a weakening of the quadrupole interaction on the neutron quasiparticle levels, which would cause a considerable elevation of its energy. However, a more reasonable explanation is that the level does exist somewhere between 350 and 950 keV, but is simply not populated by $^{133}$Sb decay and the subsequent $\gamma$ cascades. It is interesting to note that this same $\frac{1}{2}^+$ level is conspicuous by its absence in decay of $^{133}$I, as reported by Eichler *et al.*[7]

At present only a few remarks concerning $^{132}$Sb can be made. The most prominent $\gamma$ ray attributed to $^{132}$Sb decay is at 1021 keV. It is strongly suggestive that this is the transition from the $2^+$ first excited level of $^{132}$Te to ground. In Fig. 7, the systematics of first excited $2^+$ levels of even-even isotopes are plotted as Eichler has done.[29] It appears from this that a 1021-keV level for $^{132}$Te fits well with the systematics. Furthermore, the known yield[12] of $^{132}$Sb and the weakness of its $\gamma$ transition argue for a large $\beta$ branch to ground, and, therefore, a low spin value for $^{132}$Sb.

[29] E. Eichler, Rev. Mod. Phys. **36**, 809 (1964).

## ACKNOWLEDGMENTS

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# Resonance Fluorescence Measurements of In$^{115}$ Transition Strengths below 3 MeV*

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$\gamma$-transition strengths $g\Gamma_0(M1+E2)$ are measured for In$^{115}$ with electron bremsstrahlung resonant-scattered from levels previously reported at 934, 1078, 1133, 1291, and 1450 keV. In addition, new transitions at 1495, 2277, 2438, 2476, and 2742 keV are seen for which $gW\Gamma_0^2/\Gamma$ is measured. $E2/M1$ mixing ratios are deduced in cases where $g\Gamma_0(E2)$ has been previously reported.

## INTRODUCTION

THE In$^{115}$ nucleus has been studied through Coulomb excitation,[1–3] photon and electron isomer excitation,[4–7] and in $\beta$-decay studies of Cd$^{115}$ by Graeffe *et al.*[8] and Begzhanov *et al.*[9] In the present work, resonant scattering of photons in the energy range 900–3000 keV is investigated using the electron bremsstrahlung of the 4-MeV MIT High-Voltage Laboratory Van de Graaff accelerator. The theory of resonance fluorescence has been reviewed by Metzger.[10] The experimental method of Booth *et al.*[11] has been extended by the use of a 3.5-cm$^3$ Ge(Li) planar diode in ring geometry.

The resonant scattering yield determines the quantity $gW(\theta)\Gamma_0(\Gamma_0/\Gamma)$, where $g$ is $(2J^\pi+1)/2J_0+1)$, $J^\pi$ is the spin of the excited state, $J_0$ is the spin of the ground state, $\Gamma_0/\Gamma$ is the branching ratio to the ground state, $\Gamma_0$ is the partial width for photon decay of the excited nucleus to the ground state, and $W(\theta)$ is the angular distribution of the scattered radiation given by $W(\theta)=1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)$. The coefficents $A_2$ and $A_4$ are functions of the angular momenta of the ground state and excited states as well as of the multipolarity of the transition $J^\pi\rightarrow J_0$ (see Ref. 12). In order to extract the partial width $\Gamma_0$ from the resonant scattering results, both the multipole character of the deexcitation transitions and the branching ratio $\Gamma_0/\Gamma$

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[1] D. G. Alkhazov, K. I. Erotkina, and I. K. Lemberg, Izv. Akad. Nauk SSSR **28**, 1667 (1964).
[2] J. MacDonald, D. Porter, and D. T. Stewart, Nucl. Phys. **A104**, 177 (1967).
[3] F. Dietrich, Stanford University (private communication).
[4] B. T. Chertok and E. C. Booth, Nucl. Phys. **66**, 230 (1965).
[5] Y. Chauchois, Y. Heno, and M. Boivin, Compt. Rend. **259**, 3233 (1964).
[6] E. C. Booth and J. Brownson, Nucl. Phys. **A98**, 529 (1967).
[7] E. Schillinger, W. C. Miller, and B. Waldman, Phys. Rev. **83**, 320 (1951).
[8] G. Graeffe, C. W. Tang, C. D. Coryell, and G. E. Gordon, Phys. Rev. **149**, 844 (1966).
[9] R. B. Begzhanov, D. A. Gladyshev, and M. Khodzhaev, Yadern. Fiz **5**, 1145 (1961) [English transl.: Soviet J. Nucl. Phys. **5**, 816 (1967)].
[10] F. Metzger, in *Progress in Nuclear Physics*, edited by P. Frisch (Pergamon Press, New York, 1959), Vol. 7, p. 53.
[11] E. C. Booth, B. Chasan, and K. A. Wright, Nucl. Phys. **57**, 403 (1965).
[12] L. C. Biedenharn and M. E. Rose, Rev. Mod. Phys. **25**, 729 (1953).

