ZERO-PHONON GAMMA-RAY TRANSITION IN ^{60}Ni†

J. R. Van Hise* and D. C. Camp
Lawrence Radiation Laboratory, University of California, Livermore, California 94550
(Received 29 September 1969)

Using a Compton-suppression spectrometer with a central Ge(Li) detector, we have observed a 346.95-keV gamma-ray transition between the 4_1^+ and 2_2^+ states in ^{60}Ni. According to the simple vibration model, this so-called zero-phonon transition is strictly forbidden. A lower limit of 0.174 is placed on the ratio of the observed to the single-particle rates.

In many cases, the low-lying states of medium-weight even-even nuclei have been shown to exhibit a collective nature in that they possess the properties of quadrupole surface vibrations about a spherical equilibrium shape. In the quadrupole-vibrator model, small interparticle couplings remove the degeneracy of a two-phonon vibration to give a triplet of levels with spin and parity of 0^+, 2^+, and 4^+ at about twice the energy of the first excited 2^+ state. The 2^+ and 4^+ members of this triplet are seen in many nuclei, but only in a few cases so far is the 0^+ member observed. Even then, it is not always clear that it has the same collective character as the other two members. Another prediction of the simple vibrator model is that transitions between members of the two-phonon triplet are strictly forbidden.[1]

Such a zero-phonon transition, if it existed, would have a relatively low intensity because of its low energy; and it would be difficult to observe because it would be hidden in the usually intense Compton distribution present in both NaI(Tl)- and Ge(Li)-detector spectra. To our knowledge, no such zero-phonon transitions have been observed.[2]

The recent development of the Compton suppression principle,[3] incorporating a Ge(Li) detector surrounded by NaI(Tl) detectors operated in anticoincidence, better equips the spectroscopist to search for these low-intensity gamma rays if they exist. The chances of observation are best if there is a relatively large 4^+-to-2^+ or 2^+-to-0^+ energy separation within the two-phonon triplet, and if the state from which the zero-phonon gamma ray originates is strongly populated. Such a favorable case is the decay of ^{60}Co.

Experiment.—The approximately 50-μCi ^{60}Co source used in the investigation was at least five years old and was produced by the reaction ^{59}Co(n,γ) in the Livermore pool-type reactor of the Lawrence Radiation Laboratory. The Compton-suppression system used in this work is described in detail elsewhere.[3,4] Briefly, however, it incorporates a 7-cm^3, 12-mm-deep Ge(Li) detector surrounded by two 9-in.-diam by $4\frac{1}{2}$-in.-thick NaI(Tl) detectors which completely enclose the detector. The source was 30 cm away from the detector and the gamma rays were collimated by a $\frac{1}{2}$-in.-diam hole through 4 in. of lead. The detector is oriented so that its electric field is perpendicular to the collimated gamma-ray beam. Thus, no energy error is introduced when double-escape peaks are used for energy calibration.[5] The ratio achieved in this experiment for the 1.33-MeV peak height to the minimum of the Compton continuum was 120 to 1.

Results.—A 4050-min Compton-suppressed spectrum of ^{60}Co is shown in Fig. 1. Insets show the not completely suppressed double-escape peak of the 1332.5-keV γ ray and the annihilation-radiation peak due to pair interaction of the 1173- and 1333-keV γ rays in material near the detector. Also shown are a (346.95 ± 0.1)-keV transition and a single-escape peak at 821.51 keV, as well as a very weak transition at 826.18 ± 0.2 keV.

The double-escape peak at 310.51 keV and the annihilation peak provide an excellent conversion gain calibration for determination of the energy of the 346.95-keV gamma ray. The energy of the 826-keV gamma-ray transition to the 1332.52-keV level was measured recently by Rauch, VanPatter, and Hinrichsen[6] as 826.4 ± 0.2 keV, which places the second excited 2^+ level at 2158.92 keV. Hence, according to their measurement, the energy difference between the 4^+ state and the second excited 2^+ state is 346.83 ± 0.2 keV. Our observed energy of 346.95 ± 0.1 keV is in excellent agreement with this value; therefore, this transition must be a zero-phonon transition between the 4^+ and 2^+ two-phonon states at 2505.75 and 2158.80 keV. The relatively small error assigned to our measurement of the very weak 826.18-keV gamma ray results from the nearness of the single-escape peak (only 14 channels away). From our measurement of the 346.95-keV gamma-ray energy and the well-known 1173.23-keV gamma-ray energy, we deduce an energy of 826.28 ± 0.1 keV for this transition

