# Letters to the Editor

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## Radioactivity Induced in Iridium by Neutron Capture*

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EARLY studies[1] of iridium showed the presence of two long-lived induced radioactivities of half-lives about 19 hours and 70 days, presumably derived from the two stable isotopes of mass 191 (38.5 percent) and mass 193 (61.5 percent). Further investigations[2] have identified the longer-lived activity, now found to be 78 days, as due to radioactive $Ir^{192}$, and the 19-hour activity as due to $Ir^{194}$.

Spectrometric studies showed the presence of many electron lines associated with the 78-day activity, and from an evaluation of the gamma-rays a tentative nuclear level scheme had been proposed. With the increased neutron flux of the Argonne pile, a source of much higher specific activity has now been obtained and found to yield many previously unobserved electron lines. It is evident that certain of the long-lived electron lines have $K$–$L$–$M$ differences characteristic of osmium ($Z=76$) and are thus emitted following $K$-capture in $Ir^{192}$. The remainder, except for six weak lines, have $K$–$L$–$M$ differences of platinum ($Z=78$) and hence are emitted following the competing beta-decay. While the electron energies are in many cases very close to the previously reported values, the many new lines and the present interpretation lead to a considerable change in the nuclear level scheme.

TABLE I. Summary of electron lines.

| Electron energy (kev) | Relative intensity | Interpretation | Gamma-energy (kev) | Electron energy (kev) | Relative intensity | Interpretation | Gamma-energy (kev) |
|---|---|---|---|---|---|---|---|
| 49.9 | 1 | $A(\alpha-L)$ 76 | | 229.6 | 7 | $K^8$ 78 | 307.7 |
| 52.6 | $W$ | $A(\alpha-L_I)$ 78 | | 237.9 | 10 | $K^9$ 78 | 316.0 |
| 55.0 | $W$ | $A(\alpha-L_{III})$ 78 | | 282.0 | 4 | $L_I^7$ 78 | 295.6 |
| 57.5 | 2 | $A(\beta-L)$ 76 | | 284.1 | 2 | $L_{III}^7$ 78 | 295.6 |
| | | and $K^1$ 78 | 135.6 | 292.5 | 1 | $M^7$ 78 | 295.6 |
| 60.5 | 1 | $A(\alpha-M)$ 76 | | 294.4 | 3 | $L^8$ 78 | 308.0 |
| 63.4 | $W$ | $A(\alpha-M)$ 78 | | 301.0 | 5 | $L_I^9$ Pb | 316.8 |
| 68.0 | $W$ | $A(\beta-M)$ 76 | | 302.5 | 5 | $L_I^9$ 78 | 316.1 |
| 77.5 | $W$ | $K^2$ 76 | 151.0 | 304.7 | 1 | $L_{III}^9$ 78 | 316.2 |
| | | or $K^2$ 78 | 156.0 | 313.0 | 3 | $M^9$ 78 | 316.3 |
| 97.5 | $W$ | $K^3$ 76 | 169.0 | 315.4 | $W$ | $N^9$ 78 | 316.1 |
| | | or $K^3$ 78 | 173.0 | 322.0 | $W$ | $K^{10}$ 76 | 396.0 |
| 122.4 | 2 | $L_I^1$ 78 | 136.0 | | | or $K^{10}$ 78 | 400.0 |
| 124.6 | $W$ | $L_{III}^1$ 78 | 136.1 | 337.0 | 1 | $K^{11}$ 78 | 415.1 |
| 127.2 | 2 | $K^4$ 76 | 201.0 | 360.3 | $W$ | $K^{12}$ 76 | 434.0 |
| 131.9 | 6 | $K^5$ 76 | 205.7 | | | or $K^{12}$ 78 | 438.0 |
| 133.5 | $W$ | $M^1$ 78 | 136.8 | 380.2 | 4 | $K^{13}$ Pb | 467.8 |
| 135.5 | $W$ | $N^1$ 78 | 136.1 | 389.3 | 4 | $K^{13}$ 78 | 467.4 |
| 188.6 | $W$ | $L^4$ 76 | 201.2 | 402.7 | $W$ | $L^{11}$ 78 | 416.6 |
| 193.1 | 4 | $L_I^5$ 76 | 205.7 | 410.3 | 2 | $K^{14}$ 76 | 484.0 |
| 195.1 | $W$ | $L_{III}^5$ 76 | 206.0 | 454.0 | 3 | $L^{13}$ 78 | 467.6 |
| 198.0 | $W$ | $M^4$ 76 | 201.1 | 464.7 | 2 | $M^{13}$ 78 | 468.0 |
| 200.6 | $W$ | $N^4$ 76 | 201.1 | 466.8 | $W$ | $N^{13}$ 78 | 467.5 |
| 202.9 | 1 | $M^5$ 76 | 206.0 | 510.5 | 1 | $K^{15}$ 78 | 588.6 |
| 206.1 | $W$ | $N^5$ 76 | 206.7 | 525.6 | 2 | $K^{16}$ 78 | 603.7 |
| 207.8 | 9 | $K^7$ Pb | 295.4 | 533.1 | 1 | $K^{17}$ 78 | 611.2 |
| 209.2 | $W$ | $K^6$ 76 | 283.0 | 574.5 | $W$ | $L^{15}$ 78 | 588.1 |
| 216.8 | 9 | $K^7$ 78 | 294.9 | 590.7 | $W$ | $L^{16}$ 78 | 604.3 |
| 220.2 | 7 | $K^8$ Pb | 307.8 | 599.5 | $W$ | $L^{17}$ 78 | 613.1 |
| 227.9 | 10 | $K^9$ Pb | 315.5 | | | | |

