[17]J. A. Harvey, G. G. Slaughter, J. R. Bird, and G. T. Chapman, Argonne National Laboratory Report No. ANL 6797, 1963 (unpublished), p. 230.

[18]B. R. Mottelson, in *Proceedings of the International Conference on Nuclear Structure, 1960, Queen's University, Kingston, Ontario,* edited by D. A. Bromley and E. W. Vogt (University of Toronto Press, 1960), p. 525.

[19]I. Bergqvist, B. Lundberg, and N. Starfelt, Argonne National Laboratory Report No. ANL 6797, 1963 (unpublished), p. 220.

[20]B. B. Kinsey, in *Encyclopedia of Physics,* edited by S. Flugge (Springer-Verlag, Berlin, Germany, 1957), Vol. XL, p. 302.

[21]J. E. Draper, C. Fenstermacher, and H. L. Schultz, Phys. Rev. 111, 906 (1958).

[22]C. A. Fenstermacher, J. E. Draper, and C. K. Bockelman, Nucl. Phys. 10, 386 (1959).

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

[24]W. P. Pönitz, Z. Physik 197, 262 (1966).

[25]D. Sperber and J. W. Mandler, Nucl. Phys. A113, 689 (1968).

[26]K. J. Wetzel and G. E. Thomas, Phys. Rev. C 1, 1501 (1970).

[27]R. E. Bell, in *Alpha-, Beta-, and Gamma-Ray Spectroscopy,* edited by K. Sieghahn (North-Holland Publishing Company, Amsterdam, The Netherlands, 1965), Vol. 2, p. 905.

[28]L. M. Bollinger, in *International Symposium on Nuclear Structure, Dubna, 1968* (International Atomic Energy Agency, Vienna, Austria, 1969), p. 317.

[29]P. Axel, Phys. Rev. 126, 671 (1962).

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γ-Vibrational and Ground-State Rotational-Band Mixing in ^{238}Pu

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The intensities of the high-energy γ rays in the 2.1-day decay of ^{238}Np to ^{238}Pu are measured using a high-resolution Ge(Li) detector (full width at half maximum of 1.7 keV at 1333 keV). The branching ratios for the transitions from the γ-vibrational band are found to be consistent with values of $(26.5\pm 7.8)\times 10^{-3}$ for z, the band-mixing parameter for the ground-state rotational and γ-vibrational bands, and $\approx -7\times 10^{-3}$ for $z_{\beta\gamma}$, the parameter for the mixing of β- and γ-vibrational bands.

I. INTRODUCTION

It is now well established that the branching ratios for the $E2$ transitions from γ-vibrational bands to ground-state bands indicate a small mixing of these bands.[1] The rotational-vibrational interaction is usually characterized by the coupling parameter z.[1,2] A single value of z is expected to explain all the observed intensities of the transitions between the two bands in a nucleus. Considerable work has been done in support of such a description in the case of deformed nuclei of the rare-earth region,[3-11] as well as heavy deformed nuclei.[12-17] The strong excitation of two $K=2$ vibrational levels at 1030 keV (2^+) and 1071 keV (3^+) in ^{238}Pu was well established by previous work.[17-22] Borggreen, Nielson, and Nordby[17] determined the branching ratios for the transitions deexciting these two levels from conversion-electron intensities assuming a theoretical α_K for pure $E2$ transitions. They found an average value of $z\approx 0.025$. In the present work the relative γ-ray intensities are measured using a high-resolution Ge(Li) detector with calibrated relative efficiency in order to study the deexcitation of 2^+ and 3^+ γ-vibrational states.

II. EXPERIMENTAL PROCEDURE

A few μg of ^{238}Np were irradiated in the thermal-neutron beam from the Lockheed reactor. The γ-ray spectra were measured with a high-resolution (full width at half maximum of 1.7 keV at 1333 keV) Ge(Li) photon spectrometer. The detector and electronic circuitry have been discussed elsewhere.[23,24] The photopeak efficiency calibration of the detector was made using International Atomic Energy Agency calibrated sources.

