Letters to the Editor

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Communications should not in general exceed 600 words in length.

Effect of Neutron Energy on the Total Decay Curves of Fission Products

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THE study of the total decay curve of the fission products of U collected by recoil was first made by Joliot[1] using chiefly Rn-Be neutrons. A marked increase in the ratio of the intensity of long periods (~1 hour) to that of short periods (~15 min.) was produced when the source and target were surrounded by paraffin. Later, Bjerge, *et al.*,[2] using neutrons from Li plus deuterons (0.75 Mev) found that within ±10 percent the decay curves were identical for U+fast neutrons, U+C neutrons, and Th+fast neutrons. This proved true for both irradiations of a few minutes and of 100 minutes. Frisch[3] showed that the results of Bjerge *et al.* (Table I) fitted reasonably well the curve

$$J_T(t)=\text{const.}\ (t^{-1/n}-(t+T)^{-1/n}), \qquad (1)$$

where T is the time of irradiation, t the time of decay and n is from the Sargent law $\lambda=kE^n$ $(n=5)$. This result is calculated on the assumption that all energies have equal statistical weight. Thus the results of Bjerge *et al.* would not indicate that the products of U^{235} (C neutrons) were necessarily identical with those of U^{238} (fast neutrons) but only that the number of periods present was so large as to smear out any differences.

In the spring of 1940 at Paris, the author, at the suggestion of Professor Joliot, undertook to resolve, if possible, the discrepancies between the Paris and Copenhagen measurements and also to extend them to higher energies. *Very incomplete* measurements (cut off by the fall of France) with Rn-Be neutrons, seemed to confirm the difference previously observed by Joliot. Furthermore the results with C neutrons, in accord with Joliot's previous work, failed to agree with the Frisch formula by a factor of 2.

The experiments were continued for high energies during the summer of 1940 with neutrons from the Harvard cyclotron. The results are shown in curves *A*–*E*, Fig. 1, and in Table I in descending order of neutron energy.[4] The deuteron beam was controlled by hand and the mean current was estimated and held constant by taking readings every half-minute. The good agreement between the successive runs of curve *A*, and also of curve *B*, testifies to the reproducibility of the decay curves. Except possibly for curve *C*, deviations due to varying beam current were undoubtedly less than 5 percent.

The counting system consisted of an alcohol argon counter with 0.010″ brass walls. It was used with a scale of 32. The whole was checked for additivity and a resolving time of 2.3×10^{-4} sec. was found. A blank fission-catcher was placed behind the actual catcher on each run and its activity was subtracted. A constant radioactive source was used at intervals during each run to check the constancy of the counter.

Curve *E* (thermal and low energy fast neutrons) agrees excellently with Frisch's equation (Table I) and thus with Bjerge's curves for both thermal and fast neutrons.

The shape of the other curves does not vary rapidly with energy, although numerous additional products[5] are

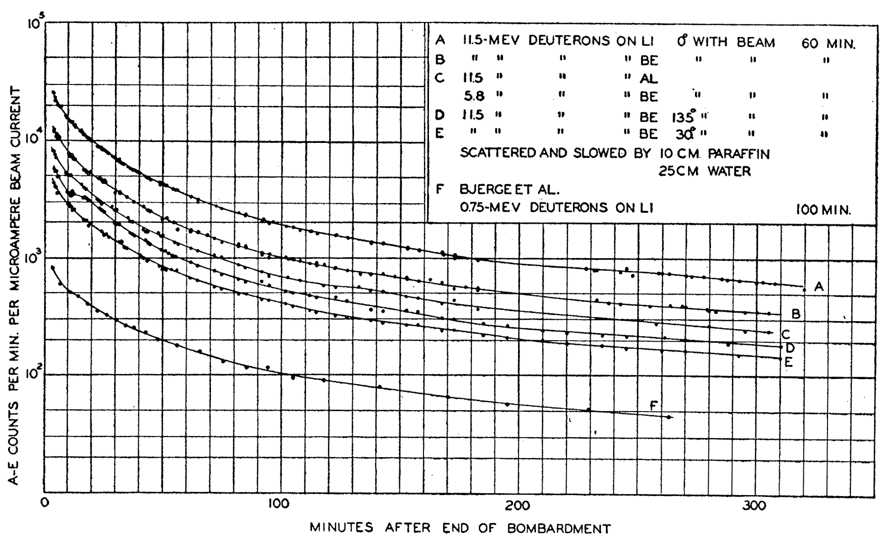

FIG. 1.

