Beta Emitter Np^{238}. I. Beta Spectroscopy*

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The beta decay of Np^{238} has been studied with several beta spectrometers. In addition to the known conversion lines corresponding to transitions of energies now determined as 44.0, 102.2, 986, and 1029 kev, new conversion lines, corresponding to transitions of 942 and 927 kev were found. These transitions indicate the presence of closely spaced levels at higher excitation energies. Intensities of conversion lines and beta groups were determined and compared with previous work. Fermi-Kurie plots confirm the allowed shape of the hard beta group (1.25 Mev) and give indication of complexity in the soft beta group (0.27 Mev). The energy deviations of the ground rotational band levels from the simple rotational energy formula are discussed.

INTRODUCTION

EARLY investigations[1–4] of the decay of Np^{238} have shown a half-life of 2.1 days, a complex beta spectrum, two highly converted transitions of 43- and 103-kev energy, and two gamma rays of 983- and 1030-kev energy. The beta components were reported to have an allowed shape, 47 percent of the disintegrations belonging to the hard component, the maximum energy of which is 1272 kev, and 53 percent to the soft component of 258-kev energy.

The present paper sets forth and interprets material gained from further beta spectroscopic work on Np^{238}, some of which has been partially reported in prior notes.[5–7]

EXPERIMENTAL PROCEDURE AND RESULTS

For the Stockholm work the Np^{238} was obtained by bombarding natural uranium metal with protons of 12.5-Mev energy in the 225-cm cyclotron of the Nobel Institute of Physics,[8] and for the Berkeley work, by irradiation of Np^{237} with neutrons in the MTR reactor, Reactor Testing Station, Arco, Idaho.[9]

The neptunium activity was chemically purified by various combinations of the procedures given by Magnusson, Thompson, and Seaborg.[10]

The following types of measurements were made:

1. Beta spectroscopy with the Stockholm intermediate-image, long-lens spectrometer.[11] (Resolution ~2 percent.) (Referred to as SS.)

2. Beta spectroscopy with the Stockholm double-focusing spectrometer.[12] (Resolution 0.5 percent.) (Referred to as SD.)

3. Beta spectroscopy with the Berkeley double-focusing spectrometer.[13] (Resolution 1.2 percent.) (Referred to as BD.)

4. Electron spectroscopy of photo and Compton electrons from a (0.0005-inch) uranium metal radiator

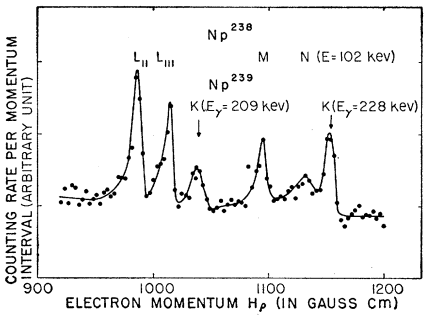

FIG. 1. Electron spectrum of Np^{238} (with some Np^{239}) in the region of the conversion lines of the 102.2-kev gamma ray. (Stockholm double-focusing spectrometer.)

* This work was supported in part by the U. S. Atomic Energy Commission.

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[1] Seaborg, Wahl, and Kennedy, *The Transuranium Elements: Research Papers* (McGraw-Hill Book Company, Inc., New York, 1949), National Nuclear Energy Series, Plutonium Project Record, Vol. 14B, p. 13.

[2] A. H. Jaffey and L. B. Magnusson, *The Transuranium Elements: Research Papers* (McGraw-Hill Book Company, Inc., New York, 1949), National Nuclear Energy Series, Plutonium Project Record, Vol. 14B, p. 978.

[3] Freedman, Jaffey, and Wagner, Phys. Rev. **79**, 410 (1950).

[4] J. W. Mihelich, Phys. Rev. **87**, 646 (1952).

[5] Slätis, Rasmussen, and Atterling, Phys. Rev. **93**, 646 (1954).