TABLE I. Partial widths and mixing ratios measured in this work for $In^{115}$ transitions.[a]

| $E_R$ (keV) | $J^\pi$ | $\Gamma_0/\Gamma$ | $gW(\theta)\Gamma_0^2/\Gamma$ | $g\Gamma_0(E2)$ | | $g\Gamma_0(M1+E2)$ | | $\delta^2$ [b] |
|---|---|---|---|---|---|---|---|---|
| | | | This work | Ref. 3 | Ref. 2 | Other | This work | |
| 0 | 9/2+ | | | | | | | |
| 934 | 7/2+ | 0.995[c] | 2.2±1.0 | ··· | <0.03 | 0.8±0.3[d]<br>3.6±2.0[e] | 2.2±1.0 | <0.02 |
| 1078 | 5/2+ | 0.81[f] | 3.1±0.9 | 2.45±0.29 | 1.1±0.2 | 6±3[d]<br>2.8±0.8[g] | 3.9±1.3<br>3.2±1.1[h] | ∞ |
| 1133 | 11/2+ | 1.00[c] | 63±11 | 14.2±1.5 | 11.5±1.6 | ··· | ($\delta=+$) 67±11<br>($\delta=-$) 84±14 | 0.25±0.07<br>0.20±0.05 |
| 1291 | 9/2+ | 0.98[c] | 13.5±3.5 | 13.3±2.0 | 10.3±1.8 | ··· | 14±4 | >2.0 |
| 1450 | 7/2+ | 0.83[f] | 7±2 | 5.4±1.3 | <4 | 18±6[f] | $9_{-4}^{+6}$ | >0.4 |
| | 9/2+ | | | | | | 11±5 | >0.3 |
| 1495 | ··· | ··· | 16±6 | 2.4±0.7 | ··· | ··· | (16±6) $\Gamma/(\Gamma_0 W)$ | ··· |
| (1570) | ··· | ··· | <6 | ··· | ··· | $(1.6_{-0.7}^{+1.8})(\Gamma/\Gamma_{iso})$[e] | ··· | ··· |
| (1654) | ··· | ··· | <5 | ··· | 130±40 | ··· | ··· | ··· |
| (1982) | ··· | ··· | <8 | ··· | ··· | ··· | ··· | ··· |
| 2277 | ··· | ··· | 70±23 | ··· | ··· | ··· | (70±23) $\Gamma/(\Gamma_0 W)$ | ··· |
| 2438 | ··· | ··· | 56±19 | ··· | ··· | ··· | (56±19) $\Gamma/(\Gamma_0 W)$ | ··· |
| 2476 | ··· | ··· | 47±16 | ··· | ··· | ··· | (47±16) $\Gamma/(\Gamma_0 W)$ | ··· |
| 2742 | ··· | ··· | 126±42 | ··· | ··· | ··· | (126±42) $\Gamma/(\Gamma_0 W)$ | ··· |

[a] Above partial widths are in units of $10^{-4}$ eV.
[b] For the 1133- and 1291-keV transitions, the magnitude of $\delta^2$ is determined from mean values of $g\Gamma_0(E2)$ taken from Refs. 2 and 3.
[c] See Ref. 8.
[d] See Ref. 5.
[e] See Ref. 6.
[f] See Ref. 3.
[g] See Ref. 4.
[h] Measured in point geometry relative to $Zn^{68}$ (1078 keV).

must be known. Because of the large low-energy background arising from nonresonant scattering (e.g., Rayleigh), photon decays to other than the ground state cannot be easily observed. If the above quantities are known, the total width of the excited state, which is related to its lifetime by $\tau=\hbar/\Gamma$, can be inferred from resonance fluorescence rather than directly measured, as in the Doppler-shift attenuation method.