TABLE I. *Relative number of counts from decay products.*

MIN. AFTER IRRADIATION	FRISCH 60 MIN.	FRISCH 100 MIN.	*A*	*B*	*C*	*D*	*E*	*F* BJERGE ET AL.
4	28.1	20.4	36.6	33.7	31.4	30.4	28.0	19.7
10	17.6	13.5	23.5	22.0	20.4	19.3	18.6	13.2
20	11.6	9.3	15.3	14.4	14.2	15.5	12.3	9.81
40	6.97	5.98	8.06	7.85	7.55	7.78	6.98	6.05
60	4.92	4.40	5.28	4.95	5.06	4.99	4.64	4.29
100	3.15	2.93	2.94	2.84	2.80	2.86	2.79	2.66
140	2.25	2.14	2.11	2.08	2.15	2.06	1.95	2.02
180	1.74	1.68	1.58	1.58	1.61	1.51	1.56	1.62
240	1.27	1.26	1.25	1.19	1.25	1.20	1.18	1.26
300	1.00	1.00	1.00	1.00	1.00	1.00	1.00	—

known to result from fission at high energies. There does seem, however, with increasing energy, to be a definite tendency towards shorter periods (Table I) which amounts to nearly 30 percent in the case of bombardment with Li neutrons. Since these are composite curves of many parent and daughter products, a 20–30 percent change at 4 to 10 min. might indicate a considerably larger increase at $\frac{1}{2}$ to 1 min. It thus appears that not only are new products formed, but also the new parent substances have *shorter periods*, and their probabilities of formation are relatively large at neutron energies of 10–25 Mev.

Circumstances have prevented the continuance of this work such as the investigation of very short periods and of the irregularity in curve *D* and a conclusive check on the Joliot-Bjerge discrepancy. Because of larger intensities, the Copenhagen results are probably more reliable.

The author wishes to express his gratitude to Professor Joliot and to the Institute of International Education and Williams College, under whose auspices he was privileged to work in Paris, and to acknowledge with deep appreciation the kindness of Harvard University, and the assistance of Drs. I. A. Getting, E. P. Clancy and L. Fussell.

[1] F. Joliot, J. de phys. et Rad. **10**, 159 (1939).
[2] T. Bjerge, K. J. Brostrøm and J. Koch, Nature **143**, 794 (1939).
[3] O. R. Frisch, Nature **143**, 852 (1939).
[4] The neutrons of curve *C* were considered to be of higher energy than those of curve *D* because the activity of the control relative to the fission was 15 percent less for *D* than for *C*, 20 percent less than for *B*, and $<\frac{1}{3}$ of *A*.
[5] Y. Nishina, T. Yasaki, H. Ezoe, K. Kimura and M. Ikawa, Nature **146**, 24 (1940); Y. Nishina, K. Kimura, T. Yasaki and M. Ikawa, Phys. Rev. **58**, 660 (1940); **59**, 323 (1941); E. Segrè and G. T. Seaborg, Phys. Rev. **59**, 212 (1941).