III. RESULTS

A typical γ-ray spectrum of the high-energy region is shown in Fig. 1. The decay of each of the photopeaks was followed over several half-lives. The unidentified γ rays in the spectrum did not belong to the decay of ^{238}Np. The closely spaced doublet of 1027.4- and 1029.9-keV γ rays is clearly resolved. The energies and relative intensities of the γ rays measured in the present experiment are presented in Table I. γ rays at 990 and 1034 keV corresponding to transitions from a level at 1034

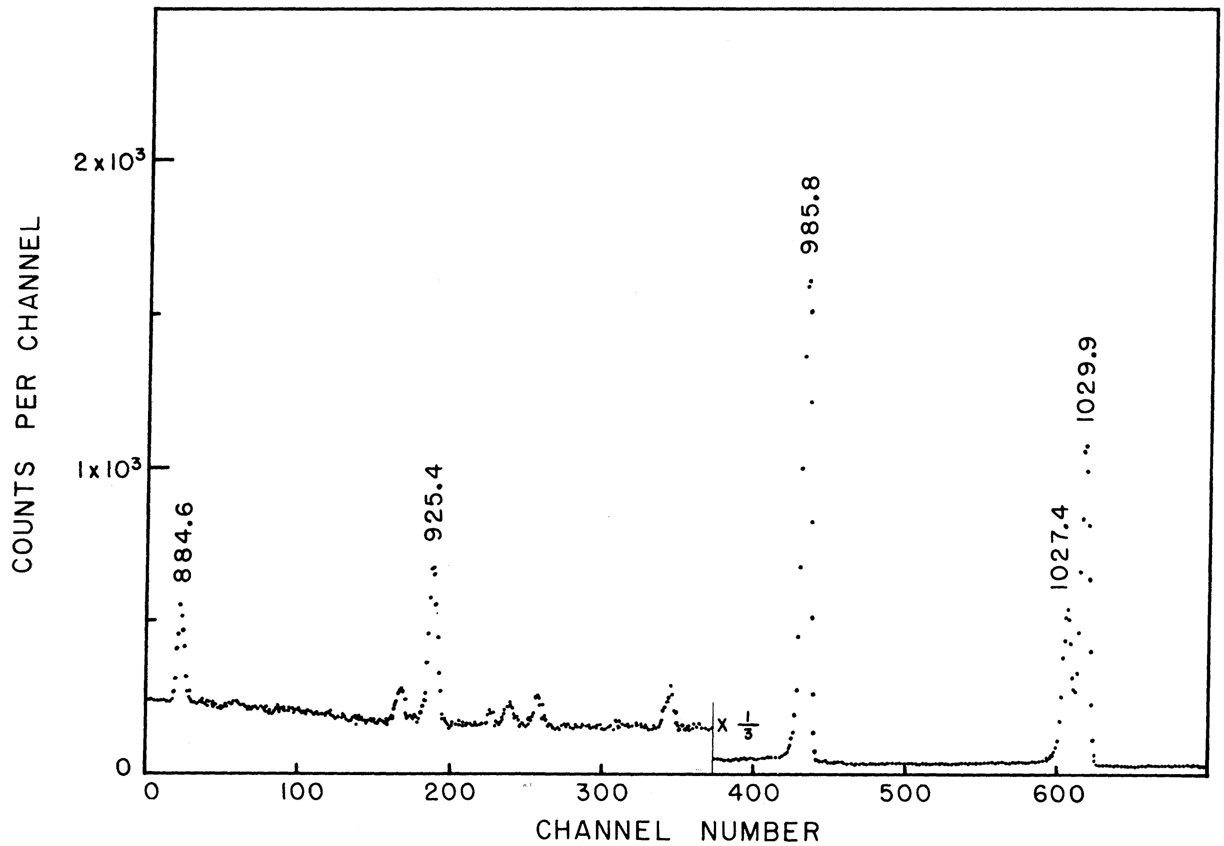

FIG.1. High-energy γ-ray spectrum from the 2.1-day $^{238}Np \rightarrow {}^{238}Pu$ decay taken with a Ge(Li) detector having an FWHM of 1.7 keV at 1333 keV. The energies are in keV.

keV in ^{238}Pu proposed by Albridge and Hollander[22] were not found, and upper limits were set for their presence. Assuming the theoretical value of 8.96×10^{-3} for α_K for the 1029.9-keV $(2, 2^+ \rightarrow 2, 0^+)$ transition, which is expected to be pure $E2$, the values for α_K for the four other transitions observed in the present work are calculated with the aid of our γ-ray intensities and the conversion-electron intensities from the work of Borggreen, Nielson, and Nordby. The experimental values are compared with the theoretical values of α_K for pure $E2$ given by Hager and Seltzer[25] in Table I. No substantial evidence was found for any $M1$ mixing. A revised decay scheme, incorporating the present relative γ-ray intensities and the earlier work on the β spectrum and conversion electrons, is presented in Fig. 2. For the branching of the soft component, earlier β-spectrum studies[17,18,20,21] assigned values of $(58\pm4)\%$, 53%, 55%, and 59%, respectively, and an average value of 56% is adopt-

TABLE I. Energies, relative γ-ray intensities, and α_K for the transitions in ^{238}Pu.