The angular distribution of the transition $J^\pi \rightarrow J_0$ is sensitive to the sign and magnitude of the mixing ratio $\delta=(J^\pi \| L+1 \| J_0)/(J^\pi \| L \| J_0)$, defined in terms of the reduced matrix elements for the ground-state transition of lowest multipolarity $L$. In favorable cases the sign of $\delta$ can be unambiguously determined from $W(\theta)$.

The above quantities are related to the reduced transition probabilities for mixed $M1/E2$ multipolarities as follows:

$$\Gamma_0=\Gamma_0(M1)+\Gamma_0(E2)$$

$$=1.05E_R{}^3B(M1\downarrow)+8.07E_R{}^5B(E2\downarrow)\times 10^{-7},$$

$$\delta^2=\Gamma_0(E2)/\Gamma_0(M1),$$

where $\Gamma_0$ is in eV, and $E_R$ is in MeV; $B(M1\downarrow)$ and $B(E2\downarrow)$ are in units of $F^2$ and $e^2$ $F^4$, respectively.

With resonant scattering in our geometry, using a 100% isotope, assuming $gW(\Gamma_0/\Gamma)=1$ and $Z=50$, a signal-to-noise ratio greater than 1 is obtained provided that

$$\Gamma_{\text{expt}}(E2)/\Gamma_W>10, \quad \text{for 1 MeV}$$

$$>1, \quad \text{for 2.5 MeV}$$

$$\Gamma_{\text{expt}}(M1)/\Gamma_W>10^{-2}, \quad \text{between 1–3 MeV}$$

where $\Gamma_W$ is the single-particle Weisskopf transition strength for either $E2$ or $M1$. The above range covers a large fraction of the $M1$-$E2$ transitions for heavy nuclei included in the Wilkinson plots.[13]

The magnitude of $\delta$ is deduced by combining the $B(E2)$ values from Coulomb excitation or $(e,e')$ scattering with resonant scattering results. In nine out of ten cases of $M1$-$E2$ mixed transitions studied by the Boston University group[11,14] in the range $0.9<E_R<2.0$ MeV for $Z>25$, the mixing ratio has been found to be less than 1. In the light of a unified model for these nuclei, this would imply an admixture of single-particle excitations with the collective states.

## EXPERIMENTAL PROCEDURE

The ring-geometry method used in this work has been described in Refs. 11 and 14. The natural-indium scattering target (95.7% $In^{115}$) weighing 1300 g was cast in an "amphitheater" shape, slanted such that the

[13] D. H. Wilkinson, in *Nuclear Spectroscopy*, edited by F. Ajzenberg-Selove (Academic Press Inc., New York, 1960), Part B, pp. 852–889.

[14] W. J. Alston, H. H. Wilson, and E. C. Booth, Nucl. Phys. **A116**, 281 (1968).

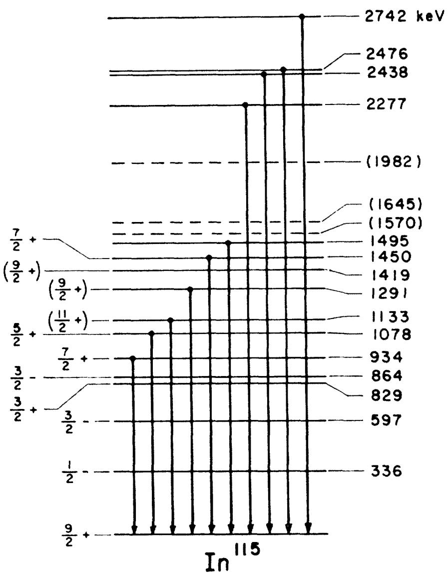


FIG. 1. Energy levels for $In^{115}$ with transitions seen in this work. The dashed horizontal lines are energy assignments reported in Refs. 2, 6, and 17 for which no transitions were observed in this work.

incident and scattered radiation traveled at 35° with respect to the normal to the target. A thickness of 4.5 g/cm$^2$ was presented to an incident photon traversing the target (see Fig. 1 of Ref. 14).