Lifetimes of Nuclear Levels with Respect to Electric Multipole Radiation

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THE liquid drop model has been used to estimate the lifetimes of nuclear excited levels with respect to electric multipole γ-ray emission involving various changes in angular momentum and different excitation energies.[1] The purpose of this note is to give the results of a calculation of these lifetimes by a method which avoids some of the approximations usually made, beyond those already embodied in the liquid drop model. The distortion of the nucleus is assumed to be given by

TABLE I. *Lifetimes of nuclear states for various excitation energies and angular momentum changes.*

ENERGY OF EXCITATION (EV)	CHANGE IN ANGULAR MOMENTUM $l=2$	$l=3$	$l=4$	$l=5$
10^4	1.5×10^{-5} sec.	0.83 hr.	3.5×10^4 yr.	2.0×10^{13} yr.
5×10^4	2.3×10^{-8} sec.	0.20 sec.	33 days	2.0×10^6 yr.
20×10^4	9.3×10^{-11} sec.	4.8×10^{-5} sec.	43 sec.	1.9 yr.

$$\mathbf{r}'-\mathbf{r}=a^2\nabla\sum_{l=2,m}^{l=\infty}\frac{\alpha_{lm}}{l}Y_{lm}(\theta,\varphi)\left(\frac{r}{a}\right)^l, \qquad (1)$$

a being the nuclear radius, Y_{lm} a real spherical harmonic normalized to unity, while $\mathbf{r}'$ represents the vector to a point in the distorted nucleus whose position in the undistorted nucleus is given by $\mathbf{r}$.[2] Since in an excited state, the α's will be given by $\alpha_{lm}=\overset{(0)}{\alpha_{lm}}\sin\omega_l t$, the total energy of these vibrations is

$$E=\frac{3a^2}{2\pi}AM\sum_{l=2,m}\omega_l^2\overset{(0)}{\alpha_{lm}}{}^2\frac{2l+1}{l},$$

AM being the mass of the nucleus.[3]

We make use of the classical expression for the rate of radiation from such a system of currents

$$I=\frac{1}{8\pi}\int|\mathbf{n}\times\mathbf{j}|^2d\Omega,$$

where

$$\mathbf{j}=\int\mathbf{j}_0(\mathbf{r})\exp(i\omega\mathbf{r}\cdot\mathbf{n}/c)d\tau,$$

provided the current density at $\mathbf{r}$ is given by $\mathbf{j}_0(\mathbf{r})\cos\omega t$. In the evaluation of this integral for $\mathbf{j}$, it is convenient to use the expansion

$$e^{ikz}=\sum(2l+1)i^l(\pi/2kr)^{\frac{1}{2}}J_{l+\frac{1}{2}}^{(kr)}P_l(\cos\theta),$$

the amplitude of the current density being obtained from (1). For the lth mode of vibration, we have

$$I=\frac{9Z^2e^2}{8\pi}\frac{\overset{(0)}{\alpha_{lm}}{}^2}{c^{2l+1}}\frac{l+1}{l(2l+1)}\frac{\omega^{2l+2}a^{2l}}{1^2\cdot3^2\cdots(2l-1)^2},$$

where it has been assumed that all the α's belonging to a given l and different m values are equal. In obtaining this result, the integral for $\mathbf{j}$ has been evaluated by retaining only the first term in the power series expansion of the Bessel function.[4]

For the mean lifetime τ_l of a level with given l value, we have

$$\frac{1}{\tau_l}=\frac{3}{4}\frac{Z^2e^2}{c}\frac{l+1}{AMa^2}\frac{(a\omega/c)^{2l}}{1^2\cdot3^2\cdots(2l+1)^2}.$$

We have calculated the lifetimes in Table I from this formula for the case of Hg, using a radius $a=\frac{1}{2}A^{\frac{1}{3}}e^2/mc^2$.

In conclusion, I should like to acknowledge my indebtedness to my colleague E. Feenberg for helpful discussions.

[1] H. A. Bethe, Rev. Mod. Phys. **9**, 226 (1937).
[2] Terms in $l=0$, 1 are absent because of the conditions of incompressibility and fixed center of gravity.
[3] Strictly, the frequencies occurring here are determined by the surface and Coulomb energies, whereas we regard them as parameters.
[4] In the derivation of Bethe mentioned above, an order of magnitude estimate of the integral is used.