Nuclear Isomerism

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CONTENTS

I. HISTORY*

As far back as 1917 Soddy (S1), in developing his general considerations about isotopy, considered the possibility of the existence of nuclei having the same charge and the same mass but still not identical. Such nuclei would be isotopic (same charge) and isobaric (same mass) and could be distinguished only by some other properties, particularly radioactive ones. They would have the same chemical properties and even the mass spectrograph could not distinguish them unless it could resolve mass differences of the order of 10^{-5} mass unit. This type of relation between two nuclei has sometimes been called (P1) isotopy of the second kind as distinguished from the isotopy of nuclei having different masses. It is now called isomerism.

These speculations were not substantiated by experiment until 1921 when Hahn (H1) discovered a radioactive substance $UZ(Pa_{91}^{234})$ which was isotopic and isobaric with the well-known UX_2 but differed from it with respect to the half-life (6.7 hr. instead of 1.15 min.) and with respect to the type of radiation emitted. The proof given by Hahn of the isomerism of UZ and UX_2 was based upon the fact that both grew out of $UX_1(_{90}Th^{234})$ by beta-decay and hence were isobaric with it and had an atomic number of $90+1=91$.

This example of isomerism remained unique for many years, and, in view of the serious theoretical difficulties which were thought to affect any possible explanation of it, it was very desirable to find some further similar instances. In the meantime, further work by Hahn (H2), Guy and Russell (G1), and Walling (W1) had confirmed Hahn's results, and finally the case of UZ has recently been investigated very thoroughly by Feather, Bretscher, and Dunworth (F2) and Bradt and Scherrer (B7).

The discovery of artificial radioactivity in 1934, and especially the wide enlargement of the field of investigation by the production of many new radioactive substances by neutron bombardment, afforded the opportunity of finding new examples of isomerism. The first indication was found in indium by Szilard and Chalmers (S3), and the first established case was that of bromine investigated by Kurchatov (K1) and collaborators, and by Fermi and his colleagues (A1).

They found that the radio-bromines produced by neutron bombardment of bromine showed three different radioactive periods of 18 min., 4.4 hr., and 34 hr. All of them were "water sensitive," i.e., were more effectively produced by slow than by fast neutrons, and were hence attributed to neutron capture. On the other hand, bromine has only two stable isotopes, one of mass 79 and the other of mass 81. The three radioactivities had to be assigned, therefore, to bromine isotopes of mass 80 and 82 and hence at least two must be due to isomers. A special investigation by Blewett (B1) ruled out the additional possibility, rather remote in view of the well-known fact that no nuclei with odd atomic number have more than 2 stable isotopes, of the existence of a third rare, stable isotope (abundance less than 1/3000), and hence isomerism

* Flügge (F1) and Stuhlinger (S34) have reviewed this subject as of 1941, and Pontecorvo (P3) has discussed results up to 1939. Berthelot (B11) has also given a general discussion in connection with his work on Br^{80}. The only recent discussion in English is in notes of lectures by Dancoff (D21).

in bromine could be considered proved. Subsequent work by Bothe and Gentner (B2) and Snell (S2) confirmed the previous results and showed that the 18-min. and 4.4-hr. periods were both due to $_{35}Br^{80}$.

The evidence for isomerism was thus accumulating and the next important step was made by v. Weizsäcker (W2), who first suggested a theoretical explanation of isomerism in agreement with the experimental facts and with current theoretical ideas. It had often been surmised that nuclear isomers might be nuclei in an excited metastable state, but this hypothesis seemed unacceptable because it was thought that there was no mechanism to insure a sufficiently long half-life for the metastable states; Weizsäcker showed that by assigning to the excited states spins differing by a few units (up to 5) from the fundamental state and energy up to a few hundred kilovolts, the half-life for reversion to the fundamental state by gamma-emission becomes long enough to allow for the existence of observable isomers. As a matter of fact this explanation was thought to be untenable before Weizsäcker's work because the half-lives for gamma-emission were estimated to be of the order of 10^{-13} second so that all nuclei should practically always be found in the fundamental state.

Weizsäcker's theory gave new impetus to the investigation of isomerism because it pointed out some consequences about internal conversion, etc. (Pontecorvo, (P2); Segrè and Seaborg, (S4)), which were confirmed experimentally.

Finally, direct proof of the growth of one isomeric state from another was given by Segrè and colleagues by chemical separation (S5).

At present more than 75 pairs of isomeric nuclei are known and the known number is increasing continuously.

II. INTRODUCTION

As we have stated above, we call "isomeric" two nuclei which have the same mass and charge, but differ by some other nuclear property, e.g., radioactive half-life. The word "isomer" is borrowed from organic chemistry in which it indicates substances with the same formula but with the atoms arranged differently so as to have different properties. A type of explanation for isomerism which depends on structural differences does not seem to be applicable to atomic nuclei. In organic molecules the nuclei of the component atoms are practically at rest, or better, vibrate around fixed equilibrium positions with amplitudes small compared with the intranuclear distances, so as to build a semirigid permanent skeleton in which electrons circulate. The situation is entirely different in nuclei. Here it is assumed that neutrons and protons interact very closely and move throughout the nucleus so that no particular configuration lasts for any appreciable time. Whereas an organic molecule resembles a small crystal, a nucleus resembles a liquid drop. The justification of this assumption is found in the uncertainty principle and in the known size of the nuclei and strength of nuclear forces (W3).

The possibility that the nucleus, considered as a liquid drop, can exist in a stable spherical state, and also a stable ellipsoidal state, has been discussed by Flügge (F1). Calculations of Feenberg (F13) and v. Weiszäcker (W19) show that two such stable forms could exist only for $44 \leqslant Z^2/A \leqslant 50$, and for U^{238}, $Z^2/A = 36$, and further calculations by Wick (W20) indicate that even these states may not be stable against deformations into other geometric shapes. Hence, though this idea may have some importance in the considerations of very heavy nuclei, it can have no bearing on the problem of isomerism in the known elements. A few other suggestions have been put forward and are discussed by Flügge, but none seem reasonable in the light of present evidence (see discussion of **0−0** transitions, Section IV(f)).

On Weizsäcker's hypothesis one of a pair of isomers is in an excited metastable state. Now the half-life for de-excitation by γ-emission of nuclear states ranges all the way from no more than 10^{-13} sec. to a few months in the examples investigated up to now, and, whereas no one would call a state with a half-life of 10^{-13} sec. metastable, it is clear that there is no qualitative difference between an excited state with a very short half-life and one with a long one. However, for practical purposes it is convenient to speak of isomers only in the case in which the half-life is long enough to allow a direct observation and to speak of ordinary excited states in the other case. We could conventionally set the limit at about one second but the application of modern electronic techniques to the measurement of delayed coincidences has extended the limit down to 10^{-7} sec. as in the work of de Benedetti (D22). Only a few such cases have been found so far, but many more will probably turn up.[1]

The ordinary way to prove that two radioactivities belong to isomeric nuclei, or in general the way to discover isomeric nuclei, is to produce them by different types of nuclear bombardments using known nuclear reactions. Of these, slow neutron bombardment gives, except for a very few cases among the lightest nuclei, only (n,γ) reactions,[2] i.e.,

[1] De Benedetti and McGowan (D22) have examined some 60 activities for isomers in the range 10^{-3} to 10^{-6} sec. with positive results in only 4 cases. One would normally expect more cases than this. Holmes, Mei, and Turgel (H41) have looked without success for lifetimes from 10^{-3} sec. to 1 sec. in 16 elements bombarded with slow neutrons. Treacy (T8) found no short-lived activities in 6 elements bombarded with 1 Mev x-rays.

[2] We indicate following Bothe the bombarding particle first and the particle or quantum emitted in the primary process,

neutron capture reactions. Gamma-rays of the order of 8 Mev[3] give (γ,n) reactions and both are very simple to interpret. Thus in the case of bromine (mentioned above) the stable isotopes have masses 79 and 81; slow neutron bombardment can produce only the masses 80 and 82 whereas γ-bombardment produces only the masses 80 and 78. The activities with 18-min. and 4.4-hr. periods are produced in both bombardments and hence are ascribed to Br^{80}. As another example, let us consider two periods, 21 minutes and 6.5 days, obtained by proton bombardment of chromium and by deuteron bombardment of iron. Both periods are due to manganese isotopes. Now chromium has stable isotopes of mass 50, 52, 53, 54, and under proton bombardment, by a (p,n) reaction, will give manganese of the same masses. On the other hand, iron has the stable isotopes of mass 54, 56, 57, 58, and under bombardment by deuterons of the energy used can give manganese practically only from (d,α) reactions. This would lead to the masses 52, 54, 55, 56. The two periods in question must hence be assigned to Mn^{54} or Mn^{52}. On the other hand a Mn^{54} is known from other reactions and has a period of 310 days. It is clear that two of the three manganese isotopes with periods of 21 min., 6.5 days, and 310 days must be isomers. Actually the periods of 21 min. and 6.5 days have both to be assigned to Mn^{52} because they can *not* be formed from V^{51} by an (α,n) or from Cr^{53} by a (d,n) reaction, and it is well known that practically all energetically possible reactions do really occur.

Gamma-rays of 1–3 Mev are effective in raising nuclei to excited states and hence in producing isomeric states of stable nuclei, but in this case no nuclear particle is ejected. In addition, inelastic collisions of e^-, p, α, and d can excite the same states.

In other cases the formation of the radioactive nuclei by various processes is not sufficient to complete the assignment and a study of the radiations emitted or other experiments becomes necessary.

III. RADIATIONS FROM ISOMERIC NUCLEI

a. Pure Isomeric Transitions

We will briefly describe the radiations emitted in the isomeric transition from an upper state 2 to a lower state 1. They are of two types: gamma-rays and conversion electrons.[4] Either a gamma-ray of frequency $\omega/2\pi$ such that

$$\hbar\omega = E_2 - E_1 \tag{1}$$

is emitted (E_2, E_1 denote the energy of the levels 2, 1), or electrons are ejected from the K, L, etc., shells of the atom. Their energy is

$$\hbar\omega - K = E_K, \tag{2}$$

$$\hbar\omega - L = E_L, \text{ etc.}, \tag{3}$$

in which E_K, E_L is the energy of the single monokinetic groups of electrons emitted, and K, L is the binding energy of the atomic electrons in the K, L shell of the atom undergoing the isomeric transition. From the standpoint of conservation of energy one can think of the gamma-ray of frequency $\omega/2\pi$ as producing a photoelectric effect on the emitting atom and for this reason this effect is sometimes called internal photoelectric effect or internal conversion. This picture gives, however, no adequate description of the actual physical process.

The ratio between the number of K electrons ejected and gamma-quanta emitted is called the partial internal conversion coefficient for the K shell (T1).

$$\alpha_K = N_K/N_\gamma \tag{4}$$

and similar definitions hold for α_L, etc. The ratio between the total number of electrons ejected and the number of quanta emitted is called simply the internal conversion coefficient. The internal conversion coefficient is thus the sum of the partial internal conversion coefficients:

$$\alpha = \alpha_K + \alpha_L + \alpha_M = N_e/N_\gamma, \tag{5}$$

in which N_e is the total number of electrons emitted. The internal conversion coefficient may vary between zero and infinity. Sometimes in older literature, and even in present literature, the internal conversion coefficient is defined as $N_e/(N_e+N_\gamma)$, i.e., the number of electrons ejected per nuclear transition. The former definition seems more convenient (T1) and we follow it in agreement with the more recent custom.

If the atom loses a K or L electron it will then emit x-rays of the K and L series as well as Auger electrons. The x-rays emitted belong to the spectrum corresponding to the atomic number of the substance undergoing the isomeric transition; e.g., in the case of Br^{80} one will observe the characteristic radiation of bromine. It should be noted that in other nuclear processes leading to the secondary emission of x-rays *after* a radioactive decay, the x-rays are characteristic of the decay product. Thus, in K electron capture the x-rays are characteristic of the preceding element in the periodic table, and in beta-decay they are characteristic of the following element. Measurement of the emission of

second; (n,γ) means thus

$$zA^M + n_0^1 = zA^{M+1} + \gamma$$

in which M is the nuclear mass.

[3] This applies to isotopes of the medium heavy elements.

[4] In a transition from an excited state, a pair of electrons (positive and negative) may be emitted, e.g., Ne^{20} (O2), but this type of transition is very fast. Another possibility in which two quanta are emitted will be discussed below (Section IV f).

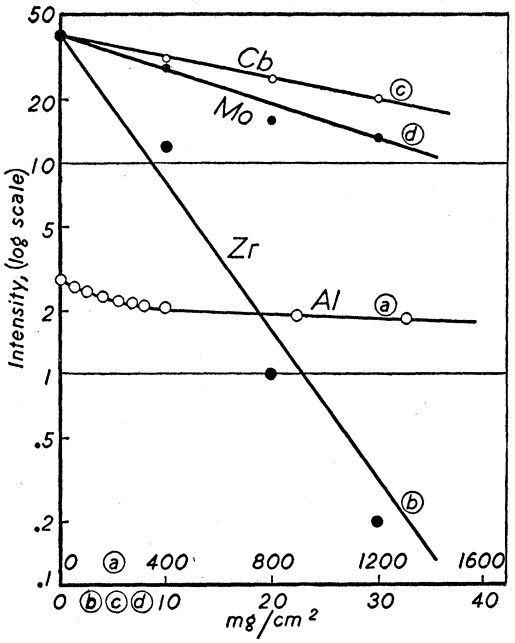

FIG. 1. Absorption curves of x- and γ-rays of Tc^{99}. (a) Absorption in aluminum of x- and γ-rays. (b) Absorption of x-rays in Zr. (c) Absorption of x-rays in Cb. (d) Absorption of x-rays in Mo. *Note:* This figure is taken from Phys. Rev. **55**, 808 (1939).

characteristic x-rays is therefore a good method for the identification of the isomeric transitions. When characteristic absorbers are used for the identification of the x-rays, comparatively weak intensities are sufficient to establish unambiguously the atomic number of the emitting atom. In Fig. 1 we show the absorption curve of the x-rays emitted in an isomeric transition in element 43 (technetium). The same x-rays have been photographed by Abelson with a bent crystal spectrograph (A7) and a microphotometer record of the spectrum is shown in Fig. 2. For quantitative measurements of how many K conversion electrons have been emitted, the fluorescent yield must be taken into account (C1).