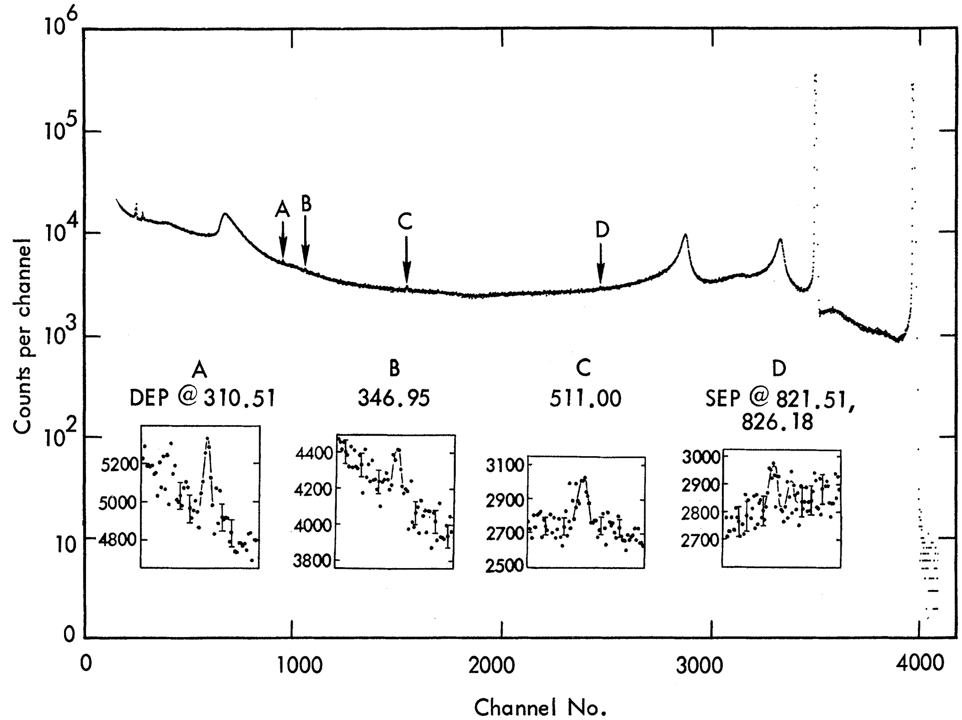

FIG. 1. A 4050-min Compton-suppressed spectrum of the decay of ^{60}Co with specified regions expanded.

—in excellent agreement with our measurement and in good agreement with Rauch, VanPatter, and Hinrichsen.[6]

The relative intensities of all of the transitions observed are shown in Table I. The intensity of the 1173.23-keV gamma ray was set equal to 10^6. We were not able to identify clearly a gamma-ray transition at 467.4 keV; however, we were able to place an upper limit on this intensity. According to Rauch, VanPatter, and Hinrichsen[6] it is the most intense gamma-ray branch from the 3^+ state at 2626.2 keV. Using this upper limit and the other intensities, we obtained the beta-branching and logft values shown in Fig. 2. An upper limit for the beta feeding of the 2158.80-keV level was determined by assuming the minimum intensity for the 346.95-keV transition (66) and the maximum intensity for the 826.18-keV transition (102). The branching ratio and logft value to the first excited state were taken from Camp, Langer, and Smith.[7] The left-hand side of Fig. 2 shows our results, with deduced energies and intensities shown in parentheses. We made no effort to observe the 2158.8-keV ground-state transition. The right-hand portion of Fig. 2 shows relevant data from Rauch, VanPatter, and Hinrichsen.[6] An initial consistency check on gamma-ray intensities is possible using the 1332.5-keV transition. Once the 1173.23-keV transition intensity is adopted at 10^6 units, an intensity can be calculated for the 1332.5-keV transitions. Our experimental value was only 0.09% higher than this calculated value.

Discussion.—The transition between the 4^+ and 2^+ members of the two-phonon triplet has been observed in ^{60}Ni. An upper limit[8] of 3.5 psec on the half-life of the 2506-keV level places a lower limit on the ratio of the experimental (exptl) and single-particle (SP) rates of the 1173-keV transi-

Table I. Cobalt-60 gamma-ray energies and intensities.

E_γ (keV)	I_γ	(%)
346.95 ± 0.10	78	(16.4)
467.4[a]	≤4	(470)
826.18 ± 0.20	55	(85)
1173.231 ± 0.036[b]	10^6	
1332.518 ± 0.034[b]	10^6+	

[a]The energy of this transition is deduced from the difference in energy of 3^+ level at 2626.2 keV (see Ref. 6) and our value for the second 2^+ level at 2158.80 keV.

[b]Weighted averages of values from G. Murray et al. Nucl. Phys. 63, 353 (1965), and D. White and D. Groves, Nucl. Phys. A91, 453 (1967).

