The Curie temperatures for parallel and antiparallel orientation are the same.

The susceptibility above the Curie temperature is given by

$$J\chi/kc=j(n_a+n_b)^{-1}\{n_a(1-(1+y^2)^{-2}(n_a-(n_a-2)y^2+n_ay^4)h_a/h_0)+n_b(1-(1+y^2)^{-2}(n_b-(n_b-2)y^2+n_by^4)h_b/h_0)\}. \quad \text{(A7)}$$

APPENDIX B. SUMMATION FORMULAS

Let

$$\mathcal{S}'f(m)=\sum_{\pm} e^{-j\epsilon\pm}\sum_{m=-(S_1\pm\frac{1}{2})}^{S_1\pm\frac{1}{2}} f(m). \quad \text{(B1)}$$

Then

$$\mathcal{S}'(1)=2e^{-j/2}[\sinh x+R\cosh x], \quad \text{(B2)}$$

$$\mathcal{S}'(\pm 1)=2e^{-j/2}[R\sinh x+\cosh x], \quad \text{(B3)}$$

$$\mathcal{S}'(m^2)=\tfrac{1}{6}Re^{-j/2}[3R\sinh x+(R^2+2)\cosh x], \quad \text{(B4)}$$

$$\mathcal{S}'(\pm m^2)=\tfrac{1}{6}Re^{-j/2}[(R^2+2)\sinh x+3R\cosh x], \quad \text{(B5)}$$

$$\mathcal{S}'(m^4)=Re^{-j/2}[15R^3\sinh x+(3R^4+20R^2-8)\cosh x]/120, \quad \text{(B6)}$$

$$\mathcal{S}'(\pm m^4)=Re^{-j/2}[(3R^4+20R^2-8)\sinh x+15R^3\cosh x]/120, \quad \text{(B7)}$$

where $x=Rj/2$. These formuals are especially useful in computing numerical values of $P_{kl}^{(n)}(j)$ for both positive and negative values of j.

To obtain approximate expressions for the $P_{kl}^{(n)}(j)$ which are valid in the region $|j|\ll 1$, we need

$$\sum_{S_1=0}^{n/2}\omega(n,S_1)R=2^n, \quad \text{(B8)}$$

$$\sum_{S_1=0}^{n/2}\omega(n,S_1)R^3=(3n+1)2^n. \quad \text{(B9)}$$

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L X-Ray Energies of Np, Pu, and Am

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Five Np, eight Pu, and five Am *L* x-ray transitions have been observed in conventional x-ray fluorescence from 200-mg amounts of Np^{237}, Pu^{239}, and Am^{241} using a Cauchois type curved crystal transmission spectrometer. The energies of these transitions have been determined, with reference to $K\alpha_1$ lines of the elements from $_{37}$Rb through $_{47}$Ag, to an accuracy of 3 to 8 ev. Disagreement with previous measurements by Barton, Robinson, and Perlman; Jaffe, Passell, Browne, and Perlman; and Day has been found while excellent agreement with the Pu measurements of Cauchois, Manescu, and Le Berquier was obtained.

I. INTRODUCTION

THE electromagnetic spectra (gamma rays and x-rays) of transuranium nuclides have been previously investigated using bent crystal spectrometers of moderate resolution. In these studies, the x-rays resulted from either internal conversion of gamma rays which accompanied alpha decay or by fluorescence from the gamma rays. Barton, Robinson, and Perlman,[1] in this manner, first observed Np and Pu *L* x-rays. The *L* x-rays of Np resulted from the radioactive decay of Am^{241} and those of Pu from the decay of Cm^{242}. Jaffe, Passell, Browne, and Perlman[2] and Day[3] recently re-investigated the electromagnetic spectrum of Am^{241} and recorded many *L* lines of Np and Am. In another study, Cauchois, Manescu, and Le Berquier,[4] using conventional x-ray fluorescence, have examined the radiation from 10 mg of Pu with a curved crystal spectrometer of high resolution and have observed four Pu *L* lines.

We have recorded five Np *L* x-ray lines, eight Pu *L* lines, and five Am *L* lines, all observed in conventional x-ray fluorescence from approximately 200 mg of each element. The energies of these transuranium x-rays have been precisely determined and our results disagree with those of Barton *et al.*, Jaffe *et al.*, and Day. However, our Pu results are in excellent agreement with those of Cauchois *et al.* We also find that the extrapolated values of Hill, Church, and Mihelich[5] are in better agreement with our measurements than the previous determinations.

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[1] Barton, Robinson, and Perlman, Phys. Rev. **81**, 208 (1951).
[2] Jaffe, Passell, Browne, and Perlman, Phys. Rev. **97**, 142 (1955).
[3] Paul P. Day, Phys. Rev. **97**, 689 (1955).
[4] Cauchois, Manescu, and Le Berquier, Compt. rend. **25**, 1782 (1954).
[5] Hill, Church, and Mihelich, Rev. Sci. Instr. **23**, 523 (1952).