Transition $K\,I_i \rightarrow I_f$	Energies (keV)	Relative intensities	$10^3\times\alpha_K$ Experiment[a]	Theory $(E2)$[b]
$2\ 2^+ \rightarrow 4^+$	884.6	3.3 ± 0.4	11.9	11.9
$2\ 3^+ \rightarrow 4^+$	925.4	$11\ \pm0.7$	9.3	10.9
$2\ 2^+ \rightarrow 2^+$	985.8	100	9.1	9.7
$2\ 3^+ \rightarrow 2^+$	1027.4	$32\ \pm2$	9.0	9.0
$2\ 2^+ \rightarrow 0^+$	1029.9	$69\ \pm5$	9.0	9.0
	990	<0.15		
	1034	<0.15		

[a]Values are obtained from the conversion-electron data of Borggreen, Nielson, and Nordby (Ref. 17).

[b]Values are obtained from the work of Hager and Seltzer (Ref. 25).

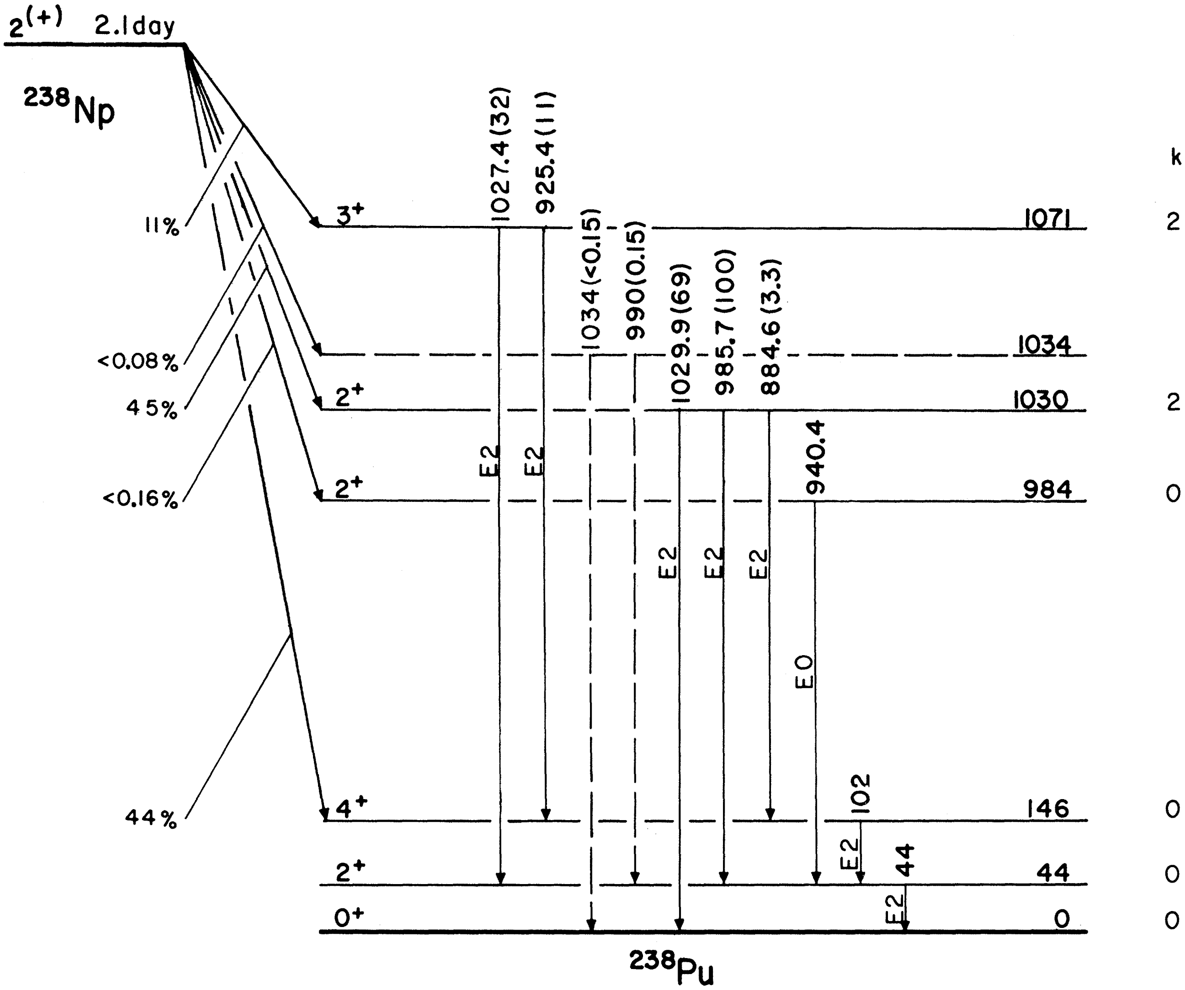

FIG. 2. Revised decay scheme of $^{238}Np \rightarrow {}^{238}Pu$.

TABLE II. $B(E2)$ ratios for the decay of γ-vibrational band.

Transition	$B(E2)$ Ratio Experiment	Theory ($z=0$)	γ- and g.s.-band coupling only: Correction factor f	z	β- and γ-band coupling included: Correction factor f	z	$z_{\beta\gamma}$
$2^+\gamma\ \frac{2\to 0}{2\to 2}$	0.57 ± 0.04	0.7	$\left(\frac{1-z}{1+2z}\right)^2$	0.036 ± 0.010	$\left(\frac{1-z+2z_{\beta\gamma}}{1+2z-3z_{\beta\gamma}}\right)^2$		
$\frac{2\to 4}{2\to 2}$	0.057 ± 0.007	0.05	$\left(\frac{1+9z}{1+2z}\right)^2$	0.010 ± 0.008	$\left(\frac{1+9z+12z_{\beta\gamma}}{1+2z-3z_{\beta\gamma}}\right)^2$	0.025 ± 0.012	≈ -0.007
$\frac{2\to 0}{2\to 4}$	$9.9\ \pm 1.2$	14	$\left(\frac{1-z}{1+9z}\right)^2$	0.018 ± 0.009	$\left(\frac{1-z+2z_{\beta\gamma}}{1+9z+12z_{\beta\gamma}}\right)^2$		
$3^+\gamma\ \frac{3\to 4}{3\to 2}$	0.58 ± 0.04	0.4	$\left(\frac{1+6z}{1-z}\right)^2$	0.028 ± 0.010	$\left(\frac{1+6z}{1-z}\right)^2$	0.028 ± 0.010	