Legend: $A$—Auger; $\alpha$—$K_{\alpha_1}$ x-ray; $\beta$—$K_\beta$ x-ray; 10—very strong, 1—weak, $W$—very weak.

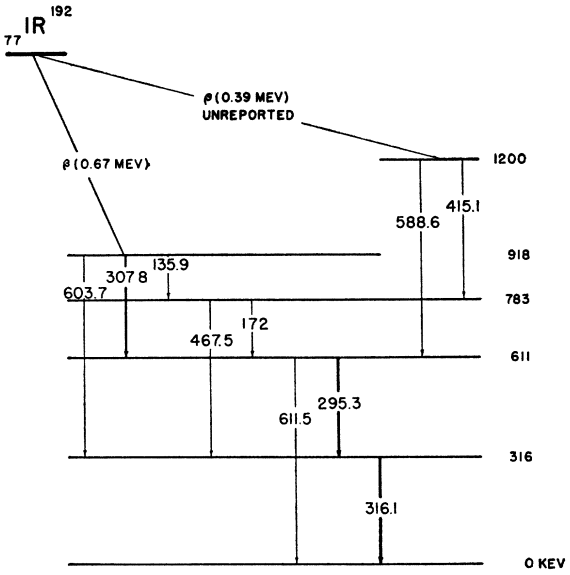


FIG. 1. Proposed nuclear energy levels in $_{78}Pt^{192}$ following $\beta$-emission from $Ir^{192}$.

In all, about 45 electron lines are observed in the energy range from 49 kev to 600 kev, as shown tabulated in column 1, Table I. In addition to the internal conversion electrons, photoelectrons from a lead radiator were also observed. An estimate of the relative intensity of each line is given in column 2. The proposed identifica-

TABLE II. Summary of gamma-rays.

| Arbitrary designation | Gamma-energy (kev) $Z=76$ | $Z=78$ | Arbitrary designation | Gamma-energy (kev) $Z=76$ | $Z=78$ |
|---|---|---|---|---|---|
| 1 | | 135.9 | 10 | 396 or | 400 |
| 2 | 151 or | 156 | 11 | | 415.1 |
| 3 | 169 or | 173 | 12 | 434 or | 438 |
| 4 | 201.1 | | 13 | | 467.4 |
| 5 | 205.7 | | 14 | 484 | |
| 6 | 283 | | 15 | | 588.6 |
| 7 | | 294.9 | 16 | | 603.7 |
| 8 | | 307.7 | 17 | | 611.2 |
| 9 | | 316.1 | | | |