[6] Rasmussen, Passell, and Stephens, University of California Radiation Laboratory Unclassified Report UCRL-2585, 1954 (unpublished).

[7] T. O. Passell, Ph.D. thesis, University of California Radiation Laboratory Unclassified Report UCRL-2528, 1954 (unpublished).

[8] We are greatly indebted to Dr. Hugo Atterling, who developed and tested the special target holder for the uranium metal and who carried out the three bombardments.

[9] We express appreciation to Dr. W. B. Lewis, Dr. Richard Smith, and others at the Reactor Test Station for facilitating the irradiation.

[10] Magnusson, Thompson, and Seaborg, Phys. Rev. **78**, 363 (1950).

[11] H. Slätis and K. Siegbahn, Arkiv Fysik **1**, 339 (1949).

[12] A. Hedgran, Arkiv Fysik **5**, 1 (1952).

[13] G. D. O'Kelley, Ph.D. thesis, University of California Radiation Laboratory Unclassified Report UCRL-1243, 1951 (unpublished).

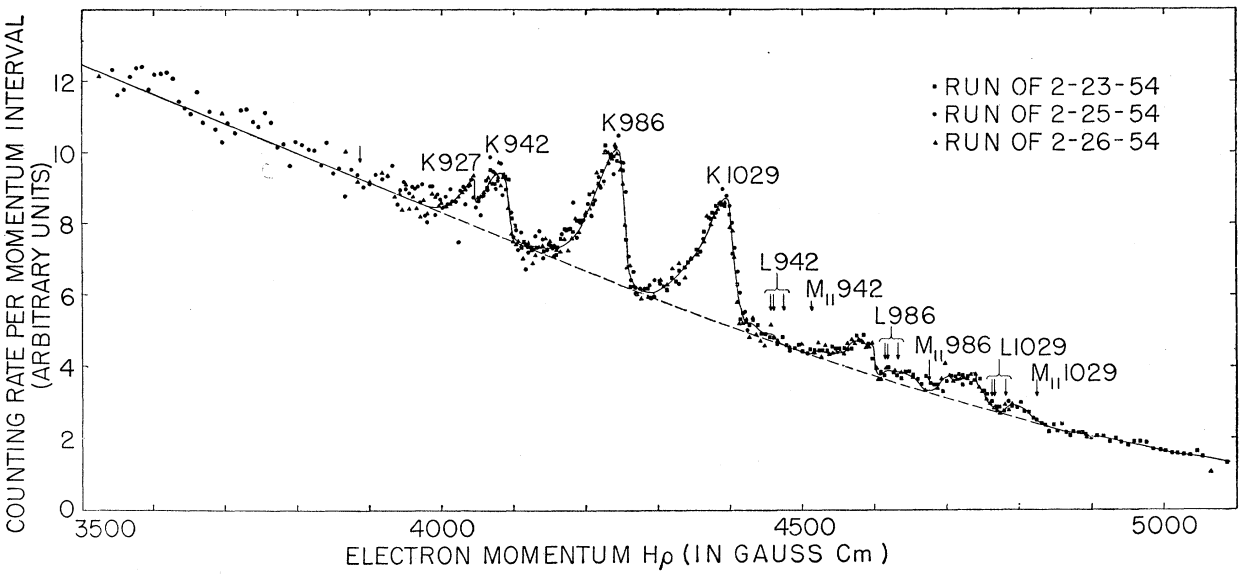

FIG. 2. The high-energy part of the Np^{238} beta spectrum. (Berkeley double-focusing spectrometer.) For interpretation of the arrows see the text.

with the Berkeley ring-focusing solenoidal spectrometer.[14] (Resolution ~2 percent.) (Referred to as BS.)