The internal conversion electrons themselves are generally detected by thin wall ionization chambers or counters. The absorption curve of soft monokinetic electrons is often sufficiently characteristic for a given instrument to be recognized at once, though it is strongly dependent upon the geometrical arrangement and the instrument used. In Fig. 3 we give as an example the absorption curve of 115-kv electrons and of very soft beta-rays for a standard ionization chamber. It is often also helpful to note that in ordinary beta-decay, low energy electrons are associated with long lifetimes; so the presence of only low energy electrons with a short half-life (for example, 200 kev with 1.3 sec.) is evidence of isomerism.

Better results are obtained with beta-ray spectrographs of the various types. The main difficulty here is to make sources sufficiently thin and intense. Because of this difficulty, the electron spectra obtained thus far with artificial radioactive substances are inferior to the best ones obtained with some of the natural radioactive substances, which are ideally suited for obtaining extremely thin sources with a considerable activity. Photographic plates, counters and ionization chambers have been used to detect the electrons and by proper microphotometric calibration or counter calibration reliable quantitative results have been obtained, e.g., (L1), (V1), (H8), (D9). In the case of electrons of very small energy, below about 20 kev, all the difficulties are increased.

Finally, the Wilson chamber has also been used though not very extensively, for scattering in the chamber tends to make "lines" look like a continuous spectrum of beta-rays. Modern proportional counters will also certainly be of use in this type of measurements (see for example (C19) and (H38)).

The knowledge of the internal conversion coefficient is very important from the theoretical standpoint, but, unfortunately, it is very difficult to measure this quantity. The problem is to count the number of quanta and the number of electrons emitted. It must be added that often both have an energy of less than 100 kev which enhances further the difficulties resulting from self-absorption in the sources, absorption in various windows, etc. However, the calibration of the measuring instruments is the most difficult step. In the case of ionization chambers or counters it is possible to calibrate γ-rays of 500 kev against electrons by using a positron emitter and comparing the direct effect of the positrons with that of the annihilation radia-

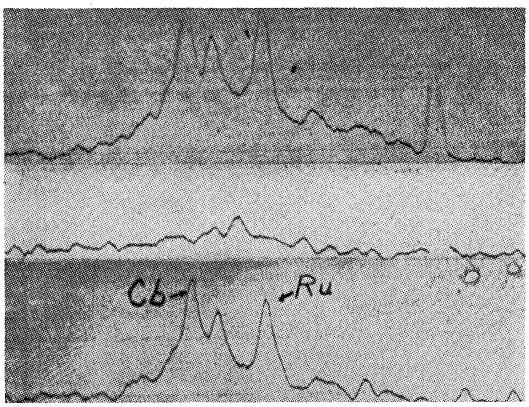

FIG. 2. A microphotometer trace of the K_α line of Tc. The three peaks of the upper and lower calibration traces correspond to the Cb, Mo, and Ru K_α doublet. The main peak of the center trace is due to the K_α of Tc. The peak to the left is due to Mo K_α which arises from a two-day Tc activity. *Note:* This figure is taken from Phys. Rev. **56**, 753 (1939).

tion (G2). Coincidence counters are also very valuable and allow some direct measurements of their own efficiency for gamma-rays (F2), (D1), (R5). Considerable progress in this direction, for example, has been made by the M.I.T. group (D9).

In cases in which an isomeric transition follows or precedes β-decay (see following section), a β-ray spectrograph enables one to count both the number of conversion electrons and the disintegration electrons, which is equal to the number of conversions plus the number of γ's (for example, see (L1)). It is also useful to employ $\beta-\beta$-coincidences to measure the number of times a β-ray is followed (or preceded) by a conversion electron, and $\beta-\gamma$-coincidences to find how often it is followed (or preceded) by a γ-ray. Formulas for the interpretation of such measurements have been given by Wiedenbeck and Chu (W21) who, however, use the older meaning of α (see Eq. (5) and f.). They also give experimental results for several γ-rays.

It is also important from a theoretical standpoint to measure the ratio between the various partial internal conversion coefficients. Generally only α_K/α_L needs to be considered. This ratio is accurately measurable with a beta-ray spectrograph and the calibration difficulties are comparatively smaller because the energy difference of the two groups of conversion electrons in many cases is small compared with their energy and hence the detection efficiencies for both groups are essentially equal.

b. Beta-Radioactivity and Isomerism

The radiations connected with an isomeric transition can be observed in the absence of any other radiations in the case of isomers of stable nuclei such as In^{115m}, Kr^{83m}, Sr^{87m}.[5] However, it happens in many cases that the nuclei having isomeric states are also beta-radioactive. Some interesting features occur then and we will describe them with a few fictitious simple examples. Figure 4 shows a typical diagram of levels for two nuclei A and B. A decays into B by beta-emission and has an excited state 2, about 100 kev above its fundamental state 1. B also has an excited state. The transition probability per unit time of state 2 with respect to the beta-disintegration is $\lambda_{2\beta}$, the transition probability from 2 to 1 is $\lambda_{2\gamma}$. The half-life of state 2 is then given by

$$\tau_2=0.69/(\lambda_{2\beta}+\lambda_{2\gamma}), \quad (6)$$

and the branching ratio between beta-emission and de-excitation is given by

$$p=\lambda_{2\beta}/\lambda_{2\gamma}. \quad (7)$$

[5] We indicate by a superscript "m" excited states of stable nuclei (see (S20)).

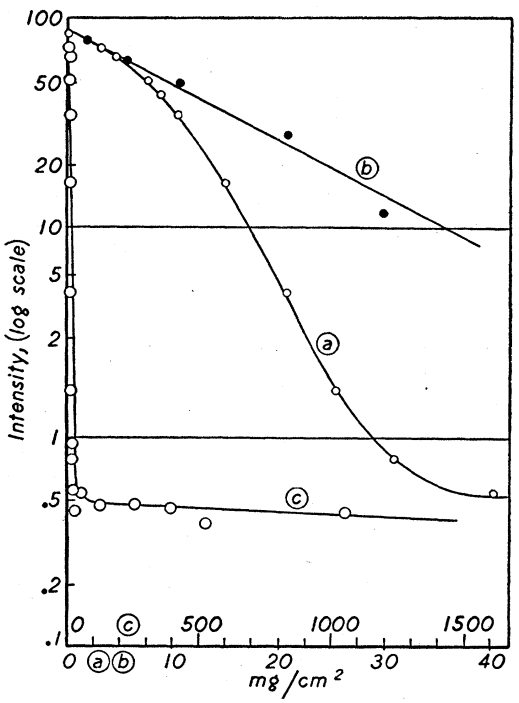

FIG. 3. (a) and (c) Absorption in aluminum of the electrons of Tc^{99}. (b) Absorption in aluminum of the β-rays of Co^{60}. *Note:* This figure is taken from Phys. Rev. **55**, 808 (1939).

Let us now consider two limiting cases which are both encountered in practice.

First let us assume $p\gg1$ (Type *II*). Then state 2 decays practically only by beta-emission and nuclei in state 2 or in state 1 behave like different and independent radioactive nuclei each emitting its own characteristic beta-spectrum and gamma-rays following the beta-decay.

In the other limiting case in which $p\ll1$ (Type *I*), state 2 decays practically only to state 1 which in turn undergoes a beta-decay. State 2 and state 1 behave like two radioactive substances of which 1 is the daughter of 2. In such a case we speak of a pair of genetically related isomers. The beta-ray spectrum of a pair of genetically related isomers corresponds to the transition starting from state 1 with decay constant $\lambda_{1\beta}$. Let us now assume that by some process we have formed nuclei in state 2 and 1 in equal numbers and that, as it occurs very often, the isomeric transition from state 2 to state 1 is accompanied by a radiation which can be easily separated, e.g., by absorption. Upon investigation of the beta-spectrum alone one observes, in the case for which $\lambda_{2\gamma}<\lambda_{1\beta}$, two different periods with an identical beta-spectrum. Initially the beta-rays come mainly from state 1 directly and the activity decays roughly with decay constant $\lambda_{1\beta}$, but later on radioactive equilibrium between state 2 and state 1 is reached, and the beta-decay shows a

constant $\lambda_{2\gamma}$ corresponding to the transition 2 to 1, whereas the beta-spectrum is still the one corresponding to the beta-decay starting from state 1.

This situation arises in most of the genetically related isomeric pairs known up to now, e.g., Br^{80}, Rh^{104}. In Fig. 5 we reproduce the absorption curve of the radiation from the 13.8-hr. and 57-min. periods of Zn^{69}. The beta-absorption curves for the two activities are obviously identical, whereas the 13.8-hr. period shows also a gamma-radiation corresponding to transition 2–1 (the transition between isomeric states) of Fig. 4.

In this particular case, no γ-rays following the β-decay have been observed. In other cases such a radiation may be present and coincidence experiments between beta- and gamma-rays are particularly useful to distinguish these gamma-rays following the beta-decay from the gamma-rays involved in the isomeric transition.

From what we have said above we conclude that the existence of identical beta-spectra connected with different periods is often a valuable clue to the identification or assignment of isomeric pairs.

The case in which $\lambda_{2\gamma} > \lambda_{1\beta}$ would not give rise to the characteristic behavior reported above, but one would just notice an anomaly of the beta-decay law. An example of such a case is the isomerism of Ba^{133} where the half-life of the γ-transition is 38 hrs., of the β-transition is $\sim$20 yr. (K9).

Summing up more quantitatively, the ionization per unit time I produced by the radiation emitted by a pair of genetically related isomers decays according to the law:

$$I = k\lambda_{1\beta}\left[N_2 \frac{\lambda_{2\gamma}}{\lambda_{1\beta}-\lambda_{2\gamma}} e^{-\lambda_{2\gamma} t} + \left(N_1 - \frac{\lambda_{2\gamma}}{\lambda_{1\beta}-\lambda_{2\gamma}} N_2 \right) e^{-\lambda_{1\beta} t} \right], \quad (8)$$

in which N_1 and N_2 are the initial population of states 1 and 2. The coefficient k takes into account the ionizing power of the radiation emitted, geometrical condition, etc. The ionization produced by the radiation corresponding to the isomeric transition (2−1) has been neglected because it can be easily separated from the other. Formula (8) is a straightforward application of the laws of radioactive decay. The initial populations N_2, N_1 will depend upon the mode of formation of the isomeric nuclei and we will discuss this point later.

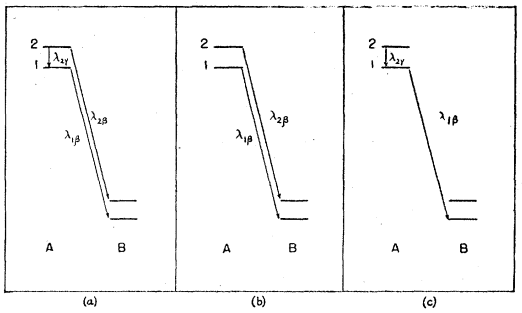

FIG. 4. Examples of energy levels for isomeric nuclei. (a) General case. (b) Type *II* $p \gg 1$. States 2 and 1 decay by beta-emission, independently. (c) Type *I* $p \ll 1$. State 2 decays to state 1 which in turn undergoes a beta-transformation.

In practice we may also expect intermediate cases between the limiting ones (case *a* and *b*) described above. They will occur when, by accident, $\lambda_{2\gamma}/\lambda_{2\beta}$ is not too different from one. Since both $\lambda_{2\beta}$ and $\lambda_{2\gamma}$ vary over a large range, independently of each other, it is clear that the probability that they will have values of the same order of magnitude is rather small. A further complication in the analysis of the radiations comes from the fact that the gamma-rays which follow the beta-emission sometimes show a complicated spectrum involving numerous transitions. This is not a mere accident, but is to be expected according to Weizsäcker's hypothesis and the selection rules of the beta-ray theory. We shall return to this point in Section V.

IV. WEIZSÄCKER'S HYPOTHESIS

a. Qualitative

We can now attack the main problem connected with nuclear isomerism, i.e., the question of the mechanism which prevents an excited state from radiating its energy in an extremely short time.

The mean-life for the emission of a gamma-ray by dipole radiation is given by the well-known formula of electromagnetic theory

$$T_\gamma = \tfrac{3}{4}(\hbar c^3/\omega^3)(1/M_{nm}^2) \quad (9)$$

in which M_{nm} is the matrix element of the electric moment of the nucleus for the mn transition. In this formula the only uncertain quantity is M_{nm}. If one assumes M_{nm} equal to the electronic charge times 10^{-13} cm, which seems a fair guess considering the nuclear charges and the nuclear dimensions, one obtains for an ω corresponding to an energy of 100 kev, $T_\gamma = 4.10^{-12}$ sec. This mean life is 10^{18} times shorter than some of the experimentally observed ones. It is clear that very powerful selection rules must be operating to prevent radiative transitions. Bohr has observed that the electric dipole moment of a nucleus may be much smaller than the estimate given above because the protons will be tightly coupled with the neutrons in the nuclear matter so that when the constituent elementary particles move within the nucleus the electrical center of gravity will approximately coincide with the mechanical one. This will reduce considerably the dipole moment of the nucleus. However, it is hard

to believe that this effect could be important enough to reduce the matrix elements sufficiently.

As mentioned in Section I, Weizsäcker (W2) has pointed out that if two nuclear levels differ in angular momentum by more than one unit of $h/2\pi$, the transition between them is strictly forbidden for dipole radiation, and generally, if the spin difference is l, the first allowed transition will be due to an electric or magnetic multipole of order 2^l.