In cases of resonance scattering with a signal-to-noise ratio less than 1, the indium scattering target was alternated with a natural-tin dummy to provide a matched nonresonant background. In other cases, a simple graphical interpolation of the background was used. A point radioactive source with a $\gamma$ line several hundred keV below the resonance energy of interest placed on the scattering ring enabled one to ascertain the over-all detector resolution *in situ*. The Ge(Li) absolute photopeak efficiency was determined with a NBS $Na^{22}$ source calibrated to $\pm 1.5\%$ accuracy.

A Tennelec TC200 amplifier, TC250 biased amplifier, and TC130 preamplifier were used with a Nuclear Data 512-channel analyzer. Except for the data taking of the 1453–1495-keV transitions (see the discussion below), the signals were RC shaped to a single 400-nsec differentiation and integration. For improved resolution in the 1453-1495-keV transitions, the time constant was increased to 800 nsec together with a corresponding reduction in the total count rate presented to the biased amplifier. The detection resolution at zero count rate with 400-nsec RC-pulse shaping was 8-keV full width at half-maximum (FWHM) arising from intrinsic resolution plus cable capacitance effects. At electron energies $E_e>1.7$ MeV, the accelerator-beam intensity was reduced in order to maintain the resolution of the system below 10 keV. At $E_e=2.3$ MeV, a total count rate of $5\times 10^4$ sec$^{-1}$ broadened the calibration $\gamma$ line-width to 12 keV, in addition to smearing out 30% of the

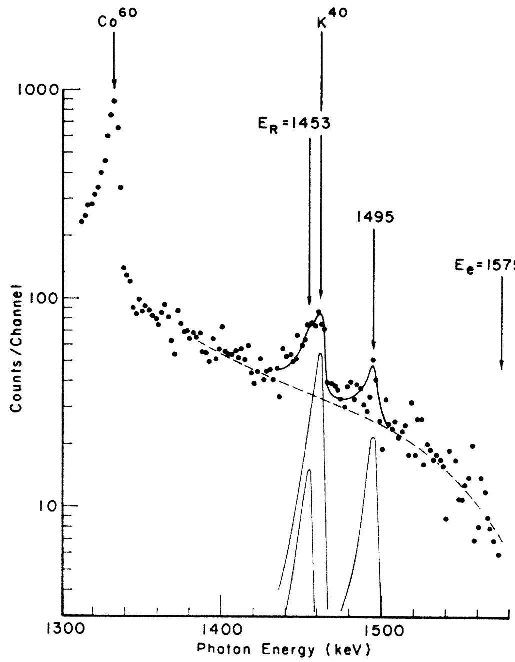


FIG. 2. Spectrum of scattered radiation for $In^{115}$ at the electron energy $E_e = 1.575$ MeV. The dashed curve is the nonresonant background measured with a matched dummy scattering target. The contaminant $K^{40}$ (1461 keV) presumably is present in the surrounding concrete shielding.

photopeak pulses toward large amplitudes because of pulse pile-up. Yields for the transitions given in Table I were corrected for this effect. Below $E_e = 1.3$ MeV, the pile-up effects were negligible and full beam current was used (250 $\mu$A).

Poor counting statistics were the primary source of error in the values of $gW(\theta)\Gamma_0^2/\Gamma$ reported in Table I, with the exception of the 1133- and 1291-keV transitions, where the 25% error quoted for these relatively fast transitions is estimated as a geometric sum of the following sources of error: photon-flux determination ($\pm$15%), Ge(Li)-efficiency determination ($\pm$5%), target-geometry corrections ($\pm$5%), and statistical data errors ($\pm$15%). The photon flux on the scattering target was obtained from the following transitions with partial widths taken from Skorka *et al.*[15]: 1611 keV ($Mg^{25}$) 24 meV; 2212 keV ($Al^{27}$) 16 meV; 2980 ($Al^{27}$) 109 meV. In addition, the partial width for the $B^{11}$ 2124-keV transitions was taken as 122 meV from the compilation of Ajzenberg-Selove and Lauritsen).[16] The scattering yields from the above levels indicated that the photon flux in our geometry was constant (within statistical errors) over the energy range 1.6–3.0 MeV, in agreement with the previous ring-geometry measurements of Booth *et al.*)[11] The magnitude of the flux at $0.9E_e$ was $(1.10\pm0.15)\times10^{10}$ photons/(sr MeV sec $\mu$A).