Where duplicate information was obtained, we present the best or the average of the best determinations. In general, regarding beta spectroscopic results, the energy measurements on the SD spectrometer are taken as standard, since this instrument is specifically designed for precision energy comparisons. However, the energy differences of the high-energy conversion lines determined on the BD spectrometer are preferred by virtue of the much greater source strength and consequent better counting statistics in the Berkeley work. The BD measurements were not as useful as SS and SD for the continuum and lines below 0.7 Mev (disintegration energy of Np^{239}) because of the larger admixture of the troublesome Np^{239}. The SS measurements form the basis for spectrum shape studies of the hard beta particles, as the background due to scattered electrons entering the counter is minimized by the intermediate image slit system.

Figure 1 shows the spectrum taken with the SD spectrometer in the region of the conversion lines of the 102.2-kev gamma ray. Note the lines assigned to Np^{239} present in small amount. By means of the well-known strong conversion lines of Np^{239} it was possible to make corrections for the small contamination of this activity when computing the intensities of the beta components.[15]

Figure 2 shows the spectrum taken with the BD spectrometer of the region above 3500 gauss cm. The K lines of the four high-energy gamma transitions are clearly evident. The arrows labeled for L and M lines each point to the calculated abscissa for the foot of the leading edge of the line (about 20 gauss cm to the right of the peak). The unlabeled arrow at 3887 gauss cm points to the calculated position of the K line of a transition 146 kev less energy than the most energetic gamma ray. (With the decay schemes proposed in the article[16] following this, which we refer to as paper II, it is important to search for such a transition.) There is no evidence for this line, and we can from these data say that it is less than 10 percent of the intense line K_{1030}.

The conversion line energy and intensity data are summarized in Table I. The energy figures are based on averages of the best Stockholm or Berkeley data. As the intensities are of considerable importance in constructing the decay scheme and as there is some variation in intensities obtained in various studies, Table I includes three intensity columns: one for the work of Freedman *et al.*,[3] one for Slätis *et al.*,[5] and one for the BD work previously unreported.

There is fair agreement in the intensity figures between the different investigations except for some extremely weak high-energy lines and except for the lowest energy 21.8-kev $L_{II}44$ line. At such low energies spectrometer measurements are subject to some uncertainty from counter window transmission losses. In view of the disagreement, the total intensity figure for conversion lines of the 44-kev transition has not been given much weight in the construction of a decay scheme.

It is of some interest to collect as in Table II yet other determinations of intensity of the low-energy conversion lines.[3,5,7,17,18,19] Passell[7] has measured on the BD spec-

[14] G. D. O'Kelley, California Research and Development Company Unclassified Report MTA-38, May 1954 (unpublished).

[15] Regarding the shape of the Np^{239} spectrum see H. Slätis, Arkiv Mat. Astron. Fysik **35A**, 3 (1947).

[16] Rasmussen, Stephens, Strominger, and Åström, following paper [Phys. Rev. **99**, 47 (1955)].

[17] Gellman, Griffith, and Stanley, Phys. Rev. **85**, 944 (1952).

[18] D. C. Dunlavey and G. T. Seaborg, Phys. Rev. **87**, 165 (1952).

[19] D. C. Dunlavey, unpublished results (1953) (110 electron coincidence events counted).

TABLE I. Conversion lines accompanying beta decay of Np^{238}.

Electron momentum gauss cm[a]	Electron line energy[a]	Shell converting	Electron binding energy (Pu)[b]	Gamma energy		Abundance per 100 beta disintegrations: Freedman, Jaffey, Wagner[c]	Slätis, Rasmussen, Atterling[d]	Berkeley double-focusing spectrometer (previously unreported)
503	21.8	L_{II}	22.2	44.0		38	28.7	...
549	25.9	L_{III}	18.1	44.0		20	21.0	...
671	38.2	M_{II}	5.6	43.8	44.0[e]	14	15.2	[f]
678	39.0	M_{III}	4.6	43.6				
713	42.9	N	1.4	44.3		3.2		
720	43.7	O	0.3	44.0				
991	80.1	L_{II}	22.3	102.4			1.4	...
1017	84.1	L_{III}	18.1	102.2	102.2	1.9	0.9	...
1097	96.7	$M_{II, III}$	~5.0	101.7		1.2	0.7	...
4046	805.3	K	121.7	927		...	0.05	0.04
4099	819.8	K	121.7	942		...	0.10	0.07
		L	...	...		...	0.06	...
4259	864.4	K	121.7	986		0.3	0.26	0.20
		L	...	...		...	0.13	0.06
4414	907.6	K	121.7	1029		0.3	0.22	0.20
		L	...	...		...	0.08	0.04
		M, N, O	...	...		...	0.06	0.02