Now the ratio between the intensity of quadrupole and dipole radiation of a given frequency is of the order of magnitude of $x^2/\lambda\!\!\!^{-2}$ in which x is a length representing the dimensions of the nucleus and $\lambda\!\!\!^{-}$ is the wave-length of the emitted radiation divided by 2π. More generally the intensity of 2^l electric pole or 2^{l-1} magnetic pole radiation is of the order of magnitude of $(x/\lambda\!\!\!^{-})^{2(l-1)}$ times that of dipole radiation. Now $x/\lambda\!\!\!^{-}$ is of the order of magnitude of 1/300 for a quantum of an energy of 100 kev and hence the intensity of quadrupole radiation is about 10^5 times smaller than that of dipole radiation, and correspondingly for higher poles. By assuming that the change in angular momentum involved in the transition is high enough to allow only radiation of a high multipole order, one can account for any of the long half-lives observed. These qualitative considerations can be refined quantitatively.

b. Multipole Radiation

The starting points of the theory are the classical expressions for the scalar (φ) and vector (A) potentials produced by the moving charges of the nucleus:

$$\mathbf{A}(\mathbf{R},t)=\int\frac{\mathbf{j}_1(\mathbf{r}',t^*)}{cr}d\tau', \tag{10}$$

$$\varphi(\mathbf{R},t)=\int\frac{\varrho_1(\mathbf{r}'t^*)}{r}d\tau', \tag{11}$$

in which r is the distance between the point P of coordinates x, y, and z, (see Fig. 6) and the volume element considered, and $t^*=t-r/c$. (c=velocity of light.) The integrals are extended over the whole space: ρ_1 is the charge density at the point of coordinates x', y', z' at the time t^* and $\mathbf{j}_1$ is the current density at the same point and time; $d\tau'$ stands for dx', dy', dz'.

Let us now assume that ρ_1 and $\mathbf{j}_1$ are harmonic functions of time, oscillating with frequency $\gamma=\omega/2\pi$. They can be represented as the real part of

$$\rho(\mathbf{r}')e^{i\omega t}=\rho_1 \tag{12}$$

and

$$\mathbf{j}(\mathbf{r}')e^{i\omega t}=\mathbf{j}_1. \tag{13}$$

These are connected by the continuity equation

$$\partial\rho_1/\partial t=-\mathrm{div}\mathbf{j}_1 \tag{14}$$

equivalent to

$$i\omega\rho=-\mathrm{div}\mathbf{j}. \tag{15}$$

We will now calculate the vector and scalar potentials in points of space at a distance from our system of charges large compared with the dimension of the system itself. From Fig. 6 one has

$$\mathbf{r}=\mathbf{R}-\mathbf{r}', \tag{16}$$

$$r^2=R^2+r'^2-2Rr'\cos\theta, \tag{17}$$

or approximately for $R\gg r'$

$$r=R-r'\cos\theta. \tag{18}$$

By substituting (12), (13), and (18) in (10) and (11) we obtain

$$\mathbf{A}(R,t)=\frac{e^{i\omega(t-R/c)}}{c}\int\frac{\mathbf{j}(\mathbf{r}')e^{ik\mathbf{n}\cdot\mathbf{r}'}}{R-r'\cos\theta}d\tau', \tag{19}$$

and

$$\varphi(R,t)=e^{i\omega(t-R/c)}\int\frac{\rho(\mathbf{r}')e^{ik\mathbf{n}\cdot\mathbf{r}'}}{R-r'\cos\theta}d\tau'. \tag{20}$$

Here as well as in the following complex expressions for **E**, **H**, etc., we understand that only the real part has to be considered. **n** is a unit vector in the direction of R and $k=\omega/c=2\pi/\lambda=1/\lambda\!\!\!^{-}$, where λ is the wave-length of the radiation emitted.

We obtain the electric and magnetic vectors from (19) and (20) by the well-known relations

$$\mathbf{E}=-\mathrm{grad}\varphi-\frac{1}{c}\frac{\partial\mathbf{A}}{\partial t}, \tag{21}$$

$$\mathbf{H}=\mathrm{curl}\mathbf{A}.$$

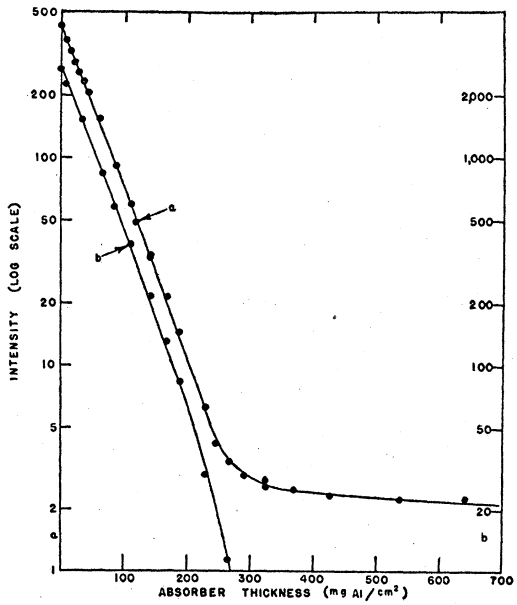

FIG. 5. Absorption curves (in aluminum) of Zn^{69}. (a) 13.8-hour activity. (b) 57-minute activity. *Note:* This figure is taken from Phys. Rev. **56**, 1095 (1939).

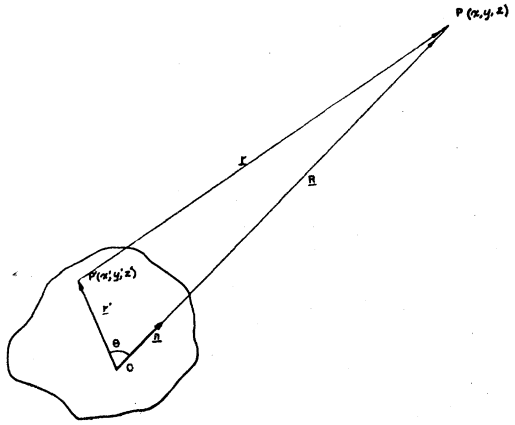

FIG. 6. The vectors **R**, **r**, **r'**, **n** as used in explaining the radiation from a system of moving charges.

In performing the differentiations with respect to the coordinates of P as required by (21), we may consider **n** as a constant and also substitute $R-r'\cos\theta$ in the denominators, by R.

We obtain

$$E=+\frac{i\omega}{cR}e^{i\omega(t-R/c)}\int\left(\rho\mathbf{n}-\frac{\mathbf{j}}{c}\right)e^{ik\mathbf{n}\cdot\mathbf{r}'}d\tau', \quad (22)$$

$$H=+\frac{i\omega}{cR}e^{i\omega(t-R/c)}\int\left(\frac{\mathbf{j}}{c}\times\mathbf{n}\right)e^{ik\mathbf{n}\cdot\mathbf{r}'}d\tau'. \quad (23)$$

The expression for **E** can be further transformed into

$$\mathbf{E}=-\frac{i\omega}{c^2}\frac{e^{i\omega(t-R/c)}}{R}\int j_\perp e^{ik\mathbf{n}\cdot\mathbf{r}'}d\tau' \quad (24)$$

by using the relation

$$i\omega\int\rho e^{ik\mathbf{n}\cdot\mathbf{r}'}d\tau'=-\int\mathrm{div}\mathbf{j}e^{ik\mathbf{n}\cdot\mathbf{r}'}d\tau'=ik\int\mathbf{j}\cdot\mathbf{n}e^{ik\mathbf{n}\cdot\mathbf{r}'}d\tau',$$

which follows from the continuity equation (15). $j_\perp$ is the projection of **j** on a plane perpendicular to **n** or, in symbols:

$$j_\perp=\mathbf{j}-(\mathbf{j}\cdot\mathbf{n})\mathbf{n}. \quad (25)$$

Formulas (22), (23), (24) show that **E** and **H** are perpendicular to each other and to **n**, and that they have the same absolute value, inversely proportional to R. These are the well-known properties of a radiation field expressed by the equations:

$$\mathbf{E}\cdot\mathbf{n}=0;\quad -\mathbf{H}=\mathbf{E}\times\mathbf{n};\quad \mathbf{E}\cdot\mathbf{H}=0. \quad (26)$$

Omitting the prime sign on r, we can develop the exponential in (24) in spherical harmonics (W6).

$$e^{ik\mathbf{n}\cdot\mathbf{r}}=\sum_{l=0}^{\infty}i^l(2l+1)P_l(\cos\theta)\left(\frac{\pi}{2kr}\right)^{\frac{1}{2}}J_{l+\frac{1}{2}}(kr), \quad (27)$$

where θ is the angle between **n** and **r**, and $J_{l+\frac{1}{2}}(kr)$ is the Bessel function of order $l+\frac{1}{2}$. If $kr\ll1$, that is, if the wave-length of the emitted radiation is large compared with the dimensions of the region occupied by the system of charges, (27) can be approximated by taking the lowest term in a power series expansion of $J_{l+\frac{1}{2}}$. We have then

$$\left(\frac{\pi}{2kr}\right)^{\frac{1}{2}}J_{l+\frac{1}{2}}(kr)=\left(\frac{\pi}{2kr}\right)^{\frac{1}{2}}\frac{(kr)^{l+\frac{1}{2}}}{2^{l+\frac{1}{2}}\Gamma(l+\frac{3}{2})},$$

(cf. (W7)) and hence *since* $2^{l+1}\Gamma(l+\frac{3}{2})=1\cdot3\cdot5\cdots(2l-1)(2l+1)(\pi)^{\frac{1}{2}}$

$$e^{ik\mathbf{n}\cdot\mathbf{r}}=\sum_{l=0}^{\infty}\frac{i^l(kr)^l}{1\cdot3\cdot5\cdots(2l-1)}P_l(\cos\theta). \quad (27a)$$

By substituting (27a) in (24) we find **E** expressed as a sum of integrals containing the various powers of kr

$$\mathbf{E}=\mathbf{E}_1+\mathbf{E}_2+\mathbf{E}_3\cdots, \quad (28)$$

in which the integral giving $\mathbf{E}_i$ contains under the integral sign $(kr)^{i-1}$. The first terms of the expansion (28) are

$$\mathbf{E}_1=-\frac{i\omega}{c^2R}e^{i\omega(t-R/c)}\int\mathbf{j}_\perp d\tau, \quad (29a)$$

$$\mathbf{E}_2=\frac{\omega}{c^2R}e^{i\omega(t-R/c)}\int\mathbf{j}_\perp kr\cos\theta d\tau, \quad (29b)$$

$$\mathbf{E}_3=+\frac{i\omega}{3c^2R}e^{i\omega(t-R/c)}\times\int\mathbf{j}_\perp(kr)^2\left(\frac{3\cos^2\theta-1}{2}\right)d\tau, \quad (29c)$$

where the prime has been dropped from $d\tau$.

E_1 corresponds to the field of electric dipole radiation; E_2 to the field of "magnetic dipole and electric quadrupole" radiation; E_3 to the field of "magnetic quadrupole and electric octupole" radiation, etc.

The opportunity of this development and the reason for the names of the radiations can be better seen after the integrands in $\mathbf{E}_1$, $\mathbf{E}_2$, etc., are again transformed using the continuity equation and partial integration. One obtains from (15) by multiplication by x, and partial integration

$$\int j_x d\tau=i\omega\int\rho x d\tau=M_x \quad (30)$$

in which M_x is the x component of the electric dipole moment of the system of charges. Similar equations are obtained involving M_y and M_z.

Substitution of (30) in (29) shows that $\mathbf{E}_1$ is due simply to the vector $M_\perp$, i.e., to the projection of M perpendicular to n. E_1 corresponds to the radiation of an electric dipole at the origin. Substitution of (30) in (29b) gives a more complicated expression. One obtains under the integral a tensor of the second order whose components have the form

$$a_{ik}=j_i x_k=b_{ik}+c_{ik}, \quad i,k=x,y,z. \tag{31}$$

It is convenient to express this tensor as the sum of two parts, one symmetrical with respect to the interchange of i and k (b_{ik}) and one antisymmetrical with respect to the same exchange (c_{ik}). The antisymmetrical part gives an electric field corresponding to a magnetic dipole.

$$N=\frac{1}{2}\int \mathbf{r}\times\mathbf{j}d\tau, \tag{32}$$

which is just the magnetic dipole corresponding to the current distribution of the moving charges; hence the name of magnetic dipole radiation. The electric field given by the symmetrical part of the tensor is that of an electric quadrupole.

Similar considerations can be extended to $\mathbf{E}_3$ which is the sum of a magnetic quadrupole and electric octupole field, etc. The names of quadrupole, octupole, etc., derive from the fact that fields like the symmetrical part of $\mathbf{E}_2$ can be obtained by two equal dipoles of opposite phases and shifted with respect to each other; the resulting system of 4 charges has no dipole moment and containing 4 poles, is called a quadrupole. Similarly with two quadrupoles we can build an octupole, etc.

The decomposition of the field produced by our system of charges in $\mathbf{E}_1$, $\mathbf{E}_2$, etc., is particularly appropriate if $kx\ll 1$ because each term is, as order of magnitude, $kx=x/\lambda$ times smaller than the preceding and the series converges rapidly. Here x stands for a length measuring the size of our system of charges; for a nucleus one could appropriately choose the nuclear radius. This proves the statement concerning the order of magnitude of the various types of radiations made at the beginning of this section.

The preceding considerations are purely classical (H40), (S36), but they can be completed by substituting the proper matrix elements for the various amplitudes of dipole moments, quadrupole tensors, etc. This calculation in a complete form has been performed by Dancoff and Morrison (D2).

c. Selection Rules

A complete discussion of the electromagnetic field produced by an arbitrary multipole is given by Heitler (H3). He gives the expression of the fields not only in the wave zone where they vary as R^{-1} but also nearer to the origin where the decrease occurs according to higher negative powers of R and shows by quantization of the field that the electromagnetic fields resulting from a 2^l-electric or magnetic pole has an angular momentum of $l\hbar$ with respect to the origin to which the multipole is referred. The calculations are complicated and it is essential for them to take into account the intermediate zones.

The fact that the radiation carries away angular momentum, together with the principle of conservation of angular momentum applied to the radiating system (nucleus) and to the radiation, brings us to establish a selection rule. If $\mathbf{I}$ and $\mathbf{I}'$ are the angular momenta vectors (in $\hbar$ units) of two nuclear states between which an electric or a magnetic 2^l-pole transition occurs, one has

$$|\mathbf{I}-\mathbf{I}'|\leqslant l \tag{33}$$

which expresses the conservation of angular momentum.

This selection rule can also be derived directly from the expansion of the electric field in spherical harmonics carried out above (Cf. (29)) and in more detail in Heitler's paper.