ed. The following values for the β branching to levels at high energy are obtained: 1071 keV (11%), 1034 (<0.08%), 1030 keV (45%), and 984 (<0.16%). The present work yields a limit for the feeding of the level at 1034 keV much lower than the value of 7% from the work of Albridge and Hollander.[22]

IV. DISCUSSION

The ratios of $B(E2)$ values are calculated from the experimental relative intensities and energies for the transitions deexciting the 2^+ and 3^+ γ levels, assuming pure $E2$ character, and are listed in Table II. The theoretical $B(E2)$ ratios for $z=0$ and the values of the coupling parameter z to explain the observed ratios are also presented. The correction factors f that enter into the expression for $B(E2)$ values, i.e.,

$$B(E2, I_i \to I_f) = B(E2, I_i K=2 \to I_f K=0)\, f(z, I_i, I_f)$$

are also listed. In spite of the large error limits involved, the z values seem to have a wide range, thus apparently not subscribing to the single-parameter band-mixing theory. This discrepancy cannot be attributed to any $M1$ admixture in the transitions, as is evident from the K-conversion coefficients presented in Table I. The smallness of $M1$ admixture is well established both in the rare-earth region and the region of the present interest. The possibility of substantial $E0$ admixture in the transition of the type $\Delta I=0$ is also not evident from the agreement between the experimental value of α_K and the corresponding theoretical value of $\alpha_K(E2)$ for the 985.8-keV $(2, 2^+ \to 0, 2^+)$ transition.

