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February 14, 1950

Transition Curves in Lead. X-Rays Causing Nuclear Reactions.

I. Experimental. Karl Strauch.

In order to measure the resonance energies for various nuclear mutations induced by x-rays, a series of foils of different materials were sandwiched between lead plates (see Fig. 1) and exposed to the x-ray beam from the synchrotron at maximum energies of 335 Mev and 214 Mev. The activities induced in the foils were counted and recorded as functions of the thickness of lead preceding the foil as shown in Fig. 2 for the reaction $Cu^{63}(\gamma,n)Cu^{62}$. Table 1 shows the relative yields, peak energies, and total cross sections relative to carbon for a number of materials for which cross sections have been measured.

Two nuclear processes are of importance in an attempt to interpret transition curves. Photons of all energies produce positron-electron pairs with a frequency that is a function of their energy. Electrons that are formed through pair production are capable of again releasing photons by bremsstrahlung.

The transition curve of Fig. 2 can be discussed in terms of these processes. The initial branch with negative slope is indicative of the preponderance of absorption of 20 Mev x-rays over the creation of additional 20 Mev photons by the combined action of pair production and bremsstrahlung. These two processes, however, with increasing thickness of lead tend to create a supply of photons that exceeds the number that is lost by absorption with the result that, after passing through a minimum, the curve rises. As the thickness of lead increases still further, a gradual depletion of potential 20 Mev photons is observed so that after passing through a maximum the transition curve decreases exponentially.

The area under the transition curve is of importance since it is the datum that is used to calculate the average energy for the mutation. Therefore, a comparison of the ratios of the areas under the transition curves for 214 Mev and 335 Mev as obtained experimentally and theoretically constitutes an important check of the validity of the theory:

	Cu	C
Theoretical	1.55	1.50
Experimental	1.51	1.43

The relative yields noted in Table 1 show the surprising result that the $Zn(\gamma,pn)$ cross section is larger than the $Zn(\gamma,2n)$.

II. Theoretical. Leonard Eyges.

If one accepts the hypothesis that the nuclear reactions which were discussed in Part I are caused by photons whose energies in each case fall into a narrow band of energies, then, after having determined the characteristic energy of incitation of the reactions, one can employ shower theory in calculating the transition curves. A transition curve depicts the variation with thickness t of absorber of $\gamma(w_o,w,t)$ the number of photons of energy w in a beam of maximum energy w_o. It is calculated by accounting for the various ways in which photons of the desired energy w can arrive at a thickness t. In making this account one must employ the probability $\phi(E_1w)$(see Fig. 3) for the creation of a photon of energy w by an electron of energy E through the mechanism of bremsstrahlung. And in the calculation of the number of electrons of appropriate energies one must know the probability $\psi(E_1w)$ (see Fig. 4) of creation of electrons by pair production and the decrease in the energy of electrons by ionization. The mathematical techniques that were available made it necessary to approximate the true picture of events by one where average values are used for the energies of electrons and photons that initiate production of photons by bremsstrahlung and of electrons by pair production.

This simplification has little effect on the results of calculations when one is dealing with the initial downward branch of the transition curve where only a small amount of multiplication and diminution of energy has taken place.

Ultimately, the use of such average values has the effect of widening divergence between experimental and calculated results. In the computation of w, the mean excitation energy, for the reaction $Cu^{63}(\gamma,n)Cu^{62}$ the error that is introduced by using average energies for the initiating particles may contain a contribution of 5 percent from the bremsstrahlung function and 35 percent from the pair production function.

The mean excitation energies for the reactions was obtained by equating the areas under the experimental transition curves to a formula containing the quantities w and w_o as variables:

$$\text{area under curve} = \int_0^\infty \gamma\ (w_o,w,t)\ dt = \frac{.38}{\sigma(w)}\ \frac{w_o}{w}\ \frac{\left\{\frac{4}{3}\left(1-\frac{w}{w_o}\right)+\frac{3}{4}\left(\frac{w}{w_o}\right)^2\right\}^2}{\left(1+.79\frac{\beta}{w}-.29\left(\frac{\beta}{w}\right)^2+\ldots\right)}$$

Here $\sigma(w)$ represents the absorption coefficient for photons and $\beta = 7$ Mev, the critical energy.

The initial minimum of the transition curve can be calculated fairly accurately by means of the equation

$$\gamma_o\ (w_o,w,t) = e^{-\sigma(w)t}\left[1 + f\ (w_o,w)\ t^2 + \ldots\right]$$

The mean energy that induces the reaction $Cu^{63}(\gamma,n)Cu^{62}$ was found to be ~ 20 Mev. This result agrees closely with the experimental findings of other investigators.