Now if a nucleus has an excited state with angular momentum I' and a fundamental state with angular momentum I, the radiation of lowest order, that is, the most probable one, connected with this transition will be an electric or magnetic multipole of order 2^l (see discussion of parity below) in which

$$l=|I-I'| \tag{34}$$

This follows immediately from (33). In fact it can be shown that

$$|I+I'|\geqslant l\geqslant |I-I'| \tag{35}$$

which gives $|I-I'|$ as the minimum value of l.

Another type of selection rule can be obtained by considering the parity of the eigenfunctions of the nucleus. The parity determines what happens to a given eigenfunction if one changes the sign of all of the coordinates of the particles. One has

$$\psi(q_1,q_2\cdots q_n)=\pm\psi(-q_1,-q_2,\cdots q_n) \tag{36}$$

in which q_i stands for the coordinates of the ith particle (excluding its spin coordinates). If Eq. (36) holds with a + sign the eigenfunction is called even; in the other case, odd.

Every matrix element of the type

$$M_{mn}=\int \psi_m^*(q_1,q_2\cdots)X^rY^sZ^t \times\psi_n(q_1,q_2\cdots)dq_1dq_2\cdots \tag{37}$$

vanishes if ψ_m and ψ_n have the same parity and $r+s+t$ is odd, or have different parity and $r+s+t$ is even. In this integral $X=\sum x_i$, etc., and all the

TABLE I. Selection rules for multipole radiation.

Power of x/λ in intensity	2	4	6	8	10
Electric radiation	Dipole	Quadr.	Oct.	16-pole	32-pole
$\|I+I'\| \geqslant \|I-I'\| \leqslant$	1	2	3	4	5
Change in parity	Yes	No	Yes	No	Yes
Magnetic radiation	—	Dipole	Quadr.	Oct.	16-pole
$\|I+I'\| \geqslant \|I-I'\| \leqslant$		1	2	3	4
Change in parity		No	Yes	No	Yes

matrix elements involved in multipole radiation are of the type (37).

This results in an extension of the well-known Laporte rule of spectroscopy. It follows from it that electric dipole radiation occurs only between states of different parity and generally electric 2^l pole radiation and magnetic 2^{l-1} pole radiation occur only between states of the same parity if l is even, only between states of different parity if l is odd.

It is useful to consider the lowest power of $(x/\lambda)^2$ entering in the intensity formulas. We shall call it *order of the transition* and denote it by Λ. It is 1 for electric dipole, 2 for electric quadrupole and/or magnetic dipole etc.

Both selection rules, the one concerning the angular momentum and the one concerning parity are summed up in Table I, which gives the multipoles of minimum order between states of a given parity for which $|I-I'| \leqslant l \leqslant |I+I'|$.

To Table I must be added the rule which follows from (34) that a transition between two states with $I=0$ is forbidden for every type of radiation. (See Section IV f.)

d. Half-Life of Excited States

Bethe (B3) has given a rough estimate of the radiation probability of excited nuclear states by replacing the integrals of Eqs. (29a), (29b), etc., by

$$\eta e x \omega (\omega x/c)^{\Lambda-1},$$

in which η is a number of the order of magnitude of 1, e is the electronic charge, x is the nuclear radius.

By forming the Poynting vector, integrating, and dividing by $\hbar\omega$ one obtains then the average number of quanta emitted per unit time per nucleus, i.e., λ_γ.

$$\lambda_\gamma = \left(\frac{\omega}{c}\right)^{2\Lambda+1} \frac{e^2}{\hbar} \eta^2 \frac{x^{2\Lambda}}{[1\cdot 3\cdot 5\cdots(2\Lambda-1)]^2}. \quad (38)$$

If we assume $\eta^2=1$ and $x=1.45\ 10^{-13}\ A^{\frac{1}{3}}$ in which A is the mass of the nucleus ($O^{16}=16$) according to the known data for nuclear radii, formula (38) gives

$$\log_{10}\lambda_\gamma = 20\cdot 30 - 2\log_{10}(1\cdot 3\cdots 2\Lambda-1) - (2\Lambda+1)(1.30-\log_{10}E) - 2\Lambda(0.84-\tfrac{1}{3}\log_{10}A), \quad (38a)$$

where E is the energy of the γ-ray in Mev and λ_γ is in sec.$^{-1}$. Here Λ is the multipole order for *electric* radiation; but since magnetic 2^l pole radiation, has for the purposes of this calculation, the same probability as electric 2^{l+1} pole radiation, the decay constant of magnetic 2^l pole radiation is obtained from the formula by inserting $\Lambda=l+1$.

This formula can be considered only as a very crude approximation because the substitution of the matrix elements by a power of the nuclear radius multiplied by the electronic charge is little more than justifiable by dimensional considerations. However, a better approximation could only be obtained by a detailed consideration of the nuclear model, which is beyond our present knowledge.

A number of authors have attempted more detailed calculations of the nuclear lifetimes on different bases. Hebb and Uhlenbeck (H5) assumed a single alpha-particle to be moving in the field of the rest of the nucleus, while Koyenuma (K8) assumed a single proton to be the moving charge which radiated. Lowen (L12), Fierz (F14), and Berthelot (B11) have used the liquid drop model, assuming the radiation to come from the vibrations of the charged nucleus. Flügge (F1) has given a formula for the lifetime on the assumption that the radiating mechanism is a rotating charged drop. Some of the available data have been compared with these theoretical expressions in the articles by Flügge (F1), Berthelot (B11), and by Wiedenbeck (W16). In our view, our present knowledge of the nucleus is not sufficient to justify the use of any particular nuclear model, and so we have used the formula (38a). One thing, however, does seem definite,[6] that the agreement between the theoretical expressions and the experimental material is good or reasonable only if the correction for internal conversion is taken into account.

If an atom were completely stripped of its electrons the decay constant of a nuclear isomeric state would be given by (38), but the presence of the atomic electrons causes a perturbation on the nucleus which induces nuclear transitions and ejection of the atomic electrons (internal conversion). This effect naturally increases the decay constant and, more precisely, to a very good approximation we may assume (T1) that the decay constant is

$$\lambda = \lambda_\gamma + \lambda_e, \quad (39)$$

in which λ_γ is given by (38) and λ_e is the decay

[6] This has been pointed out by Dancoff in his notes on nuclear isomerism (D21).

constant corresponding to the transition probability induced by the electrons.

The half-life of an excited state, τ, is given by

$$\tau = 0.69/\lambda_e + \lambda_\gamma = 0.69/\lambda_\gamma(1+\alpha), \qquad (39a)$$

and since α, the internal conversion coefficient, may have values very large compared with 1 it is clear that internal conversion may be the essential factor in determining the half-life of the excited state.

In Fig. 7 we have plotted $0.69/\lambda_\gamma = \tau_\gamma$ and τ as given by (38) and (39a) as a function of the energy of the gamma-ray for $A=80$, $Z=35$. The values of α required by (39a) have been taken from theoretical calculations which will be reviewed in the following sections. From Fig. 7 is seen at once the importance of internal conversion in reducing the half-life of the low energy states. In spite of the extreme crudity of the approximations involved it appears also that, for a given energy, transitions with various Λ have half-lives different enough to make it possible reasonably to assign an Λ to a given transition once its half-life and energy are known.

It is perhaps worth pointing out one or two things concerning the various formulas for the decay constant referred to above. The one of Bethe, Eq. (38), uses only the most general concepts. Whatever the theory, the rate of radiation caused by electric 2^l pole quanta will be proportional to $\omega^{2l+2}x^{2l}$ where ω and x have meanings given above. If we simply divide by ω to get the decay constant, the result is Eq. (38). However, in the formulas of Fierz, Lowen, Flügge, and Berthelot, a particular model of the nucleus, the liquid drop, is used and in this case the energy of the vibrations in the drop is proportional to ω^2.[7] Therefore, the decay constant becomes proportional to ω^{2l} instead of ω^{2l+1}. Again the energy of the oscillation involves the (nuclear radius)^2, and so when this term is divided into the rate of radiation, the resultant decay constant is proportional to the nuclear radius to the $2l-2$ power. Finally, since the total charge Z is assumed to contribute, λ depends on Z^2 whereas in Bethe's formula, no dependence on Z is introduced.

An attempt has been made to compare experimental results with the formulas of Bethe and of Fierz (F14). In the Table of isomers given below theoretical values of half-lives are derived from the former, which in general gives somewhat too long values for the half-life. The formula of Fierz in general gives somewhat too small values of the half-life. In some 25 cases for which there seems good data, the two formulas suggest different Λ values for only 4 cases. The data are not good enough really to determine whether the dependence on ω and the nuclear radius follows one formula, the other, or neither. With more accurate data on the conversion coefficient, which is an uncertain quantity in the calculation since α for magnetic 2^l pole radiation will not be equal to α for electric 2^{l+1} pole, more detailed comparisons of theory and experiment will be possible.*

[7] Just as the energy of an harmonic oscillator $x=a\cos\omega t$ is $\frac{1}{2}ma^2\omega^2$.

e. Internal Conversion

Fortunately calculations of α, though considerably complicated, rest on a much more solid basis than the estimates of λ, because, whereas the latter involve the very uncertain evaluation of nuclear matrix elements, which in turn depend on a detailed knowledge of nuclear structure, the former depend solely upon electrodynamics and our knowledge of atomic structure, and can pretend to an accuracy comparable with that of most of the ordinary spectroscopic calculations.

The pertinent calculations have first been performed by Hulme, Mott, Taylor, and F. Oppenheimer (H4, T1, T2) for heavy elements and dipole and quadrupole radiation, and extended later by Hebb and Uhlenbeck (H5), Dancoff and Morrison (D2) and Hebb and Nelson (H6) to lighter elements and higher multipole orders.**

The general idea of such calculations is to evaluate the probability of the transition of the K, L, etc., atomic electrons to states of the continuum

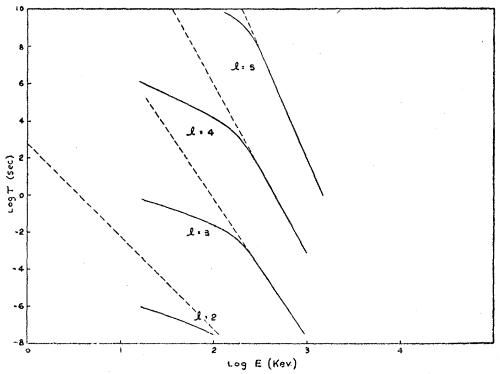

FIG. 7. Logτ *vs.* log$E$ for $Z=35$, $A=80$.
– – – – τ_γ according to (38a).
———— τ according to (39a). Logarithms to base 10 and values of Λ indicated in the figure.

* *Note added in proof:* Axel and Dancoff (A11) find good agreement between 50 experimental cases and a theoretical formula which has the same energy and nuclear radius dependence as Eq. (38).

** *Note added in proof:* Recent calculations have been published for magnetic conversion coefficients by Schafroth (S37), Drell (D25), Lowen and Tralli (L20) and for electric dipole conversion coefficients by Griffith and Stanley (G23). Also distributed privately is an extensive table for both electric and magnetic radiation by Rose, Goertzel, Spinrad, Harr, and Strong.

under the influence of the perturbation created by the electromagnetic field of a multipole located at the origin, radiating one quantum per second. A distinctive feature of this probability is that it depends substantially upon the electric and magnetic field in the vicinity of the nucleus where the K and L electrons are located. In this region the field decreases with a power of r connected to the multipole order (r^{l+1} for electric 2^l pole) and hence internal conversion affords a method of exploring the multipole order. The ordinary theory of perturbations involving time is used and the main problem is to calculate matrix elements for the perturbing potential connecting the K and L states with states of the continuum.

A calculation covering all possible cases would be too complicated, especially if one takes into account relativistic effects which are important for high velocities of the K electrons (heavy elements) or of the ejected electrons. However, for most of the isomeric transitions known, both the energy of the ejected electrons and the kinetic energy of the K electrons (e.g., 18 kev for $Z=40$; 43 kev for $Z=60$) are small compared with mc^2 so that relativity effects are not very important.[8]

Conversion in the K Shell.—Dancoff and Morrison give formulas for the conversion by the two K electrons of electric 2^l-pole radiation in a non-relativistic approximation. The formula is valid for $v/c \ll 1$ (v is the velocity of the ejected electrons).

$$\alpha_K{}^l = \frac{16\alpha l}{l+1}\left[\Gamma(l+\tfrac{1}{2})\right]\left[\frac{2}{\nu}\right]^{l+1}\frac{n^4}{(1+n^2)^{l-2}} \times \frac{\left[(l+1)(1+n^2)^{l-2}e^{-2n\,\mathrm{ctn}^{-1}n} - V_l\right]^2}{[l^2+n^2][(l-1)^2+n^2]\cdots[1+n^2](1-e^{-2\pi n})}. \quad (40)$$

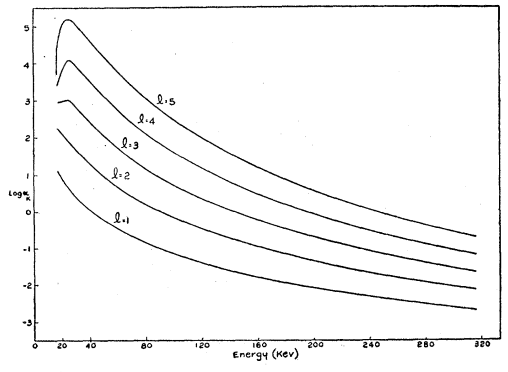

FIG. 8. Internal conversion coefficient for the K shell as a function of γ-ray energy. Electric radiation, $Z=35$.

[8] For $Z>60$, $E>250$ kev, and for magnetic transitions, relativistic effects must be taken into account.