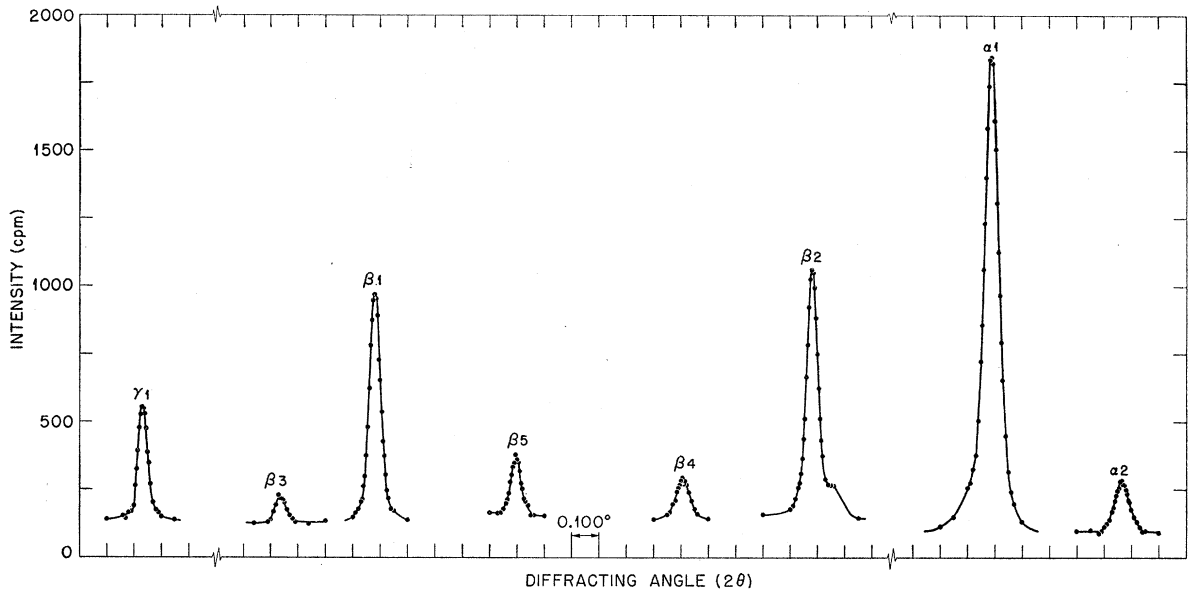

FIG. 1. Pu L x-ray transitions.

II. EXPERIMENTAL

Approximately 200 mg of each of the isotopes Np^{237}, Pu^{239}, and Am^{241} were prepared in the oxide form. Each of these compounds was then hand-loaded into specially constructed brass holders. All of the hazardous handling was carried out in glove boxes. In order to permit excitation of the sample and to minimize loss of fluorescent radiation, the sample holder contained a Be window of 1-in. dimater and 0.031-in. thickness. The Be window together with a silastic O-ring seal assured confinement of the compound.

This holder was inserted into the sample holder of a General Electric *SPG* x-ray fluorescence unit. The transuranium compounds were irradiated using a tungsten target x-ray tube operating at 40 kv dc and 20 ma with both voltage and tube current regulated. The fluorescent radiation emerged through a converging collimator and was analyzed with a 5.73-in. Cauchois type curved crystal transmission spectrometer employing the $(33\bar{1})$ planes of mica and a detector slit of 0.01° resolving width. The dispersion of the instrument, over the range used, was close to 0.25xu/0.01°. Wavelength positions on the goniometer were determined using the $K\alpha_1$ lines of the elements ranging from $_{37}$Rb through $_{47}$Ag. The $K\alpha_1$ wavelengths reported by Inglestam[6] were used as standards. Neighboring $K\alpha_1$ lines were recorded before and after each transuranium x-ray measurement. Intensities were measured using a two-atmosphere Kr-filled proportional counter and linear amplifier. In order to discriminate against radiation different in energy from that under investigation, pulses were fed through a single-channel differential pulse-height analyzer and then to a present time scaler.

[6] E. Inglestam, Nova Acta Reg. Soc. Sci. Upsaliensis 4, No. 5 (1936).

The x-ray lines were recorded by manual setting of the goniometer in steps of 0.005° through the center part of the line and 0.01° at the sides. Counts were accumulated for a one-minute time interval. Numerous runs were taken for each line and then the average number of counts at each setting was determined.

At an energy of 14 kev, the energy dispersion of the instrument is close to 4 ev/0.01° while at 22 kev the dispersion is close to 10 ev/0.01°. The uncertainty resulting from line peak determinations and goniometer error is less than 0.008° in the measurement of the stronger transuranium lines. The accuracy of our method has been checked in measuring numerous x-ray lines, including U L lines, and comparing with the values reported in the tables of Cauchois and Hulubei.[7]

III. RESULTS

Neptunium

Five lines of the Np L x-ray spectrum were recorded. Energy values were obtained using the conversion factor $\lambda_s E = 12372.2$ xu kev, given by DuMond and Cohen.[8] Table I lists these values along with the meas-

TABLE I. Np L x-ray energies in kev.

