of the betatron. The thresholds for these reactions are about 8 and 10 Mev. The fact that 4.5-hour activity is observed at 7 Mev also indicates that it is not due to inelastic neutron scattering.

[20] The shape of the $Au^{197}(\gamma,\gamma')Au^{197*}$ cross section has not been determined as accurately as that reported for In^{115} in this paper, since the γ-rays from the isomeric state in gold have very low energy, and the half-life of this state is very short making accurate measurements very difficult.

[21] C. S. del Río and V. L. Telegdi, Bull. Am. Phys. Soc. **27**, No. 5 (1952).

[22] G. B. Collins and B. Waldman, Phys. Rev. **59**, 109 (1941).

[23] S. G. Cohen, Nature **161**, 475 (1948).

$(\gamma,2n)$ Reaction in In^{115}

The cross section for the reaction $In^{115}(\gamma,2n)In^{113*}$ is shown in Fig. 6.‡ This cross section probably has a maximum around 20 Mev with a value at this position of about 0.1 barn. The total $(\gamma,2n)$ cross section in In^{115} should include also the reactions which lead to the ground state of In^{113}. This could be readily calculated if the cascade branching ratios of the excited levels in In^{113} were known. It is not easy, however, to estimate these ratios in this case with any assurance. Taking into account the spins of the ground and isomeric states of In^{113}, it seems quite reasonable to assume that 1 in 3 reactions go to the isomeric state. This may range from 1 in 2 to 1 in 5.

The values of $\sigma(\gamma,2n)/\sigma(\gamma,n)$ are shown in Table II at several energies where the measured values of $\sigma(\gamma,2n)$ have been multiplied by 3.

It is of interest to compare the measured ratio between these cross sections with that expected from statistical theory. For this comparison we used Weisskopf's formula[19] for the probability of emission of two neutrons by a highly excited nucleus.

$$\sigma(\gamma,2n) = \sigma(\gamma,n)[1-\{1+(a/E)^{\frac{1}{2}}(E-E_b)\}e^{-(a/E)(E-E_b)}], \quad (4)$$

where E = energy of incident γ-ray minus binding energy of a neutron. E_b = threshold for the $(\gamma,2n)$ reaction minus threshold for the (γ,n) process, a = constant typical of each nucleus. The value of a used (a = 6.5) was taken from the Final Report of the Fast Neutron Data Project.[24] The (γ,n) threshold was taken at 9.5 Mev and E_b = 6.5 Mev. The results are also shown in Table II and are in fair agreement.

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‡ In this section $\sigma(\gamma,2n)$ contains an unknown contribution of (γ,γ') reaction in In^{113}.

[24] Feld, Feshbach, Goldberger, Goldstein, and Weisskopf, U. S. Atomic Energy Commission Report NYO-636, January, 1951 (unpublished).