V_l satisfies the recursion relation:

$$V_{l+1} = V_l(1+n^2)\frac{l+2}{l+1} + \frac{2^{l+1}l}{(2l+2)!}\left(\frac{1}{1+n^2}\right)\prod_{i=1}^{l}(i^2+n^2), \quad (41)$$

and

$$V_0 = 0. \quad (42)$$

In these formulas α is the fine structure constant, ν is the energy of the gamma-ray in units mc^2 and

$$n = Z\alpha/(2\nu - Z^2\alpha^2)^{\frac{1}{2}} = \left(\frac{\text{binding energy of the } K \text{ electrons}}{\text{kinetic energy of the conversion electrons}}\right)^{\frac{1}{2}} = \frac{Ze^2}{h\nu}. \quad (43)$$

Formula (4) is much simplified if the condition $n \ll 1$ is satisfied, i.e., if the binding energy of the K shell is small compared with the kinetic energy of the conversion electrons or, better, if the velocity of the K electrons is small compared to the velocity of the conversion electrons. In such a case

$$\alpha_K{}^l = Z^3\alpha^4\frac{l}{l+1}\left(\frac{2}{\nu}\right)^{l+\frac{1}{2}}. \quad (44)$$

If we neglect the spin influence, magnetic multipole radiation is not converted in the K shell.

In a relativistic approximation, i.e., using Dirac wave functions, and neglecting the binding energy of the K electrons ($n \ll 1$), Dancoff and Morrison find

$$\alpha_K{}^l = \frac{2Z^3\alpha^4}{\nu^3}\left(\frac{\nu+2}{\nu}\right)^{l-\frac{1}{2}}\left[\frac{(l+1)\nu^2+4l}{l+1}\right], \quad (45)$$

$$\beta_K{}^l = \frac{2Z^3\alpha^4}{\nu}\left(\frac{\nu+2}{\nu}\right)^{l+\frac{1}{2}}, \quad (46)$$

in which $\alpha_K{}^l$ and $\beta_K{}^l$ are the conversion coefficients for electric 2^l-pole and magnetic 2^l-pole radiation in the K shell.

Quantitative results for gamma-ray energies under 0.2 Mev and $Z<40$ will be given by formula (40). For $Z<30$, high energies, and not extremely high multipole order (45) and (46) give usable estimates. For $Z>50$ numerical calculation is necessary for accurate results. These calculations, together with many others of importance in nuclear physics could be made relatively easily using the Fermi-Thomas potential for the atomic field and integrating Schrödinger's equation numerically with modern calculating machines. In the formulas given above hydrogen wave functions have been used.

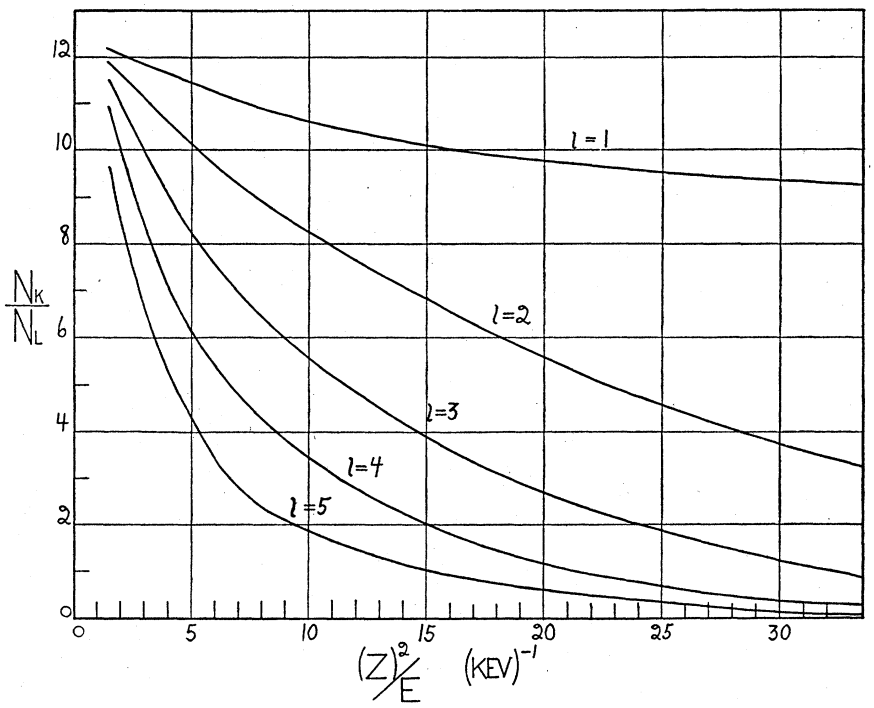

FIG. 9. Curves for N_K/N_L as a function of Z^2/E for electric multipole radiation. *Note:* This figure is taken from Phys. Rev. **58**, 489 (1940).

Conversion in the L Shell and Numerical Results.—Similar calculations relative to the conversion in the L shell have been performed by Hebb and Nelson (H6). They also give numerical results for the electric multipole conversion coefficient in both K and L shell.

The final formulas valid under the same approximations as the ones for the K shell are even more complicated and we do not report them here. Hebb and Nelson give a very convenient table, from which α_K and α_L can be calculated. A graph of α_K, $Z=35$, as a function of energy is given in Fig. 8, and Fig. 9 reproduces from Hebb and Nelson's paper the graph of α_K/α_L as a function of Z^2/E. It is to be noted that the table referred to gives $\log[\gamma^{2l+2}\alpha_K]$ as a function of W/γ^2 where W is the same as ν used above, that is the energy of the γ-ray in units of mc^2, and $\gamma=Z/137$. Hence

$$\frac{W}{\gamma^2}=\frac{(137)^2E}{mc^2Z^2}$$

or $36.7E/Z^2$ if E is in kev. For best results the table, rather than the graph should be used to calculate α_K/α_L and it is possible to improve the approximation in all the foregoing formulas by taking into account the screening of the nuclear charge for the various orbits as is done in x-ray theory. This is done by replacing Z by $Z_{\text{eff}}=Z-\sigma$ where $\sigma=0.30$ for the K shell, $\sigma=4.15$ for the L shell. The results given by Hebb and Nelson are accurate for $Z=35$, and departures for $25<Z<50$ should be from 10–20 percent.

For magnetic multipole radiation and the L shell the conversion coefficient is given by

$$\beta_L=\frac{Z^3\alpha^4}{4\nu}\left(\frac{\nu+2}{\nu}\right)^{l+\frac{1}{2}}\left\{1+\frac{Z^2\alpha^2}{4}\frac{\nu+2}{\nu}\left[\frac{l+1}{2l+1}+\frac{l(2l+1)}{4}\left(\frac{2l-1}{2l+1}-\frac{\nu}{\nu+2}\right)^2\right]\right\}, \quad (47)$$

which can be seen to contain β_K (Eq. (46)) as a factor. Again the approximation may be improved by taking screening into account.

f. Case of the 0–0 Transitions

A special case is afforded by transitions between two states both having $I=0$. Such a transition is strictly forbidden for all types of electromagnetic radiation.

If the two states have the same parity, atomic electrons can be ejected in a direct transition and the transition probability depends upon the penetration of atomic electrons in the nucleus. R. H. Fowler (F3) has calculated this probability. The 1.426 Mev γ-ray in RaC is completely converted according to Ellis and Aston (E2) and is generally considered to be a 0–0 transition, entirely forbidden by quantum de-excitation (F3). The same penetration effect is operating also in cases in which radiative transitions are possible, but it is then relatively

unimportant (T2). Another possible case has been reported by Bowe, *et al.* (B13) who find in Ge^{72} (resulting from the decay of Ga^{72}) a highly converted ($\alpha>1$) 0.7 Mev γ-ray with lifetime 5×10^{-7} sec. No agreement can be obtained by the Weizsäcker formula.

If, however, the two states have different parity, even this type of transition mechanism is barred and the transition can only occur as a consequence of a second-order effect as the simultaneous emission of two quanta or of two electrons. Sachs (S6) has calculated the probability of such effects which might be observable in some cases. It would be very characteristic of them, in the case of the two electron emission, that the electrons would be emitted in coincidence and that they would have a very broad energy distribution instead of a sharp line as in the ordinary transitions in which conversion electrons of a single gamma-ray are emitted. Up to now possible experimental evidence of this kind of transitions exists only for the case of the 1.5 min. isomer Ir^{192}, which seems to emit a continuous γ-spectrum, as well as conversion electrons. Calculations concerning the case of one electron and one γ-ray emission for various values of the energy of the intermediate states and parity combinations have been made by Goldberger (G11).

g. Application of the Theory

Summing up the results of the foregoing section we see that the half-life of an excited nuclear state depends upon the nuclear charge, E and Λ, i.e., upon the atomic number, energy, and order of the transition to the fundamental state. The calculation of this dependence is, however, very unprecise, and requires more exact knowledge of the nuclear structure than we possess.

The conversion coefficients α_K, α_L, β_K, β_L are also a function of Z, E, l, and their values can be calculated on a much more solid basis than τ, i.e., by using electrodynamics and atomic theory.

Experimentally one can measure Z, E, τ, the number N_K and N_L of K and L conversion electrons, and N_γ the number of gamma-rays emitted per disintegration. It is generally possible to measure accurately the first three of these quantities and N_K/N_L; N_K and N_γ or their ratio is much more difficult to measure and hence known only roughly, except in the case of conversion electrons being accompanied by disintegration electrons (see for example the cases of In^{114} and In^{115} investigated by Cork and Lawson (L1)).

In applying the preceding theoretical considerations to experiment, we will consider first the case in which magnetic multipole radiation is negligible compared with electric multipole radiation. This will generally occur for l even and a transition between states of the same parity or for l odd and a transition between states of different parity (cf. Table I). In such cases the numbers of electrons ejected by conversion of magnetic multipole radiation will also be negligible.

Since theory gives the functional relations,

$$\tau=\tau(Z,E,\Lambda) \text{ according to the formula (39a) and (38)}; \quad (48)$$

$$\alpha_K=\alpha_K(Z,E,l) \text{ according to the table in (H6)}; \quad (49)$$

$$\alpha_L=\alpha_L(Z,E,l) \text{ according to the table in (H6)}; \quad (50)$$

by measuring Z, E, τ, α_K, α_K/α_L, one has three independent estimates of Λ ($\Lambda=l$ in this case) and they should all agree.

Another method for revealing the l values in successive γ-rays is the angular correlation of successive γ-rays. The theory has been worked out by Hamilton (H10) and Goertzel (G12), and experimentally Brady and Deutsch (B14) have shown the effect to exist in Co^{60} and Sc^{46} (see discussion, Section VII). The angular correlation is sensitive to the I values of the three states involved in the two transitions. Still a further possibility for gaining information is the polarization correlation of successive γ-rays calculated by Falkoff (F8). The effect is sensitive to the magnetic or electric character of the radiation, whereas the angular correlation is not. The polarization correlation of the quanta from annihilation has been experimentally verified by Bleuler and Bradt (B12), and Deutsch and Metzger (D24) have successfully measured the effect for the γ-rays of Rh^{106}. Both of the above effects assume rapid emission of the second γ-ray, and consequently are of no use in isomeric transitions.

In the case in which magnetic multipole radiation has an intensity comparable with electric multipole radiation, i.e., for l odd and transitions between states of the same parity or for l even and transitions between states of different parity, one can still evaluate Λ from τ and the energy according to (38) neglecting for the moment the influence of α, or inserting a rough value, but the α_K/α_L will not be given by the diagrams in Fig. 9. This discrepancy will point to the presence of magnetic multipole radiation, and we make the supposition that any discrepancy between the experimental value of α_K/α_L and the value given in the diagram is due to magnetic multipole radiation. The ratio between the number of K conversion electrons N_K and L conversion electrons N_L is then given by

$$\frac{N_K}{N_L}=\frac{N_{\gamma e}\alpha_K+N_{\gamma m}\beta_K}{N_{\gamma e}\alpha_L+N_{\gamma m}\beta_L}, \quad (51)$$

in which $N_{\gamma e}$ and $N_{\gamma m}$ are the numbers of quanta emitted by electric and magnetic multipole radia-

tion.[9] The meaning of $N_{\gamma e}$ and $N_{\gamma m}$ is the following: If we can decompose the electric field corresponding to our radiation into the sum of the field due to an electric multipole E_e plus the field due to a magnetic multipole E_m, then

$$N_{\gamma e}/N_{\gamma m}=E_e^2/E_m^2.$$

In this formula α_K, α_L, β_K, β_L are furnished by the table in (H6) and formulas (46) (47), N_K/N_L is measured directly and one finds the ratio $N_{\gamma e}/N_{\gamma m}$, i.e., the ratio of the intensity of electric and magnetic multipole radiation.

Even more interesting than $N_{\gamma e}/N_{\gamma m}$ is the ratio between the numbers of nuclear transitions due, respectively, to the electric and magnetic multipoles of the nucleus, which we will call λ_e/λ_m.

This ratio is related to N_K/N_L by the formula

$$\frac{\lambda_e}{\lambda_e+\lambda_m}=\frac{1+\alpha_K+\alpha_L}{1+\alpha_K+\alpha_L+(\alpha_K N_K-\alpha_L N_L)(1+\beta_K+\beta_L)/(\beta_L N_K-\beta_K N_L)}, \tag{52a}$$

which in the practically important limiting case in which all the internal conversion coefficients α_K, α_L, β_K, β_L are large compared to 1 gives:

$$\frac{\lambda_e}{\lambda_e+\lambda_m}=\frac{(\alpha_K+\alpha_L)\left(\frac{N_K}{N_L}-\frac{\beta_K}{\beta_L}\right)N_L}{(N_K+N_L)\left(\frac{\alpha_K}{\alpha_L}-\frac{\beta_K}{\beta_L}\right)\alpha_L}. \tag{52b}$$

An example of this mixed radiation is given by Te^{131} with half-life of 30 hours (H6)[10] and probably more of them will be found in the complicated spectra of natural radioactive substances (see e.g., (M1)) but no extensive calculations on the conversion coefficients for such heavy elements are available at present, such as would be necessary for a systematic comparison with experimental material.

The details of the application of these ideas to several specific cases is given in Section VII.

A more direct test of the theory would be to measure the nuclear spin of a nucleus before and after an isomeric transition either spectroscopically with the help of the hyperfine structure or by molecular beam methods. Kr^{83} and some other cases may afford a possibility in this direction though a spectroscopic attempt by Mrozowski and Segrè in 1940 has failed because of insufficient intensity. It is clear that the amounts of radioactive substances obtainable with present-day methods will make such an experiment feasible.