[15] S. J. Skorka, J. Hertel, and T. W. Retz-Schmidt, Nucl. Data Tables **2**, 347 (1966).

[16] F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. **A114**, 1 (1968).

## RESULTS

Figure 1 shows the energy levels of $In^{115}$ with the transitions seen in this work. With the exception of the 829- and 1078-keV states, the spin and parity assignments are those of Graeffe *et al.*[8] For the 829- and 1078-keV levels the assignments are from Begzhanov *et al.*[9] and Ref. 3. Below 2 MeV, the energy assignments which have been previously reported are those of Graeffe *et al.*[8] with the exception of the 1078-, 1570-, 1645-, and 1982-keV levels, which are taken from Refs. 17, 6, 2, and 17, respectively. The levels at 1495, 2277, 2438, 2476, and 2742 keV have not been previously reported. The accuracy of these new energy assignments is estimated to be $\pm$5 keV.

934-keV level: Using the branching ratio $\Gamma_0/\Gamma = 0.995$ obtained by Graeffe *et al.*[8] a mean value of $g\Gamma_0(M1+E2) = 0.20\pm0.06$ meV is obtained from this work and Refs. 5 and 6. Since this transition was not observed in the later Coulomb-excitation work of Dietrich *et al.*,[3] the lower limit of $g\Gamma_0(E2) < 3$ $\mu$eV of MacDonald *et al.*[2] is preferred to the Na(I) measurement of Alkhazov *et al.*,[1] giving a mixing ratio $\delta^2 < 0.02$.

1078-keV level: The spin assignment of $\frac{5}{2}+$ is adopted from the work of Dietrich *et al.*[3] The ground-state transition was observed in the present work in ring geometry using the planar Ge(Li) diode and in point geometry at 125° with a large (35-cc) coaxial diode. The latter measurement was a direct comparison of In with the $0\to2^+$ first-excited-state transition in $Zn^{68}$ (1078 keV), using a matched natural Zn target. Taking the adopted value[18] of the reduced transition probability for the Zn transition as $B(E2\uparrow) = 1.60\pm0.14\times10^{-49}$, a partial width is obtained for $In^{115}$ in terms of the angular

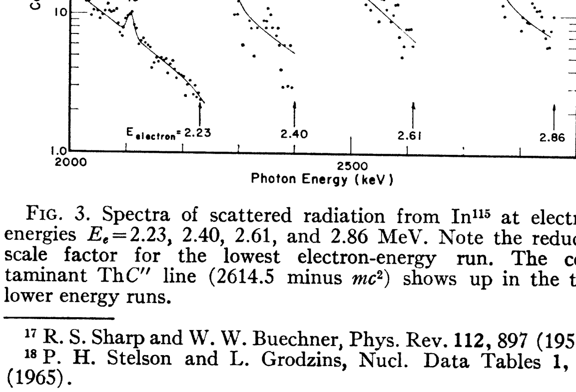


FIG. 3. Spectra of scattered radiation from $In^{115}$ at electron energies $E_e = 2.23$, 2.40, 2.61, and 2.86 MeV. Note the reduced scale factor for the lowest electron-energy run. The contaminant ThC'' line (2614.5 minus $mc^2$) shows up in the two lower energy runs.

[17] R. S. Sharp and W. W. Buechner, Phys. Rev. **112**, 897 (1958).