[a] Calibration for 44-kev gamma lines from ThB line taken as $H\rho_A = 534.11$ from the work of D. I. Meyer and F. H. Schmidt, Phys. Rev. **94**, 927 (1954) Calibration for 102-kev gamma lines from ThB F line taken as $H\rho_F = 1388.56$ from the work of G. Lindström, Arkiv Fysik **4**, 1 (1951). Calibration for higher energy lines from Cs^{137} K line taken as $H\rho = 3381.3$ from the work of Lindström, Siegbahn, and Wapstra, Proc. Phys. Soc. (London) **B66**, 54 (1953). The SD measurement of absolute energy of K_{986} is used, but the energy differences to other high energy lines is taken from BD work (see reference 6).
[b] Hill, Church, and Mihelich, Rev. Sci. Instr. **23**, 523 (1952).
[c] See reference 3.
[d] See reference 5.
[e] The recent measurements of J. M. Hollander and W. G. Smith (private communication) give a best energy for this transition of 44.11 ±0.04 kev based on their work with a permanent magnet spectrograph.
[f] Berkeley measurements give the $M_{II}:M_{III}:N, O$ ratio as 1.85:1.35:1 (see reference 7).

trometer the relative intensities of these lines, using both Np^{238} and Cm^{242} samples. A very thin counter window was used and no transmission correction was made.

Dunlavey and Seaborg[18] and Dunlavey[19] have determined $L:(M+N+O)$ ratios with Cm^{242} samples by track counting in electron-sensitive photographic emulsions, and their results are presented in Table II also.

The $E2$ nature of the 44.0- and 102.2-kev transitions is clearly confirmed by comparison of the L subshell conversion results with the theoretical calculations of Gellman *et al.*[17]

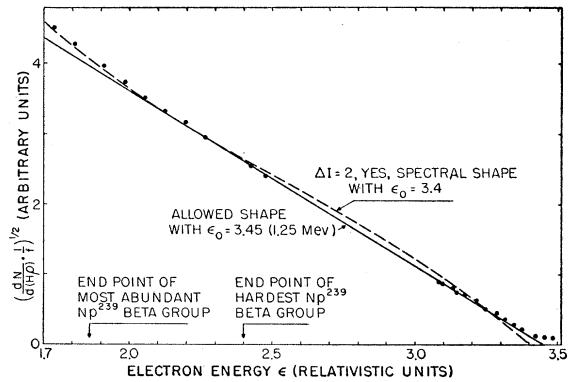

FIG. 3. Fermi-Kurie plot of the hard beta spectrum of Np^{238}. (Stockholm long-lens intermediate-image spectrometer.)

The hard beta spectrum was taken repeatedly in the intermediate image spectrometer in an effort to determine precisely the shape. The intermediate image spectrometer was felt to be especially suitable for spectrum shape studies, as it has a very low scattered electron background. The logft values of the hard beta particles are in good agreement with a first forbidden $\Delta I = 2$, yes, assignment, although Freedman *et al.*[3] reported an allowed spectrum shape. The reinvestigation was in part prompted by the availability of accurate tables[20] for determination of spectrum shape correction factors. These tables show that the correction factor for the $\Delta I = 2$, yes spectrum shape for high atomic numbers is considerably less pronounced than the $Z = 0$ approximation correction sometimes used. In the conventional Fermi-Kuri plot of Fig. 3 (where the Fermi function was obtained from the National Bureau of Standards tables)[21] are shown a straight solid line and a dashed $\Delta I = 2$, yes, line calculated from the tables of Rose *et al.*[20]

[20] Rose, Perry, and Dismuke, Oak Ridge National Laboratory Report ORNL-1459, 1953 (unpublished).
[21] *Tables for the Analysis of Beta Spectra*, National Bureau of Standards Applied Mathematics Series 13 (U. S. Government Printing Office, Washington, D. C., 1952).