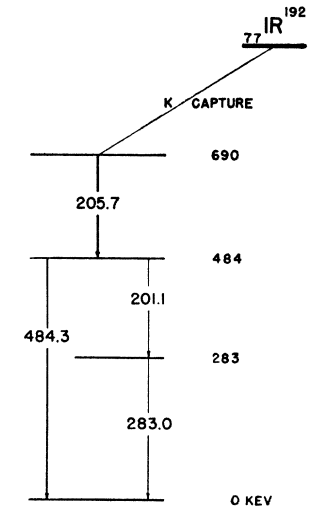


FIG. 2. Proposed nuclear energy levels in $_{76}Os^{192}$ following $K$-capture in $Ir^{192}$.

tion of each electron line is presented in column 3 and the resultant gamma-energies in column 4. Arbitrary superscripts are used to denote the gamma-rays increasing in order with the energy. Seven of the low energy electron lines are of Auger origin, as noted in column 3. A summary of the energies of the gamma-rays associated with each process is offered in Table II.

It is now possible to arrange a scheme of 6 levels for the excited platinum 192 nucleus as shown in Fig. 1, which is satisfied remarkably well by 10 of the observed gamma-rays. A proposed level scheme for the osmium 192 nucleus is portrayed in Fig. 2. The $K$-capture process is also substantiated by the presence of Auger lines characteristic of osmium. Six of the weaker electron lines do not enter in $K$–$L$ combinations and are assumed to be $K$ lines for either osmium or platinum. A choice is made for the two gamma-rays designated as 6 and 14, since their energies fit satisfactorily in Fig. 2.

The early exposures of the freshly irradiated specimen showed a few electron lines which did not appear on later photographic plates, indicating that they were associated with the 19-hour radioactivity in $Ir^{194}$. From the electron energies, a single gamma-ray of energy 327.5 kev is indicated for the $Pt^{194}$ nucleus. A similar energy has been known to exist in the $K$-capture decay of $Au^{194}$.

* This project was made possible by the joint support of the ONR and AEC.

[1] J. Cork and R. Thornton, Phys. Rev. **51**, 59 (1937); McMillan, Kamen, and Ruben, Phys. Rev. **52**, 375 (1937).

[2] M. Deutsch, Phys. Rev. **64**, 265 (1943); J. Cork, Phys. Rev. **72**, 581 (1947); M. Levy, Phys. Rev. **72**, 352 (1947); R. Hill and W. Meyerhof, Phys. Rev. **73**, 812 (1948).

## On Some Recent Calculations on Cascade Shower Theory

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THERE have recently appeared a number of works[1-3] on the electron-photon cascade theory. In each case the authors were concerned with the solution of the diffusion equations of the cascade theory of electron showers when the ionization loss term was included. Bhabha and Chakrabarty[4] developed an elegant and simple series solution of the diffusion equations and showed that the first two terms of the series gave results which were quite satisfactory for all practical purposes. It was also pointed out by Jánossy and Messel[5] that the solutions given by B.C. could be quickly and easily evaluated. Their solutions have also the added advantages:

(a) the first-order correction for the effects of ionization loss is expressed as a shift of the energy spectrum by an amount of the order of the critical energy,

(b) the series may be used either to evaluate the number of electrons $[N(E, t)]$ or photons $[\gamma(E, t)]$ above a specified energy $E$ (and this is the physically important quantity), or to evaluate the total number of electrons $[N(0, t)]$ or photons $[\gamma(0, t)]$ at various depths $t$.