Another consequence of Weizsäcker's theory worth mentioning is the improbability of the existence of two metastable states of the same nucleus. Assuming four spin units as the minimum spin difference between the excited and the fundamental state, we see that in the most favorable case of spin 0 in the fundamental state we would expect a spin of 4 and of 8 in the two excited states. A spin of 8 is to be considered very exceptional even after the discovery of a spin $I=7$ in Lu by Schüler and Gollnow (S10). Of the seventy odd cases now known, only one case, that of Sb^{124}, outside of Cd^{111} and Te^{121} in which one half-life $\sim 10^{-8}$ sec., has been reported (M16). It is discussed in Section VII.

A very important question about the excited states is their relation to the nuclear model. The most successful nuclear model which has been developed thus far is the droplet model, and though this model is certainly still a very crude approximation one would like to deduce from it at least qualitatively some of the spectroscopic features capable of explaining isomerism. Two main types of movement of the drop have to be considered: surface vibrations and rotations. The rotation of a nucleus as a whole would give rise to rotational levels given by

$$E=(h/2J)I(I+1), \tag{53}$$

in which J is the moment of inertia of the nucleus. If we represent this with a solid sphere of mass M, J is given by $2/5MR^2$, where R is the nuclear radius and by using the mass-radius relation we have

$$E=(2.43\times 10^6/A^{5/3}),\ I(I+1)\text{ electron volts.} \tag{54}$$

The transition probabilities between the rotational states would be exceedingly small because a rotating sphere does not radiate at all and the radiation would be due only to departure from the spherical shape. However, the energy levels resulting from vibrations are also rather close to each other and the rotational levels cannot be considered as a "fine structure" compared with the vibrational ones as in ordinary molecular spectra. The coupling between rotation and vibrations is thus very important. Frenkel (F6) has attempted a description of the low nuclear levels based upon a vibrating rotating droplet model.

Even for the pure rotation the Pauli principle in case of nuclei having certain symmetry properties rules out many energy levels for reasons

[9] According to Mr. Nelson there are no interference effects which would invalidate formula (51).

[10] The quantity computed in (H6) for the examples reported is $\lambda_e/(\lambda_e+\lambda_m)$ and there is a misprint in the case of Te^{131}: It should read, "The experimental data on the radiation can be interpreted consistently if the gamma ray is $\frac{2}{3}$ magnetic multipole radiation $l=4$, and $\frac{1}{3}$ electric multipole radiation $l=5$." We are indebted to Mr. Nelson for this remark and for the calculation of (52a and 52b).

similar to those which rule out half of the rotational levels in homonuclear diatomic molecules with nuclei of spin zero. This aspect of the problem has been discussed by Teller and Wheeler (T3).

Mattauch (M12) has made the interesting observation that there are no isomeric pairs with an even number of protons and an even number of neutrons. He suggests as a possible interpretation of this fact that for a nucleus of this type (even-even) the low levels have a large spacing, and for this reason the transition probabilities between them never become small enough to give rise to isomerism. The case of Pb^{204}, while not completely certain, is a violation of the rule, and the case of Ge^{72}(B13) mentioned above also constitutes an exception within the extended limits of isomeric times. However, "Mattauch's rule" should not be expected to be without exception, and perhaps its principal use in isomeric studies is to suggest the probable isotope in case the mass number is unknown.

V. PRODUCTION OF ISOMERIC NUCLEI

Isomeric nuclei have been produced in many ways. We can divide the methods of production into (a) electromagnetic excitation and (b) nuclear reactions. The first type has been studied only recently; the excitation has been produced directly with high energy x-rays (P5) or with the electric field produced by fast moving charged particles; alpha-particles (L2), protons (B4), and electrons (C2) (M22) have been used in this connection. The second method of production, by nuclear reactions, is older; as we have already said, the first pair of isomers was discovered in a product of beta-decay (H1). Up to the present slow neutron capture, inelastic collision of fast neutrons, and photoelectric effect, as well as bombardment by charged particles, have been used to form isomers through transmutation.

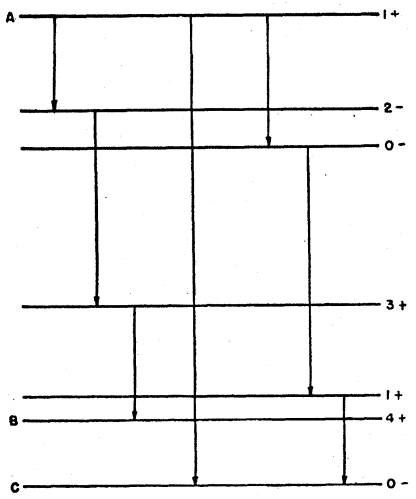

FIG. 10. Nuclear levels. Starting from level A it is possible to reach the metastable level B by a cascading process. The fundamental state C can be reached from A by another cascading process or by a single jump. Only electric dipole radiation has been considered.

In a few cases the isomeric nucleus is formed directly (direct production); in the great majority, however, the formation occurs in two steps: first, the formation of a highly excited state of the nucleus; and second, the decay from this highly excited state to the metastable one by a process of cascading (indirect production).

The cases of direct production are mainly the ones in which the isomeric state is reached by beta-decay. Direct production is impossible by electromagnetic excitation, because the same selection rules which insure the metastability of the isomeric state also prevent a nucleus in the fundamental state from absorbing radiation corresponding to the transition to the metastable state. That this is so is borne out by the experiments cited at the end of this section. In the cases of transmutation in which there is a capture of a particle, direct production is also practically impossible because the nucleus after the capture is left in a state excited by several Mev, much higher than can be expected for any isomeric state.

In the cases of indirect production the primary process will leave the nucleus in a highly excited state and from this a process of cascading will lead to the metastable state. In order to reach conspicuous spin differences in a very short time by dipole or quadrupole radiation, many steps with $l=1$ or 2 will be required. In Fig. 10 we give a very schematic diagram to explain qualitatively this cascading process. The levels in this figure are designated by the symbol + if they are of even parity, − if they are odd. Let us assume that the nucleus is formed by transmutation and is left in state A which has $I=1$ and is even. The nucleus starts to lose its excitation and this may happen in many ways each competing with the other. In Fig. 10 we have drawn jumps corresponding to three competing processes, e.g., one single jump may lead to the fundamental state, a series of jumps may lead to the same state, or finally a series of jumps may lead to the metastable state B. In the latter case the nucleus is left in an excited state and the half-life corresponding to the jump from B to C will be very long because of the large spin difference.

Though not yet well known in detail this process of cascading is revealed experimentally by the number of quanta emitted per neutron capture and by the low energy of the gamma-radiation emitted in connection with slow neutron capture. Measurements of the energy are somewhat conflicting (R1), (F5), (M11). The most recent measurements (M11) suggest that the most probable energy in the case of Cd (n,γ) may be as high as 5 Mev.

The cascading process is considerably complicated by the broadening and overlapping of the highly excited states and little experimental information is available on it.

Among the few experiments performed on this subject we may mention some concerned with the behavior of slow and resonance neutrons in forming isomers. Much of the experimental material refers to genetically related isomers and the cross sections should be calculated from the experimental data taking this circumstance into account.

In formula (8) we have given the ionization produced by a pair of genetically related isomers. We still need the relation between the initial populations N_1 and N_2 and the cross section for their formation.

This is given by:

$$N_2=\Phi\frac{\sigma_2}{\lambda_{2\gamma}}(1-e^{-\lambda_{2\gamma}t}), \tag{55}$$

$$N_1=\Phi\left\{\frac{(\sigma_1+\sigma_2)}{\lambda_{1\beta}}(1-e^{-\lambda_{1\beta}t})+\frac{\sigma_2}{\lambda_{2\gamma}-\lambda_{1\beta}}(e^{-\lambda_{2\gamma}t}-e^{-\lambda_{1\beta}t})\right\}, \tag{56}$$

in which σ_1 and σ_2 are the cross sections for the formation of the two states, Φ is proportional to the number of projectiles falling on the sample per unit area and per unit time and t is the bombardment time. At any successive time the activity measured is given by (8). Formulas (55) and (56) follow immediately from the radioactive decay law.

If $t\gg 1/\lambda_{1\beta}$ and $t\gg 1/\lambda_{2\gamma}$, we have

$$N_2=\Phi(\sigma_2/\lambda_{2\gamma}), \tag{57}$$

$$N_1=\Phi(\sigma_1+\sigma_2)/(\lambda_{1\beta}). \tag{58}$$

Unfortunately many experimental data have been reduced without taking the genetical relation into account and the time of irradiation is not given, so that the cross sections cannot be recalculated from the data.

Measurements on the relative cross sections for the formation of the Rh^{104} or Br^{80} isomers show that the resonance energy is the same for both levels (S28, A2, F10, P6). This is interpreted as a proof that the slow neutron is captured in a single level for both isomers, and that the process leading to the formation of the isomers follows the capture. As an application of this the equality of the resonance energy for the capture process leading to 2 substances has also been used (G10) to clarify some assignment of isomeric pairs. Pontecorvo has also measured the effect of a variation of the energy of the neutrons producing the radioactive rhodium upon the relative cross section. From his data one obtains a ratio for the cross sections of formation of the excited and fundamental state

$$\sigma_2/\sigma_1=1/13.5$$

for thermal neutrons. For neutrons of an average energy less than 0.1 Mev, but well above the thermal he finds $\sigma_2/\sigma_1=1/7.4$. This shows that the capture by many levels leads in the average to a different cascading process than the absorption by a single or few levels. For even faster neutrons (2.4 Mev) Reddeman (R2) finds $\sigma_2/\sigma_1=1/2.64$. Similar experiments have been performed on Br^{80} by Soltan and Wertenstein (S21) and on Br^{80}, Zn^{69}, and a Pt isomeric pair by Nag (N1). Their results agree qualitatively with the ones on Rh described above.

If the energy of the neutrons captured is increased so that capture occurs over many levels of all possible angular momenta, one might expect that the influence of the level in which the capture occurs will be washed out and in the limiting case only the statistical weights $(2I+1)$ of the isomeric states themselves should determine the formation cross section.

In the case of slow neutrons, the absolute value of the cross sections in these reactions is subject to the well-known wide fluctuations characteristic of the slow neutron capture reactions. In a number of cases the capture cross sections for slow neutrons leading to the isomers have been measured. We give in Table II the results of Seren, Friedlander, and Turkel (S14), the most recent and extensive work on the subject. In each case where the upper and lower states are known, the upper state has been placed first.

The following considerations should apply to formation of isomers by slow neutron capture. Referring to Fig. 10, the state A will have a spin differing by $\frac{1}{2}$ unit (the angular momentum of the neutron) from the capturing nucleus. From the isomerism and the β-decay of the resulting isomers, it may be possible to determine which of the two isomeric states B and C has a large spin, which a small. In Table II, the one which has a spin closer to that of A should have the larger cross section. In Section VII, these considerations have been applied to Co^{60} and Br^{80}.

When sufficient evidence is available, the rest of the isomers in Table II, with one or two possible exceptions, also seem to provide agreement with the above ideas.

Returning to the primary process, i.e., to the formation of the highly excited state from which the cascading process starts, we will consider the electric excitation.

The simplest case and a very typical one has been discovered by Pontecorvo and Lazard (P5) who formed In^{115m} by irradiating ordinary indium with a continuous spectrum of x-rays, whose maxi-

TABLE II. Neutron cross sections.

Radioactive isomer	Half-life	Thermal neutron cross section in units of 10^{-24} cm²	Ratio
$_{20}Ca^{49}$	30 min.	0.55	2.68
$_{20}Ca^{49}$	150 min.	0.205	
$_{22}Ti^{51}$	6 min.	0.141	3.6
$_{22}Ti^{51}$	72 d.	0.039	
$_{27}Co^{60}$	10.7 min.	0.66	0.030
$_{27}Co^{60}$	5.3 yr.	21.7	
$_{30}Zn^{69}$	13.8 hr.	0.31	0.288
$_{30}Zn^{69}$	57 min.	1.09	
$_{32}Ge^{71}$	40 hr.	0.073	0.0162
$_{32}Ge_{71}$	11 d.	~0.45	
$_{34}Se^{81}$	57 min.	0.033	0.072
$_{34}Se^{81}$	19 min.	0.46	
$_{35}Br^{80}$	4.4 hr.	2.76	0.34
$_{35}Br^{80}$	18 min.	8.1	
$_{45}Rh^{104}$	4.2 min.	11.6	0.085
$_{45}Rh^{104}$	44 sec.	137	
$_{47}Ag^{110}$	22 sec.	97	47
$_{47}Ag^{110}$	225 d.	2.3	
$_{48}Cd^{115}$	43 d.	0.14	0.127
$_{48}Cd^{115}$	2.5 d.	1.1	
$_{49}In^{116}$	54 min.	144.6	2.79
$_{49}In^{116}$	13 sec.	51.8	
$_{52}Te^{127}$	90 d.	0.073	0.094
$_{52}Te^{127}$	9.3 hr.	0.78	
$_{52}Te^{129}$	32 d.	0.0154	0.116
$_{52}Te^{129}$	72 min.	0.133	
$_{52}Te^{131}$	30 hr.	<.008	0.036
$_{52}Te^{131}$	25 min.	0.222	
$_{55}Cs^{134}$	3 hr.	0.016	0.000625
$_{55}Cs^{134}$	1.7 yr.	25.6	
$_{63}Eu^{152}$	9.2 hr.	1380	1.73
$_{63}Eu^{152}$	5–8 yr.	796	
$_{66}Dy^{165}$	1.25 min.	120 (probably low)	0.0458
$_{66}Dy^{165}$	140 min.	2620	
$_{73}Ta^{182}$	16.2 min.	0.034	0.00165
$_{73}Ta^{182}$	117 d.	20.6	
$_{72}Ir^{192}$	1.5 min.	260	0.26
$_{72}Ir^{192}$	70 d.	1000	
$_{78}Pt^{197}$	18 hr.	1.1	0.244
$_{78}Pt^{197}$	3.3 d.	4.5	

mum energy was 1.85 Mev. Miller and Waldman (M22) have shown that this reaction has a threshold at 1.04 ± 0.02 Mev. The isomeric state is known to be 0.34 Mev above the ground state. This result should be interpreted by assuming that In^{115} has at 1.04 Mev an excited level which combines both with the fundamental one and with the isomeric one. This level is excited directly under the x-ray irradiation and is the starting point for a cascading process by which the metastable level is reached. The excitation is due to a line absorption in a very narrow level as has been shown by Guth (G5), and a measurement of the excitation function under these circumstances gives only an isochromat of the x-rays used, but no information concerning the nuclear process. However, if one increases very much the energy of the x-rays, other nuclear levels may become effective as starting points of cascading processes, and a jump in the cross section for the production of the isomer is expected. This behavior has been actually observed by Miller and Waldman (M22).