TABLE II. Intensities of conversion lines of the 44-kev transition.

Ratio	Freedman *et al.*[a] Np^{238}	Slätis *et al.*[b] Np^{238}	Passell[c] Cm^{242}	Berkeley double-focusing[c] Np^{238}	Dunlavey, Seaborg[d] Cm^{242}	Dunlavey redetermination by same method[e] Cm^{242}	Gellman *et al.*[f] (*E*2 theoretical)
$L_{II}:L_{III}$	1.91	1.37	1.44	1.26	...	...	~1.2
$(L_{II}+L_{III}):(M+N+O)$	3.26	3.27	3.42	3.33	4.8	2.93±0.64	...

[a] See reference 3.
[b] See reference 5.
[c] See reference 7.
[d] See reference 18.
[e] See reference 19.
[f] See reference 17.

The endpoint energies were chosen to give qualitative best fits to the experimental points in each case. Parts of the spectrum are obscured by soft beta rays or by high-energy conversion lines. We are inclined to give most weight to the fit near the end of the spectrum. There the slopes of allowed and forbidden spectra are quite different, with the data agreeing much better with the allowed line. Very pertinent to the shape study is the question of possible complexity of the hard beta spectrum. If there were admixture of two groups with endpoints differing by only 44 kev, it would hardly be possible to determine their abundances by resolution of a Fermi-Kurie plot. Our belief that the hard beta spectrum consists of essentially a single group going to the 44-kev first-excited state is based on *L* x-ray—beta coincidence work reported in paper II.[16] (The contrary result previously reported[6] was shown to be in error by later experiments using the same apparatus.) The fit for the lower energy points of Fig. 3 seems better for the forbidden shape, but this may be due to an incomplete subtraction of the Np^{239} spectrum, endpoints of which are indicated by arrows in Fig. 3.

Thus, we support the conclusion of Freedman *et al.*[3] that the hard beta group has allowed shape, and we find an energy 1.25 Mev compared with their 1.272 Mev.

Figure 4 shows a Fermi-Kurie plot of the soft beta continuum from SS data after subtraction of hard beta and Np^{239} beta contributions. Parts of the spectrum are obscured by conversion lines. The Fermi-Kurie plot has a definite curvature, indicating the probable presence of more than one soft beta group, but it is not felt that the data are of sufficient accuracy to justify any resolution of the plot. The endpoint of the most energetic soft beta group seems to be about 0.27 Mev, in satisfactory agreement with the 0.258 Mev of Freedman *et al.*[3]

The intensity ratio between soft beta rays and hard beta groups was found to be 55:45 in this investigation. This ratio is in good agreement with the ratio 53:47 of Freedman *et al.*[3]

SPECTROSCOPIC MEASUREMENT OF URANIUM RADIATOR PHOTOELECTRONS

In order to study the relative intensities of the high-energy gamma rays (unresolvable by scintillation spectrometer), the spectrum of electrons ejected from a 0.0005-inch thick uranium metal radiator was studied in the Berkeley thick-lens solenoidal beta spectrometer.[14]

The sample of Np^{238} was enclosed in a cylindrical aluminum shield of sufficient thickness to absorb the beta radiation of Np^{238}, and on the plane face of the shield in the normal position for the spectrometer source was attached a disk of uranium metal 0.0005-inch thick and 0.5-inch in diameter.