[18] P. H. Stelson and L. Grodzins, Nucl. Data Tables **1**, 21 (1965).

distributions as follows: $g\Gamma_0\bar{W}_{In}(125)/\bar{W}_{Zn}(125) = 0.51\pm0.15$ meV. With $\bar{W}_{In}(125)=1.0$ and $\bar{W}_{Zn}(125) = 0.63$ for the $\frac{9}{2}\rightarrow\frac{5}{2}\rightarrow\frac{9}{2}$ and $0\rightarrow2\rightarrow0$ transitions, respectively, the point geometry result listed in Table I is in agreement with both ring-geometry resonance fluourescence and Coulomb excitation reported in Ref. 3, the accuracy of which is preferred over the earlier work of MacDonald *et al.*[2] A mean value of the $g\Gamma_0(E2)$ values in columns 5, 7, and 8, weighting each measurement by its inverse percentage error, gives $g\Gamma_0(E2)|_{\text{mean}} = 2.9\times10^{-4}$ eV.

1133- and 1291-keV levels: Branching ratios of $\Gamma_0/\Gamma(1133) = 1.00$ and $\Gamma_0/\Gamma(1291) = 0.98$ are taken from Graeffe *et al.*[8] The $\gamma$ transitions to the ground state are predominantly $M1$ and $E2$, respectively, with mixing ratios given by $\delta_+^2(1133) = 0.25\pm0.07$ and $\delta_-^2(1133) = 0.20\pm0.05$ and $\delta^2(1291) > 2.0$. The + and − subscripts for the mixing ratios denote the sign of $\delta$.

1450- and 1495-keV levels: $\gamma$ transitions from these levels are shown in Fig. 2 together with the 1332.5-keV calibration line of $Co^{60}$ and the contaminative line from $K^{40}$ (1461 keV). The background, shown by the dashed curve, was taken separately with a dummy Sn target. The photopeak shape was obtained from the calibration line and approximated by a skewed Gaussian curve. Near 1460 keV, a photopeak of width 14 keV was seen, broadened beyond the net 8-keV resolution present in the $Co^{60}$ line. The three photopeaks shown in Fig. 2 were fitted to the experimental points given the curve shown with a solid line having a $\chi^2$ value of $43\div37$ points.

For a gain of $2.00\pm0.02$ keV/channel on an absolute scale using the $Co^{60}$ line, the locations of the photopeaks were at $1453\pm4$, $1461\pm4$, and $1495\pm5$ keV.

The 1453-keV line is identified with the 1450-keV transition seen by Graeffe *et al.*[8] and Chertok and Booth[4] and the 1449-keV line in Ref. 3. Taking $\Gamma_0/\Gamma = 0.83$ from the latter work, values of $g\Gamma_0(M1+E2)$ are shown in Table I for positive and negative values of $\delta$ assuming spin assignments of $\frac{7}{2}+$ or $\frac{9}{2}+$.

The level of 1495 keV is possibly the 1485-keV level reported in Ref. 3, with spin in the range $5/2+\rightarrow13/2+$. Since the branching ratio is unknown, the partial width is quoted in Table I in terms of $gW\Gamma_0/\Gamma$.

1570-, 1645-, and 1982-keV levels: No resonance fluorescence was observed from these levels. The limits shown in Table I are estimated with an upper limit of two standard deviations away from the nonresonant background over a region of 15 keV. It is possible that the intense 1645-keV $\gamma$ seen by MacDonald *et al.*[2] was due to target impurities or a reaction induced by their $O^{16}$ ion beam.

2277-, 2438-, 2476-, and 2742-keV levels: The spectra of scattered radiation at electron energies of 2.23, 2.40, 2.61, and 2.86 MeV are shown in Fig. 3. Note the contaminative Th$C''$ line with its single escape peak at 2103.5 keV. From Table I, $\Gamma_0$ cannot be deduced without knowledge of the branching ratios, multipole mixings, and spin changes for all observed transitions. The data-accumulation time for the above spectra ranged 7–12 h. Additional runs at other electron energies were used along with those in Fig. 3 to produce the results in Table I, whose errors are primarily due to poor counting statistics.

One could assert that transitions other than the above four are present in Fig. 3 if the following criteria are used: Regions are called resonances where there exist integrated counts exceeding two standard deviations above background over 15 keV at identical photon energies for two or more different electron energies. With these criteria transitions at $2070\pm10$ and $2540\pm10$ keV are possible with values of $gW\Gamma_0^2/\Gamma = (13\pm7)\times10^{-4}$ and $(34\pm17)\times10^{-4}$ eV, respectively. Because of the large errors (statistical), the preceding transitions are not included in Fig. 1 and Table I.

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