Directly connected with the x-ray excitation is the excitation by electron impact. This type of excitation has been demonstrated, again in the case of In^{115m} by Collins and Waldman (C2) by bombarding indium with 1.3-Mev electrons. They found a cross section of the order of magnitude of 10^{-32} cm². The theory of electrical excitation by electrons has been developed by Wick (W24). Similar calculations have recently been published by Sneddon and Touschek (S30). In these calculations the density of nuclear levels as a function of energy and the matrix elements of the nuclear electric dipole and quadrupole moments play an essential part. The uncertainty of these quantities make the final results, as far as the absolute cross sections are concerned, little more than an estimate of the order of magnitude. However, the ratio between the cross section for electrical excitation by x-rays and by electrons can be calculated much more accurately because it is largely independent of nuclear structure. Broadly speaking a quantum is more effective than an electron of the same energy by a factor of the order of 137.

The case of excitation by the electrical field of heavy charged particles has been sketched by Weisskopf (W4) and is affected in the same way as the calculations of Wick by the uncertainty in the nuclear matrix elements involved.

Experiments on the electrical excitation of isomers both by particles and quanta will certainly contribute to a better knowledge of important nuclear quantities; Guth (G5) has given an example of the way in which the experimental results can be used.

In the case of the formation of isomers by beta-decay Weizsäcker's theory in connection with all

current theories of beta-decay make it likely that with the exception of some special cases the beta-decay would lead directly only to the formation of a single isomeric state. This is made clear by Fig. 11a in which we represent a level C of a beta-radioactive nucleus decaying to a level A of another nucleus. Since the selection rules for beta decay allow transitions with a spin difference of 0 or 1, according to the various modifications of Fermi's theory (K6), we must assume that the level A has the same spin as C or a spin very close to that of C. On the other hand, the isomeric level D must have a spin much different from C and hence from A. This renders a direct beta transition from D to A unlikely, and much more likely the transition from D to B as indicated.

Figure 11b shows an alternative in which the spins of the levels C and D would be reversed from Fig. 11a. This case is known in Cd^{115} (H16), where the transition $D-A$ is the 43-day isomer, the transition $C-B$ is the 2.3-day isomer, and the transition $B-A$ is the 4.5-hr. In^{115} isomer.

Possible exceptions would be cases in which the spin of C was intermediate between the spins of A and B or cases in which the energy difference between A and B could compensate the action of the spin difference on the beta-decay probability or even make one beta-transition impossible. An example of this situation is afforded by Sr^{87m} carefully investigated by DuBridge and Marshall (D3). These investigators have found an excited state of Sr^{87} 0.36 Mev above the fundamental. Its half-life is 2.75 hours. From these data one would expect $\Delta=5$. The spin of Sr^{87} is 9/2 and hence probably the spin of Sr^{87*} is 1/2 and the parities of the states opposite if we do not want to admit a spin of 17/2. The spin of Rb is 3/2 (K2, M2) and a beta-transition from Rb^{87} to Sr^{87m} is energetically impossible because the levels are as in Fig. 12 and the beta-transition from Rb^{87} to Sr^{87m} would be endoenergetic.

Among the fission products of uranium we know

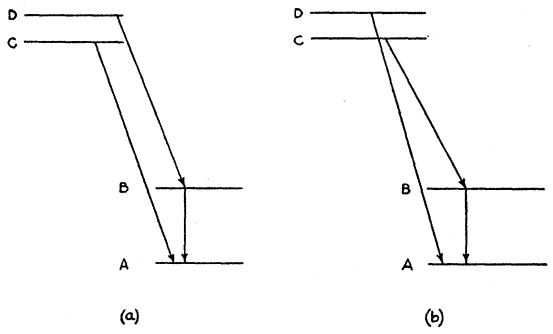

FIG. 11. Examples of Type *II* isomerism. (a) Level D has spin close to that of B. (b) Level D has spin close to that of A.

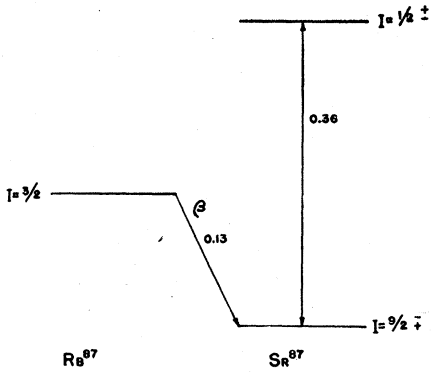

FIG. 12. Nuclear levels in Rb and Sr.

various examples of beta-decay of antimony leading to isotopes of tellurium possessing isomeric states and an investigation of the branching processes would be of interest.

VI. SEPARATION OF ISOMERS[11]

A chemical method for separating nuclear isomers has been proposed by Segrè, Halford, and Seaborg (S5) and applied by them, as well as by de Vault and Libby (D4) to separate the bromine isomers. Later the same method was applied to tellurium by Seaborg, Livingood, and Kennedy (S7), and to selenium by Langsdorf and Segrè (L3). Its physico-chemical aspects have also been extensively studied, especially by J. E. Willard, Seaborg, Friedlander, and Kennedy (W5, S8).

When in a molecule one of the constituent atoms undergoes an isomeric transition, various effects may occur which may destroy the chemical bond. First, the simple recoil from the emission of a gamma-ray gives to the atom undergoing the transformation a kinetic energy of E ev:

$$E=\hbar^2\omega^2/2Mc^2=0.54\times10^{-3}\epsilon^2/M, \qquad (59)$$

in which ϵ is the energy of the gamma-quantum in kev and M the atomic weight of the nucleus (O=16). If the gamma-ray is internally converted the recoil energy is of course larger because it corresponds to the recoil from the emission of a particle having a finite rest mass and is given by

$$E=(4.80/M)\times10^{-5}(H\rho)^2. \qquad (60)$$

$H\rho$=momentum of the electron in gauss-cm. E is given by (59) and (60) in ev.

These recoil energies may sometimes be sufficient to break the molecule; however, e.g., in the case of bromine 80, the recoil energy is only 0.0155 ev for the gamma-ray recoil, or 0.034 ev for the conversion electron recoil. This is definitely smaller than the

[11] A review of this subject has been written by K. Starke, Physik. Zeits. **42**, 184 (1941).

chemical bond energy and should not lead to a breaking up of the molecule.

However, in the case in which internal conversion occurs another effect is instrumental in bringing about chemical changes: an electron orbit, in an inner shell of the atom, becomes vacant and the outer electrons fall in until even the valence electrons are affected. Then the chemical bond will break and the atom having suffered the isomeric transition detaches itself from the molecule becoming an ion or changing its valence. It is then possible to pick it up by chemical methods as in the well-known Szilard-Chalmers separation in neutron bombardments. For example, if we prepare bromobenzene or some other organic compounds of bromine, using Br^{80} in the upper isomeric state ($\tau = 4.5$ hr.), we can later extract the organic compound with water and a small amount of sodium sulphite. In the water fraction upon precipitation with silver nitrate we find pure Br^{80} in the lower isomeric state ($\tau = 18$ min.). The molecules in which Br has undergone an isomeric transition have broken down and set the bromine free. In the water layer this bromine has been converted to Br^- and precipitated by the silver nitrate whereas none of the bromine which has not undergone the isomeric transition has broken loose from the organic molecule. Of course one can also observe the growth of the 18-min. Br^{80} in the organic compound after the separation and thus check most directly the genetical relation between the two bromine isomers.

As pointed out above, it seems that internal conversion is essential for the working of this method. This has been pointed out by Willard (W6), and Fairbrother (F7) and confirmed by an experiment of Seaborg, Friedlander, and Kennedy (S8). These authors prepared zinc di-ethyl with Zn^{69} in its upper state and tellurium di-ethyl with Te^{127} or Te^{129} in its upper isomeric state. They vaporized the compounds and introduced them into a vessel containing two electrodes at a few hundred volts potential difference. In the case of tellurium, the atoms in the lower isomeric state were collected from the vapor. In the case of zinc no activity was collected as had been observed by Kennedy, Seaborg, and Segrè (K3). Since the two starting compounds are rather similar and the chemical binding of the zinc and tellurium atom has in both cases about the same strength, it is natural to ascribe their different behavior to the fact that whereas in tellurium one has a very large internal conversion coefficient, in the case of zinc the internal conversion is very small.

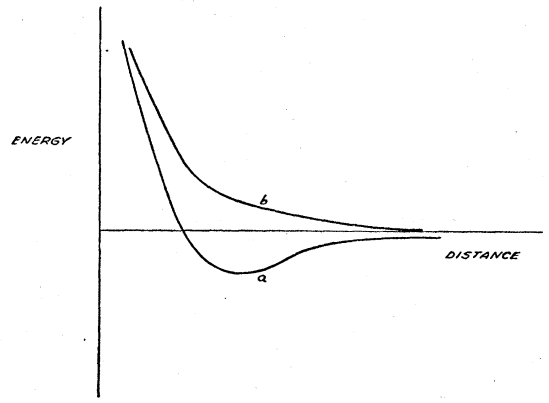

FIG. 13. Potential energy as a function of internuclear distance for a molecule: *a* in normal state, *b* in which one atom has undergone an isomeric transition with internal conversion.

This result is even more remarkable if one takes into account the fact that the energy difference between the isomeric states in the case of zinc is 439 kev and only about 100 kev in the case of tellurium. The recoil energy for a gamma-ray in the first case is 1.5 ev where the recoil energy for the conversion electron in the second case is only about 0.7 ev. In spite of this strong difference, the chemical isomeric separation in tellurium is very much more efficient than in zinc, pointing out that internal conversion, not recoil, plays an essential part in the method. This can be understood under various mechanisms. One has already been outlined and this is the simple successive fall of the electrons into the vacant places occasioned by the emission of the conversion electron until even the valence electrons fall into an inner shell breaking the chemical bond.

Besides we must consider that the ejection of the conversion electron is a process very short compared with the molecular vibration periods. After the conversion electron has been ejected the molecule may find itself in a state of predissociation. This is seen most clearly by imagining that the ejection of the K or L electron increases suddenly by one unit the effective nuclear charge of the atom and this will cause a great change in the wave functions of the outer electrons.[12] In Fig. 13 we have drawn the potential curves *versus* nuclear distance for the molecule (curve *a*); by the application of the Franck-Condon principle we see how a molecule in the fundamental vibrational state because of the isomeric transition jumps from curve *a* to curve *b* and thus reaches a state of predissociation. A theoretical study of these phenomena has been made by Cooper (C13). No detailed experimental investigations on the particular mechanism of decomposition are available yet, and those put forward above are hypothetical, no decision being possible between them on the available experimental evidence. However, from the quoted experiments of Willard (W6), Seaborg, Friedlander, and Kennedy (S8), Kennedy, Seaborg, and Segrè (K3)

[12] This effect may be enhanced by the ejection of Auger electrons following the evacuation of the K shell.

it is apparent that there is a close relationship between the yield of the isomeric separations and the internal conversion coefficient. In an ideal case in which only the molecules undergoing the isomeric transition with ejection of a conversion electron are decomposed and extracted we would have

$$\alpha = p/(1-p), \tag{61}$$

in which α is the internal conversion coefficient and p is the fraction of the total activity extracted by the chemical method.

DeVault and Libby (D5) have measured p for several reactions involving Br^{80} and have found values of p varying between 0.026 and 0.095. It is reasonable to assume that the highest observed p, gives according to (61) a lower limit for α. Hence in the case of Br^{80} $\alpha > 20$. This is in agreement with the experiments of Grinberg, and Roussinow (G4) (see Section VII) who find no unconverted 47-kev γ-rays.

The chemical method affords thus an indirect way of measuring the internal conversion coefficient. Also in the case of the three tellurium isomers and of Se^{81} the yield of the chemical method indicates that the internal conversion coefficient is high.[13] The lower values of p observed in some cases (L4) (D5) are almost certainly to be ascribed to the chemical features of the reactions employed.

The chemical separation of isomers can also be operated in some cases by an exchange reaction as shown by Imre (I1) who concentrated the 18 min. Br^{80} on the surface of a silver bromide precipitate suspended in an aqueous solution containing ions of the 4.5-hr. Br^{80}. Segrè (S9) had similarly concentrated the 18-min. Br^{80} as an invisible layer on the surface of metallic silver immersed in bromobenzene containing the 4.5-hr. Br^{80}. Electric fields in non-conducting solutions can also be used to collect the lower isomeric state (C15) (G13).

VII. SELECTED CASES OF ISOMERISM

In the following section a detailed consideration of the available data on several isomers is given. The cases have been picked somewhat at random, but partly because considerable amounts of data are available for them, and consequently the conclusions which can be drawn regarding the theory given in the previous sections are clearer. Three cases of type *I* isomerism are given, although many more have received careful study. Two cases of essentially type *II* are included, and these represent the only ones besides $UX_2 - UZ$ for which detailed investigations have been performed.

[13] Recent work by R. R. Williams (W23) indicates maximum yields in the Te isomers of considerably less than 100 percent. Whether this should be taken to indicate conversion in considerably less than 100 percent of the cases is, however, open to considerable question.

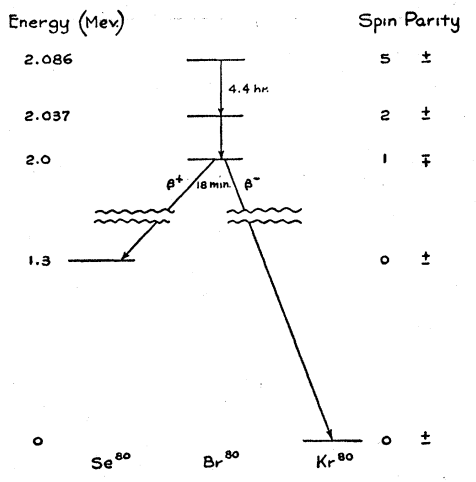

FIG. 14. Decay scheme. Energy, spin and parity.