Figure 5 shows one of the several series of measurements. The two prominent peaks are due to photoejection of *K* electrons by the 1029- and 986-kev gamma rays of Np^{238}. Centers of the peaks lie about 10 kev lower in energy than calculated, but this is accounted for by the thickness of the uranium radiators. Diffuse peaks due to *L* shell conversion are seen at higher energies. At energies just below the K_{986} peak the electrons due to Compton scattering events sharply rise. The Compton electrons unfortunately obscure the region of great interest where the *K* photopeaks of the weaker 941- and 925-kev gamma rays are expected. One can only say that these gamma rays are in somewhat lower intensity than the higher energy gamma rays.

The dotted lines of Fig. 5 indicate how the main peaks were resolved for determination of their relative intensities. The areas of the peaks are in the ratio $K_{1029}:K_{986}=1:0.90$. For these energies the photoelectric absorption cross section varies nearly inversely as the square of the gamma energy.[22] Making such a correction, we obtain the gamma intensity ratio $\gamma_{1029}/\gamma_{986}=1/0.83$. An

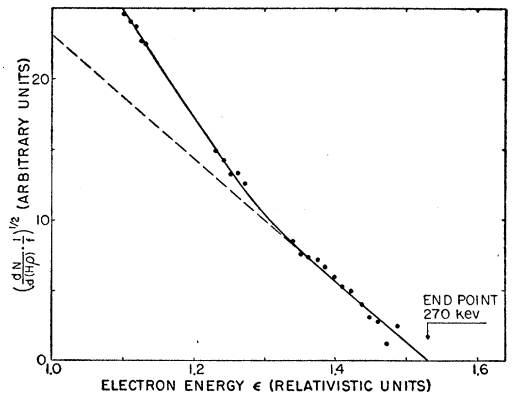

FIG. 4. Fermi-Kurie plot of the soft beta spectrum of Np^{238}. (Stockholm long-lens intermediate-image spectrometer.) Contributions from the hard beta group and from the beta spectrum of Np^{239} contamination have been subtracted out.

[22] C. M. Davisson and R. D. Evans, Revs. Modern Phys.**24**, 79 (1952).

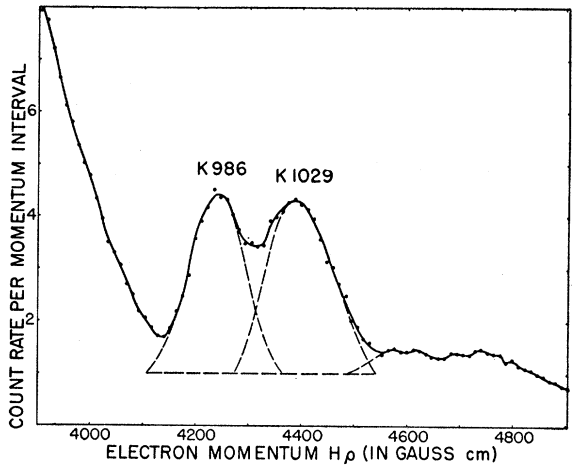

FIG. 5. Spectrum of electrons ejected from a thin uranium metal radiator by the gamma radiation of Np^{238}. (Berkeley thick-lens beta spectrometer.) Dotted lines show how the K photolines for the two most intense gamma rays were resolved for the purpose of the relative intensity determination.

effect which is difficult in our case to estimate quantitatively arises from the change in angular distribution of photoelectrons with energy.[22] The angle of the accepted electron trajectories in the solenoidal beta spectrometer with respect to the axis is between 20° and 24°, so qualitatively the effect should give higher effective transmission for the K_{1029} as compared with the K_{986} electrons. The effect should not be large with our geometries and is therefore neglected. Our ratio is to be compared with that of 1.02:1 determined by Freedman *et al.*[3]

It might be possible to observe photopeaks from the weaker gamma rays if a radiator of lower atomic number than uranium were used (increasing the energy difference between the K photoelectron energy and the Compton electron maximum), but this experiment has not been done by us.