Line	Experimental energy (kev)	Jaffe *et al.*	Day	Extrapolated
α_2	13.758±0.004	13.79±0.04	13.776±0.003	13.76
α_1	13.940±0.003	13.98±0.04	13.961±0.003	13.95
β_2	16.833±0.005	16.89±0.02	16.857±0.006	16.84
β_1	17.745±0.005	17.78±0.01	17.764±0.003	17.74
γ_1	20.781±0.007	20.82±0.02	20.796±0.005	20.77

[7] Y. Cauchois and H. Hulubei, *Constantes Selectionnées, Longueurs D'Onde des Emissions X et des Discontinuites d'Absorption X* (Hermann and Company, Paris, 1947).

[8] J. W. DuMond and E. R. Cohen, Revs. Modern Phys. 25, 691 (1953).

urements of Jaffe *et al.* and Day, and the extrapolated values of Hill *et al.* Our values are lower by about 40 ev than those of Jaffe *et al.* and about 20 ev lower than those of Day. Comparison of the extrapolated values with our values shows good agreement for all lines. The extrapolated values were calculated with a slightly different conversion factor but this difference is not significant.

The resolution of our spectrometer was much higher than that used by Jaffe *et al.* and Day. All the transuranium x-ray lines which we report were completely resolved. The Np L spectrum was similar to that of Pu and the Pu L spectrum is shown in Figs. 1 and 2.

Plutonium

Eight lines of the Pu L x-ray spectrum were recorded and their energies are listed in Table II. Cauchois *et al.*

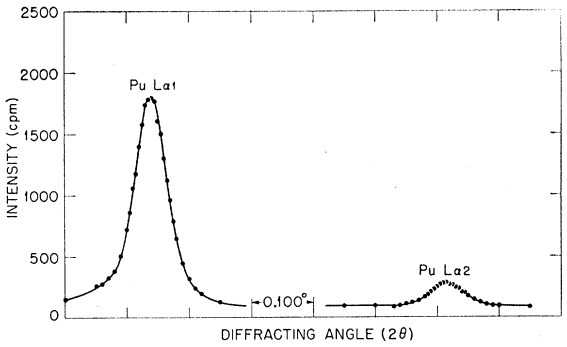

FIG. 2. Pu $L\alpha$ x-ray transitions illustrating the high resolution of the spectrometer.

have previously observed four of these lines. We have converted their wavelength values to energies and list them in Table II. These values evidently are preliminary ones and an accuracy has not been assigned. They report that their final work, however, will give results to within 2 ev. Comparison of these two sets of values shows excellent agreement on all four lines. The values by Barton *et al.* also shown in Table II, are high except for $L\beta_5$ which is a weak line. The extrapolated values again compare favorably with our measurements. The Pu L lines are shown in Figs. 1 and 2. The relative intensities of the lines are not significant because of the effects of crystal absorption, detector efficiency, and adjustment of pulse height selection. The Pu sample contained some U as an impurity and the U $L\beta_1$ line is seen on the side of Pu $L\beta_2$.

Americium

Five Am L lines were measured and the results are given in Table III along with those of Jaffe *et al.* and Day. In all cases, the Am x-rays resulted from fluorescence. Our values for Am, as they were for Np, are lower than those of Day. The better agreement of the $L\beta_1$ and $L\gamma_1$ extrapolated values with our measurements is seen. The Am spectrum was similar to that shown for Pu.

TABLE II. Pu L x-ray energies in kev.

Line	Experimental energy (kev)	Cauchois *et al.*	Barton *et al.*	Extrapolated
α_2	14.083±0.004	14.085	14.14±0.01	14.08
α_1	14.278±0.003	14.273	14.31±0.01	14.28
β_2	17.252±0.005	17.256	17.28±0.02	17.24
β_4	17.551±0.005			17.54
β_5	17.946±0.005		17.91±0.02	
β_1	18.290±0.006	18.288	18.35±0.02	18.27
β_3	18.535±0.008			18.54
γ_1	21.410±0.008		21.46±0.04	21.39

TABLE III. Am L x-ray energies in kev.

Line	Experimental energy (kev)	Jaffe *et al.*	Day	Extrapolated
α_2	14.407±0.004		14.416±0.030	14.41
α_1	14.614±0.003	14.66±0.03	14.629±0.003	14.62
β_2	17.672±0.005			17.66
β_1	18.845±0.005	18.76±0.04	18.871±0.005	18.83
γ_1	22.056±0.008		22.076±0.018	22.04

The Am used in our experiment contained Y as an impurity and a weak Y $K\alpha_2$ line was recorded. The measured energy of the Y $K\alpha_2$ line agreed well within the uncertainty of 4 ev with the value calculated from the tables of Cauchois and Hulubei.

IV. CONCLUSION

L x-ray transitions of Np, Pu, and Am have been measured by crystal diffraction using conventional x-ray fluorescence. The x-ray energies were determined with an accuracy of 3 to 8 ev. Previous measurements of the energies of transuranium x-rays resulting from radioactive decay and gamma-ray fluorescence differ. We do not believe that the energies of transuranium x-rays are dependent on the manner of production to the extent of the energy differences reported.

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