The presence of a possible level at 984 keV belonging to the β-vibrational band raises the question whether there is any coupling between β- and γ-vibrational bands. The β and γ interaction is taken into account by introducing an additional parameter $z_{\beta\gamma}$, and the correction factors $f(z, z_{\beta\gamma}, I_i, I_f)$ are listed in the work of Lipas.[26] The parameter $z_{\beta\gamma}$ enters only into the correction factor for the branching of the 2^+ γ level and not the 3^+ γ level. From the data on the 2^+ γ level in Table II, $z_{\beta\gamma}$ is estimated to be about -0.007, while the new value of z is 0.025 ± 0.012, which is in agreement with 0.028 obtained for the branching of the 3^+ γ level. Thus the mixing of the γ-vibrational and ground-state rotational bands can be explained by a single parameter z, the average value of which is 0.0265 ± 0.0078, if we include a small amount of β and γ interaction.

[1] P. Gregers Hansen, O. B. Nielsen, and R. K. Sheline, Nucl. Phys. 12, 389 (1959).

[2] O. Nathan and S. G. Nilsson, in *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, The Netherlands 1965), Chap. X.

[3] C. J. Gallagher, Jr., O. B. Nielsen, and A. W. Sunyar, Phys. Letters 16, 298 (1965).

[4] O. B. Nielsen, in *Proceedings of the Rutherford Jubilee Conference*, edited by J. B. Berks (Academic Press Inc., New York, 1961), p. 317.

[5] Y. Yoshizawa, B. Elbek, B. Herskind, and M. C. Olesen, Nucl. Phys. 73, 273 (1965).

[6] R. Graetzer, G. B. Hagemann, K. A. Hagemann, and B. Elbek, Nucl. Phys. 76, 1 (1966).

[7] C. Gunther and D. R. Parsignault, Phys. Rev. 153, 1297 (1967).

[8] L. Varnell, J. D. Bowman, and J. Trischuk, Nucl. Phys. A127, 270 (1969).

[9] L. L. Riedinger, N. R. Johnson, and J. H. Hamilton, Phys. Rev. 179, 1214 (1969).

[10] J. H. Hamilton, A. V. Ramayya, and L. C. Whitlock, Phys. Rev. Letters 23, 1178 (1969).

[11] E. Bodenstadt, in *Proceedings of the International Conference on Radioactivity in Nuclear Spectroscopy, 1969* (Gordon and Breach, Science Publishers, Inc., New York, to be published).

[12] E. Arbman, S. Bjornholm, and O. B. Nielsen, Nucl. Phys. 21, 406 (1960).

[13] J. M. Hollander, C. L. Nordling, and K. Siegbahn, Arkiv Fysik 23, 35 (1962).

[14] S. Bjornholm, F. Boehm, A. B. Knutsen, and O. B. Nielsen, Nucl. Phys. 42, 469 (1963).

[15] P. H. Stelson, R. W. Lide, and C. R. Bingham, Nucl. Phys. A144, 254 (1970).

[16] M. R. Schmorak, C. E. Bemis, Jr., M. Zender, F. F. Coffman, A. V. Ramayya, and J. H. Hamilton, Phys. Rev. Letters 24, 1507 (1970).

[17] J. Borggreen, O. B. Nielson, and H. Noroby, Nucl. Phys. 29, 515 (1962).

[18] M. S. Freedman, A. H. Jaffey, and F. Wagner, Jr., Phys. Rev. 79, 410 (1950).

[19] H. Slatis, J. O. Rasmussen, and H. Atterling, Phys. Rev. 93, 646 (1954).

[20] J. O. Rasmussen, H. Slatis, and T. O. Passell, Phys. Rev. 99, 42 (1955).

[21] S. A. Baranov and K. N. Shlyagin, J. Nucl. Energy 3, 132 (1956).

[22] R. G. Albridge and J. M. Hollander, Nucl. Phys. 21, 438 (1960).

[23] J. M. Palms, P. Venugopala Rao, and R. E. Wood, Nucl. Instr. Methods 64, 310 (1968).

[24] J. M. Palms, P. Venugopala Rao, and R. E. Wood, IEEE Trans. Nucl. Sci. 16 (No. 1), 36 (1969).

[25] R. S. Hager and E. C. Seltzer, Nucl. Data A4, 1 (1968).

[26] P. O. Lipas, Nucl. Phys. 39, 468 (1962).