DISCUSSION

It is obvious that the several hard gamma rays of similar energies signify close-lying levels in Pu^{238} in the vicinity of 1 Mev, and the possibility of their interpretation in terms of Bohr-Mottelson type rotational bands seems promising.

In attempting to construct a decay scheme from electron spectroscopic data, one seeks to find as many cases as possible where the energies of two or more transitions add to equal the energy of another transition. In this connection, it may be pointed out that the energy differences between the high-energy gamma K conversion lines are known much better than their absolute energies.[23] The possible sums are listed below.

$$E_{\text{hard beta}}-E_{\text{soft beta}}\approx 980 \text{ kev}; \quad E_{\gamma 986}=986 \text{ kev}; \quad (1)$$

$$E_{\gamma 1029}-E_{\gamma 986}=43.2 \text{ kev}; \quad E_{\gamma 44}=44.0 \text{ kev}; \quad (2)$$

$$E_{\gamma 986}-E_{\gamma 942}=44.6 \text{ kev}; \quad E_{\gamma 44}=44.0 \text{ kev}; \quad (3)$$

$$E_{\gamma 1029}-E_{\gamma 927}=102.3 \text{ kev}; \quad E_{\gamma 102}=102.2 \text{ kev}. \quad (4)$$

It is difficult to decide which of the gamma sums are true and which are coincidental. From the above beta spectroscopic information a simple level scheme with levels at 986 and 1073 kev was proposed,[6] accounting for all four energetic gamma rays through transitions to the known levels of 0, 44, and 146 kev. Scintillation counter coincidence studies (reported in paper II) later showed the proposed scheme to be incorrect in some respects. Hence, the decay scheme proposals and accompanying interpretation will be left to paper II.

It is of some interest to compare our values for the energies of the states of the ground rotational band with the predictions of the Bohr-Mottelson theory.[24] To a first approximation the energies should be given by $E=(\hbar^2/2\Im)I(I+1)$ with only even I values above a spin-zero base state. If one uses the first excited state energy, 44.11 kev, as determined by Hollander and Smith (private communication), the rotational quantum energy is 7.35 kev and by the simple formula the second excited state should lie at 147.0 kev. From our energy data it actually lies at 146.3 kev. The theory predicts such a deviation, and a "vibration rotation interaction" correction term of the form constant $\times I^2(I+1)^2$ subtracts from the simple energy formula. In samples of Cm^{242} the gamma transition between the 6+ and 4+ rotational states of Pu^{238} has been observed[25] and its energy measured by scintillation spectroscopy as 157±2 kev. Thus, we may check the theoretical correction term by calculating the constant using the energies of the 2+ and 4+ levels and independently using energies of the 2+ and 6+ levels. In the former case we calculate for the constant 0.0026±0.001 and in the latter, 0.0036 ±0.0015 kev. More accurate measurements of all the low-energy transition energies would be of great interest.[26]

The L-subshell conversion coefficients clearly confirm the $E2$ character of the 44- and 102-kev transitions.

The resolution of M-subshell conversion lines of the 44.0-kev transition permits some comparison with the theoretical calculations of Church and Monahan.[27] Church's threshold conversion coefficients (nonrelativistic) indicate that M shell conversion with an $E2$ transition occurs predominantly with the p electrons (M_{II},M_{III}). Such is the experimental observation here. It is interesting to note that the M_{II}:M_{III} ratio 1.37:1

[23] For a more detailed discussion on the determination of these energy differences see Rasmussen, Passell, and Stephens (reference 6).

[24] A. Bohr and B. R. Mottelson, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. **26**, 14 (1952), see p. 33.

[25] Asaro, Thompson, and Perlman, Phys. Rev. **92**, 694 (1953).

[26] *Note added in proof.*—Hollander and Smith have recently measured, with their permanent magnet electron spectrographs, the energies of 4+ to 2+ and 6+ to 4+ transitions in Pu^{238} as 101.9±0.3 kev and 157.7±0.5 kev, respectively. With these energies there is no discrepancy with the theoretical formula including the interaction term.