In the meantime Snyder[2] developed solutions of the cascade equations using a different approach. He showed that the solution of the cascade equations could be reduced to the solution of certain difference equations. The method is fairly long and is far from yielding solutions which lend themselves to easy computation. In fact, the solutions given by Snyder are of practical value only for computing the total number of electrons or photons for $E=0$, at various depths. In order to obtain results for any other value of $E$, the evaluation of a triple complex integral is required. This in itself is a serious drawback. Snyder also pointed out that his solutions yielded values for $N(0, t)$ at the cascade maximum which were about 35 percent higher than those obtained by B.C., who used the first two terms of their series. Hence, it was concluded that the results of B.C. were inaccurate. At the same time Snyder pointed out that for a shower initiated by an electron of energy $E_0$

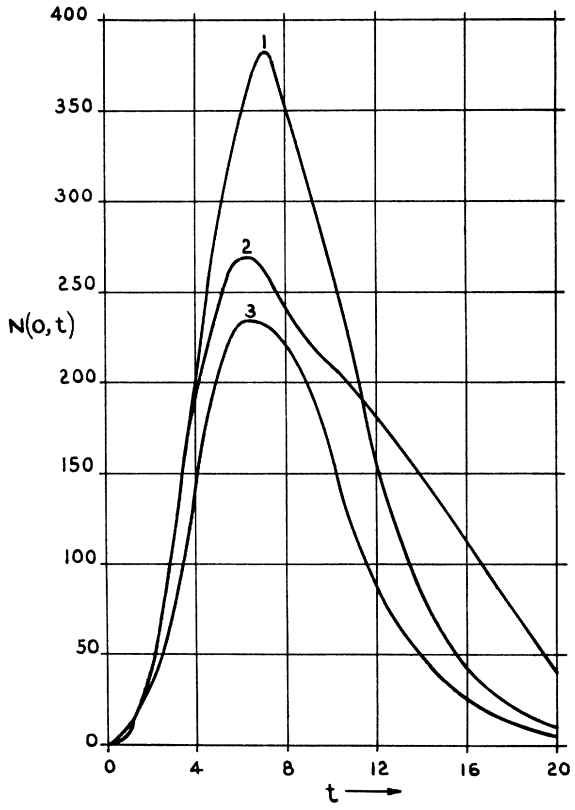


FIG. 1. $N(0, t)$, the average number of electrons induced by an incident electron of energy $E_0$, plotted against the depth $t$ in cascade units. We have marked the curve given by Snyder's solution 1, that given by Bernstein for lead 2, and that by B.C. 3. In each case $\ln E_0/\beta = 8$.

$$\int_0^t N(0, t)dt = E_0/\beta, \tag{1}$$

where $\beta$ is the ionization loss. He then mentioned that the first two terms of the B.C. solution contribute only 70 to 85 percent of $E_0/\beta$ and hence these authors did not use a sufficient number of terms of their series. B.C. had given in their paper a very satisfactory explanation for the above, which appears to have been overlooked by both Snyder and Bernstein.[3] We quote from reference 1.

"From the physical point of view, however, Eq. (1) must be taken with caution, especially in substances of high atomic number where the critical energy is low. It is not true that all the energy of a cascade is dissipated by the collision loss of cascade electrons alone. A good deal of energy is lost in the form of quanta of energy less than $2\ mc^2$ which are incapable of further pair creation. Thus the complete series for $N(0, t)$ must give too many cascade electrons of low energy at large thicknesses, and the first two or three terms of the series may well give a truer picture of the physical process in substances of high atomic number."

Bernstein lately has taken Snyder's solution and applied to it a correction by means of a perturbation method. He used a more refined approximation to the Bethe-Heitler cross sections than had hitherto been used. The method employed by Bernstein is straightforward but naturally even more tedious than that of Snyder—and again of the same limited applicability. From Bernstein's results there evolves an interesting feature. He finds that Snyder's results give a value for $N(0, t)$ which is much too high at the cascade maximum. We have plotted in Figs. 1 and 2 the results