Table 1

	Relative Yield	Energy (Mev)	σRel. $= \int \sigma(E)\, dE$
$C^{12}(\gamma,n)$	1.0	30	1.0
$Cu^{63}(\gamma,n)$	14	20	9.3
$Cu^{65}(\gamma,n)$	17	(20)	(n)
$Zn^{64}(\gamma,n)$	11	21	7.7
$Zn^{64}(\gamma,2n)$	1.0	32	1.1
$Zn^{64}(\gamma,pn)$	3.2	34	3.0

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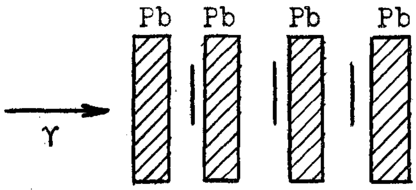

Fig. 1

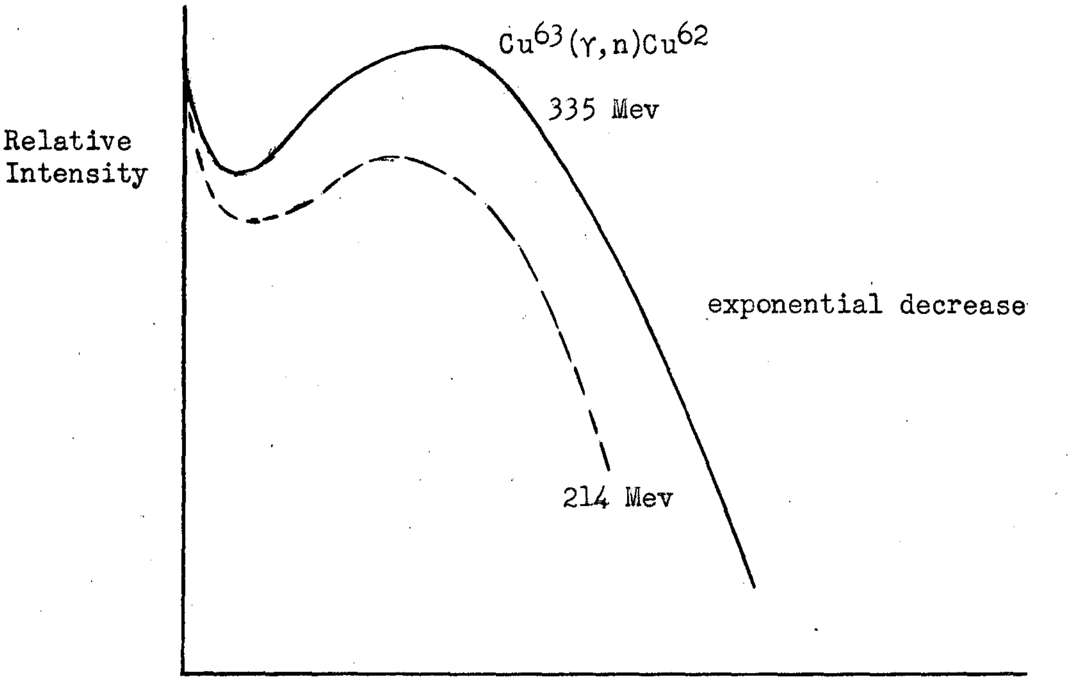

Fig. 2

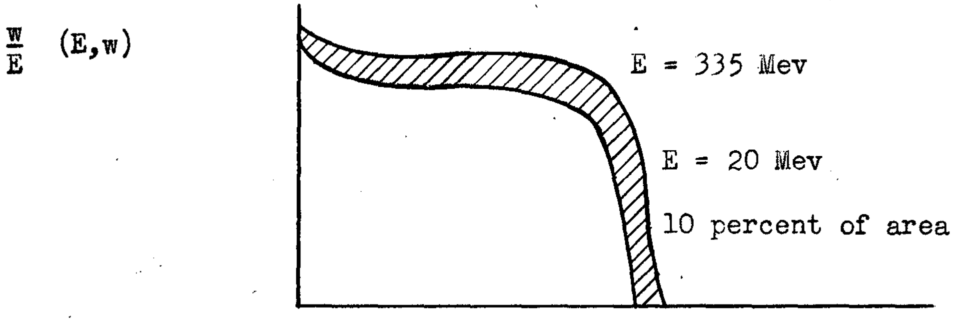

Fig. 3
Cross section for Bremsstrahlung

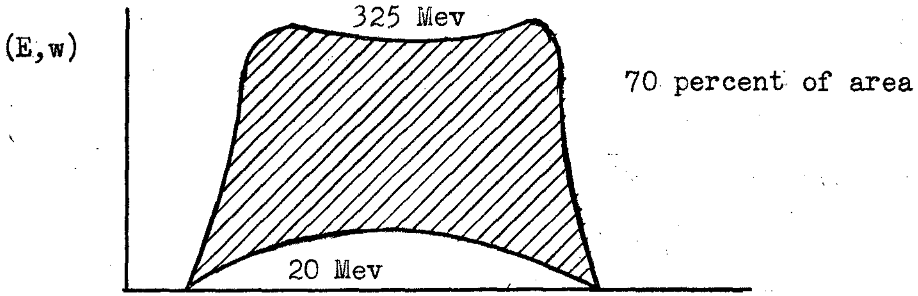

Fig. 4
Cross section for pair production