[27] E. L. Church and J. E. Monahan, Phys. Rev. **94**, 762 (1954).

is exactly equal to the L_{II}:L_{III} ratio obtained by Slätis *et al.*[5]

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Beta Emitter Np^{238}. II. Scintillation Spectroscopy and Coincidence Studies*

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The relative intensities of electromagnetic radiation from Np^{238}, determined by scintillation spectroscopy, set an upper limit for K capture of K/beta <1 percent.

On the basis of extensive scintillation counter coincidence measurements together with the beta spectroscopic results of the preceding article, two alternate decay schemes, differing only in minor detail, are proposed for Np^{238}. The levels of Pu^{238} involved are three close-lying ground rotational band members and a cluster of three levels near 1 Mev, two of which appear to belong to the same rotational band. Conversion coefficient determinations permit multipolarity assignment for a number of the gamma transitions and consequent spin and parity assignments for a number of excited states. Selection rules and other intensity rules involving the Bohr-Mottelson K-quantum numbers are tested, providing K-assignments for levels. There is a high degree of K-purity of those states where tests were possible. The question of possible "vibrational" character of the band near 1 Mev is discussed speculatively.

INTRODUCTION

SUPPLEMENTING the beta spectroscopic studies of Np^{238}, as reported in the preceding paper[1] (referred to here as paper I), we have carried out scintillation spectroscopic studies of the electromagnetic radiation and have also performed various coincidence studies with scintillation counting equipment. The coincidence results are of key importance in the establishment of a probable decay scheme.

SCINTILLATION SPECTROSCOPY AND THE QUESTION OF *K*-CAPTURE

The Np^{238} sample was prepared by thermal-neutron bombardment of Np^{237} in the homogeneous reactor at the University of California Radiation Laboratory, Livermore, California. The integrated neutron flux during the irradiation was sufficiently small that no significant amount of Np^{239} was formed. Chemical purification involving lanthanum fluoride precipitation followed by two TTA (thenoyltrifluoroacetone) solvent extraction steps similar to the procedures described by Magnusson, Thompson, and Seaborg[2] was made to purify the neptunium fraction from fission products and other impurities.

The 50-channel pulse-height[3] analyzer was used to study the gamma spectrum of Np^{238} from a sodium iodide scintillation crystal. This spectrum shows an unresolved photopeak near 1 Mev made up of 4 high-energy gamma rays,[1] a photopeak near 100 kev made up of 102-kev gamma and K x-rays, and a low-energy x-ray peak of about 20 kev. Scintillation spectroscopy in Stockholm showed the same peaks and no others.

The apparent resolution (ratio of energy width at half-height to photopeak energy expressed in percent) of this 1-Mev photopeak was 10.6 percent compared with 7.3 percent for the 0.84-Mev photopeak of Mn^{54} and 7.5 percent for the 1.06-Mev photopeak of Bi^{207}. This result clearly shows the composite nature of the 1-Mev peak in Np^{238}.

The 1-Mev photopeak decayed with a half-life of 2.04 days, in excellent agreement with the 2.10-day half-life previously reported by Freedman *et al.*[4]

The decay of the peak in the 100-kev region was complex. This complexity can be explained by the presence of a considerable quantity of Np^{237} and the growth of its alpha decay daughter, Pa^{233}, into the

* Much of this work was performed under the auspices of the U. S. Atomic Energy Commission.

[1] Rasmussen, Slätis, and Passell, preceding paper [Phys. Rev. **99**, 42 (1955)].

[2] Magnusson, Thompson, and Seaborg, Phys. Rev. **78**, 363 (1950).

[3] A. Ghiorso and A. E. Larsh, Jr., University of California Radiation Laboratory Report UCRL-2647, 1954 (unpublished).

[4] Freedman, Jaffey, and Wagner, Phys. Rev. **79**, 410 (1950).