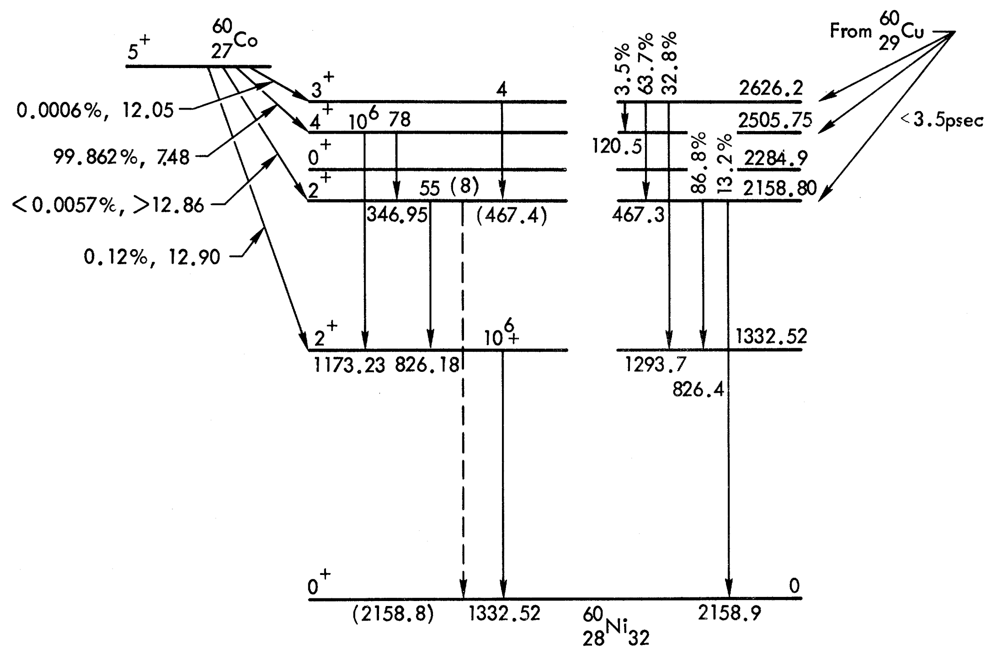

FIG. 2. The decay of ^{60}Co to the levels of ^{60}Ni with relevant data from ^{60}Cu. See text for discussion.

tion. That is,

$$\lambda_{1173}{}^{\text{exptl}}/\lambda_{1173}{}^{\text{SP}} \geq 4.7, \qquad (1)$$

where $\lambda^{\text{SP}} = 1.6\times 10^8 A^{4/3} E_\gamma{}^5$ as given in Appendix IV of Lederer, Hollander, and Perlman[9] for gamma rays with $E2$ characters.

Further, we have the following relationship which gives the ratio of experimental to SP rates for the 347-keV transition as

$$\frac{\lambda_{347}{}^{\text{exptl}}}{\lambda_{347}{}^{\text{SP}}} = \frac{I_{347}}{I_{1173}} \frac{\lambda_{1173}{}^{\text{exptl}}}{\lambda_{1173}{}^{\text{SP}}} \left(\frac{1173}{347}\right)^5, \qquad (2)$$

where I_{347}/I_{1173} is the ratio of measured intensities for the 347- and 1173-keV gamma rays, and the exponent of 5 on the energy ratio results from an assumption of $E2$ character for both gamma rays.

When the result from Eq. (1) is used in Eq. (2) we find that the ratio $\lambda_{347}{}^{\text{exptl}}/\lambda_{347}{}^{\text{SP}}$ must be greater than or equal to 0.174. Thus, not only does the (in vibrator language) zero-phonon transition exist, but its rate is not too much smaller than single-particle strength. Although such a model failure might be attributed to level mixing while simultaneously retaining the simple vibrational picture, it would be interesting to know whether the recent formulations of Baranger and Kumar[1] could incorporate this observation more naturally.

†Work performed under the auspices of the U. S. Atomic Energy Commission.

‡Summer visitor to Lawrence Radiation Laboratory. Permanent address: Department of Physics, Tri-State College, Angola, Ind.

[1]D. A. Bromley and J. Weneser, Comments Nucl. Particle Phys. 1, 75 (1967). (In this reference are included the references to the theoretical work of Baranger and Kumar.)

[2]While Ref. 1 suggests that such a transition has been observed in work on ^{113}Cd(n,γ), we were unable to substantiate this fact from the references given in Ref. 1.

[3]D. C. Camp, "Nuclear Spectroscopy via Ge(Li) Detectors in Compton Suppression and Pair Spectrometers," Proceedings of the International Conference on Radioactivity in Nuclear Spectroscopy, Vanderbilt University, Nashville, Tennessee, 11-15 August 1969 (to be published).

[4]D. C. Camp, in Semiconductor Nuclear Particle Detectors and Circuits (National Academy of Sciences, Washington, D. C., 1969), p. 693.

[5]R. Gunnink, R. A. Meyer, J. B. Niday, and R. P. Anderson, Nucl. Instr. Methods 65, 26 (1968).

[6]F. Rauch, D. M. VanPatter, and P. F. Hinrichsen, Nucl. Phys. A124, 145 (1969).

[7]D. C. Camp, L. M. Langer, and D. R. Smith, Phys. Rev. 123, 241 (1961).

[8]Nucl. Data, Sec. B, 2, No. 5 (1968).

[9]C. M. Lederer, J. M. Hollander, and I. Perlman, Table of Isotopes (John Wiley & Sons, Inc., New York, 1967), 6th ed. Note: Our quantity λ^{SP} is given the symbol T_{SP} in this reference.