Br^{80}

The case of Br^{80} is a classic in the history of artificial radioactivity. Its establishment as a bona fide case of nuclear isomerism has been discussed in Section I. Attempts to determine which was the upper state on the basis of reaction thresholds were inconclusive because as will be seen, the isomeric levels are very close together. In addition, the question whether the type was *I* or *II* was unknown. However, the chemical method of separation introduced by Segrè, Seaborg, and Halford (S5) showed conclusively that the 4.4-hr. isomer decayed into the 18-min. isomer, establishing this as a type *I* case. (See Section VI for a discussion of this method.) Shortly afterward the conversion electron lines of two γ-rays were photographed by Valley and McCreary (V1). They observed three electron lines which could be ascribed to the *K* and *L* lines of a 49-kev γ-ray, and the *L* line of a 25-kev γ-ray, or the *K* and *L* lines of a 37-kev and a 49-kev γ-ray, the *L* line of the former and the *K* line of the latter falling on one another. This point was settled by the experiments of Grinberg and Roussinow (G4), who showed from absorption measurements, using critical absorbers, that a γ-ray of energy between 35.9 and 37.4 kev was emitted. They observed no quanta of energy 49 kev and measured a conversion coefficient of 1 $(N_e/(N_e+N_q)=0.5)$ for the 37-kev γ-ray. From these data it is fairly clear that Br^{80} possesses a state 86 kev above the ground state, and that the direct transition from this state to the ground state is very highly forbidden. The transition to the state at 37 kev, however, has a 4.4-hr. half-life, and the transition from the 37-kev state is presumably rapid.

The matter has been further studied in detail by Berthelot (B11), who has remeasured the con-

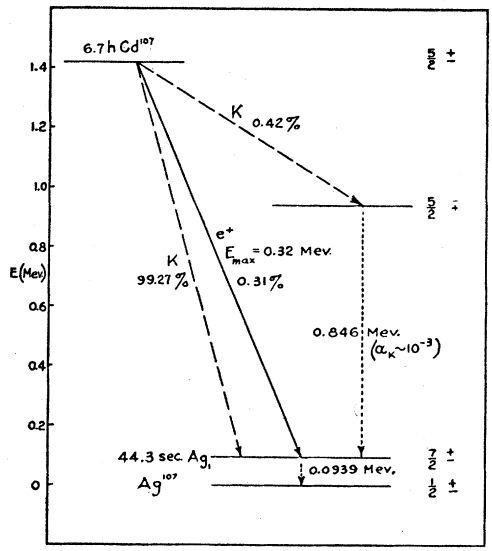

FIG. 15. Decay scheme. Energy, spin and parity.

version coefficient of the 37-kev γ-ray, and has determined the K and L conversion coefficients of each γ-ray. His method of separating the electrons was to use absorption which will be considerably less accurate than to use a β-ray spectrograph with thin windowed counter (the sensitivity of photographic film to electrons varies rapidly in this energy region). Assuming again that the conversion of the 49-kev γ-ray is complete ($\alpha=\infty$), he finds $\alpha_K/\alpha_L=7.3$ for the 49-kev γ-ray, and $\alpha_K/\alpha_L=7$ for the 37-kev γ-ray with $\alpha_K+\alpha_L=0.64$. Comparing these values with the theory of Hebb and Nelson (H6), he concludes that the 49-kev γ-ray is magnetic octupole and the 37-kev γ-ray is magnetic dipole. The calculated half-life is of the right order of magnitude, but there is a strong objection to his proposed scheme. According to the selection rules (Table I), the parity of the 86-kev level and the ground state must be the same, and therefore the transition between these two states should proceed by an electric 2^4 pole transition with a lifetime shorter than 4.4 hr. because of the greater energy involved. Consequently, it seems more likely that, for example, the 37-kev γ-ray is electric dipole, as was suggested by Roussinow and Grinberg (G4), the parity of the states and spins are as shown in Fig. 14. According to Konopinski (K6), the 18-min. β^--transition, and the corresponding β^+-transition discovered by Barber (B15), are once forbidden. Since the spin of Kr^{80} is 0, the most logical spin assignments would be those in the diagram. Accurate measurements with a β-ray spectrograph of α_K/α_L might help in clarifying the situation.

The spin of Br^{79} is $\frac{3}{2}$ so the nucleus Br^{80} formed by slow neutron capture will have spin 1 or 2. In the resultant cascade process, one would expect on the basis of the above assignment, a greater formation of the 18 min. than the 4.4 hr. Actually as is seen in Table II, this is true, the ratio being 2.9.

Ag^{107}

The isomerism in Ag^{107} was discovered by Alvarez, Helmholz, and Nelson (A3), who considered that the small value of α_K/α_L observed in the 93-kev γ-ray from the 6.7 hr. Cd activity indicated a large spin change in the transition in the Ag nucleus resulting from K capture. They found a 40-sec. Ag activity corresponding to this transition. This case has been fully investigated by Bradt *et al.* (B10), who measured the half-life as 44.3 sec. The isomeric state has also been produced by x-ray excitation by Wiedenbeck (W13), and has been assigned by Helmholz to Ag^{107} on the basis of bombardment of separated Cd isotopes (H27). The level scheme proposed by Bradt *et al.*, who find positrons of upper limit 0.32-Mev and 0.846-Mev γ-rays as indicated, is given in Fig. 15. They compare the number of unconverted isomeric γ-rays to the number of annihilation quanta, obtainable from the positrons, and they also compare the number of positrons to the number of internal conversion electrons. From these two ratios, knowing the relative efficiency of the counters for positrons and annihilation radiation, they calculate $\alpha=16\pm3$. The value of α for electric 2^4 pole radiation is 165, for magnetic 2^3 pole 24. Therefore, the assignment would seem to be definite to magnetic 2^3 pole. However, the ratio α_K/α_L is 0.92, while the theoretical ratio for the magnetic transition is 4.2, for the electric transition, 0.58. On this basis the radiation would be 80 percent electric and 20 percent magnetic. The discrepancy is perhaps due to the fact that the calculation of conversion coefficients by non-relativistic calculations in this region is not accurate. The calculated half-life on the basis of Eq. (39a) is too long by a factor of 1500, while for $\Lambda=3$ it would be too short by a factor of 4000. Considering all the evidence, it seems probable that the spin change is 3, with electric octupole radiation forbidden, which makes the spin of the 93-kev state 7/2 since the spin of Ag^{107} is known to be 1/2. The 0.846 γ-ray is electric dipole. The parity of the ground state, and the 0.093-Mev state must be opposite since the electric 2^3 pole radiation is forbidden. The β^+-transition and the K capture are allowed transitions.

Mn^{52}

A case of the type *II* isomerism is that of Mn^{52}. These isomers were discovered by Livingood and Seaborg (L5), who produced them by the reaction $Fe^{54}(d,\alpha)Mn^{52}$. Hemmendinger (H7) produced them by the reaction $Cr(p,n)Mn$, and investigated the

radiations. Peacock and Deutsch (P13) and Osborne and Deutsch (O4), using a β-ray spectrograph and coincidence methods studied the activities thoroughly, and the results given here are taken from their papers. The isomers have periods of 6.5 days and 21 min. The 6.5-day period emits positrons with an upper limit of 0.582 Mev, followed by three γ-rays in cascade, of energy 0.734, 0.940, and 1.46 Mev. $\beta-\gamma$-coincidences are independent of the β-energy, showing the spectrum of β-rays is simple. This isomer also undergoes K capture, which is followed by the same three γ-rays. The ratio λ_K/λ_β is 0.54, and an analysis of this data seems to indicate that the transition is an allowed one with $\Delta I=0$ or 1 and no parity change (G14).

The 21-min. period studied by Osborne and Deutsch (O4) has a positron spectrum with upper limit of 2.66 Mev followed by a single γ-ray of 1.46 Mev. This is almost certainly the same γ-ray observed in the longer period, and indicates that the first excited state involved in these transitions is at 1.46 Mev. Adding up the total energies of decay, one finds that the 21-min. period is the upper state by $2.66-0.582-0.734$, or 0.40 Mev. Osborne and Deutsch confirmed this by finding one conversion electron from a 0.392-Mev γ-ray for every 2×10^3 disintegrations. The conversion coefficient for a γ-ray of this high energy will be low, so that there must be considerably many more γ-rays than electrons. Assuming magnetic 2^4 pole radiation, the conversion coefficient would be 0.039, and consequently the half-life of the transition would be $21\times2\times10^3\times0.039$ or about 1600 min. A transition with $\Delta=5$ gives 1.6×10^5 min. for a half-life, which is not good agreement but considerably better than $\Delta=4$ which gives 20 sec. Therefore, we might assume that the two isomeric states differ by 4 units of spin, and that their parities are opposite, so that electric 2^4 pole radiation is forbidden. To avoid assigning spins larger than 4, it would seem logical to assign $I=0$ to the

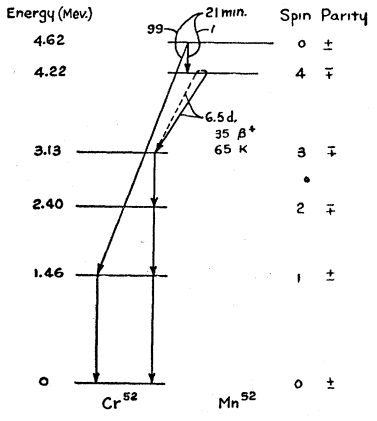

FIG. 16. Decay scheme. Energy, spin and parity.

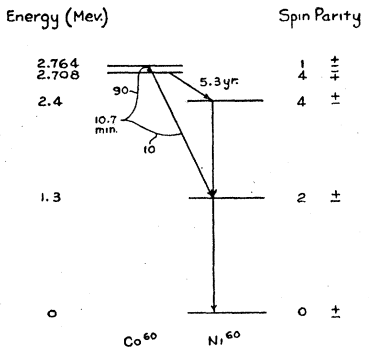

FIG. 17. Decay scheme. Energy, spin and parity.

21-min. level, $I=4$ to the 6.5-day level. This leads to a level scheme such as given in Fig. 16. The 21-min. β^+-transition is allowed to the 1.46-Mev state, but forbidden to the ground state since a 0–0 transition is at least twice forbidden by G-T selection rules. The three excited states in Cr^{52} must have increasing spins, so that the direct transitions to the ground state which has spin 0 are sufficiently forbidden. More definite knowledge of the character of the 1.46-Mev state would seem to be imperative in order to formulate a level diagram with certainty.

Co^{60}

Co has only a single stable isotope, Co^{59}, and bombardment with slow neutrons produces two radioactive periods, 10.7 min. and 5.3 yr., which must be assigned to Co^{60}. A thorough investigation of these activities has been made by Deutsch, Elliott, and Roberts (D13). The 5.3-yr. activity is, of course, the easier to study. Careful measurements using a β-ray spectrograph and $\beta-\gamma$- and $\gamma-\gamma$-coincidences has shown that β-rays of maximum energy 0.308 Mev are emitted followed by two γ-rays in cascade, having energies 1.1 and 1.3 Mev. A study of the angular correlation of the two γ-rays by Brady and Deutsch (B14) indicates that each is a quadrupole radiation, and that the states involved probably have spins 0, 2, and 4, since ground state of Ni^{60}, into which Co^{60} decays, undoubtedly has spin 0. This assignment is further borne out by the observation (D20) that less than one 2.4-Mev γ-ray for every 10^5 disintegrations is observed; in other words, that the direct transition from the 2.4-Mev state to the ground state is highly forbidden. The level scheme of Fig. 17 is a possible one on the basis of these data. Since the directional correlation of γ-rays does not distinguish electric and magnetic radiation, the parities of the states are arbitrary and have been picked to allow the minimum value of I of the 10.7-min. state. The transition from the 5.3-yr. state of Co^{60} to the ground state of Ni^{60} is, of course, highly forbidden,

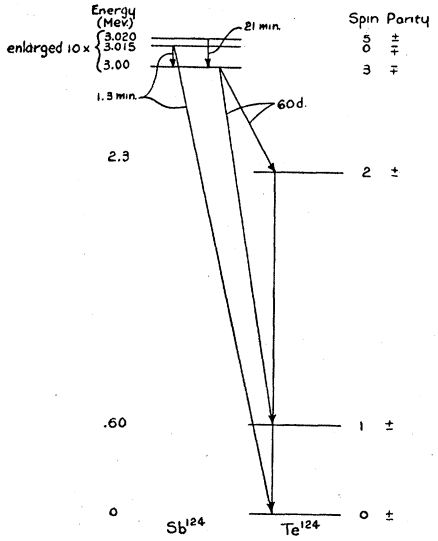

FIG. 18. Decay scheme. Energy, spin and parity.

and the 0.308-Mev transition is either once or twice forbidden.

Turning now to the 10.7-min. period, Deutsch, Elliott, and Roberts (D13) find conversion electrons of a 0.056-Mev γ-ray, which must be the type I isomeric transition. This occurs in about 90 percent of the cases. In the other 10 percent of the cases, a β-ray of maximum energy 1.28 Mev (from evidence to follow, this must be 1.45) is emitted followed by a γ-ray which has been found by Peacock (D20) to be identical with the 1.3-Mev γ-ray emitted in the long-lived activity. Assuming as mentioned above that the 1.3-Mev level (see Fig. 17) has a spin of 2, the 10.7-min. level must have a spin of 1 with the same parity.[14] Then the β-ray transition will be allowed; the γ-ray transition to the 5.3-yr. level would then proceed as an electric 2^3 pole ray, the parities of the two isomeric levels being opposite. The half-life given by the theory for this transition is about 0.2 sec., which is not in good agreement with 12 minutes, the "partial half-life" for the transition. However, electric 2^4 pole gives 3×10^5 sec. which disagrees by an even larger factor. A measurement of the ratio of K to L conversion electrons in this case might settle the order of the γ-transition, but this is difficult with the short half-life. The level scheme of Fig. 17 would seem to fit the facts fairly well.

One further point is worth mentioning. Both 10.7-min. and 5.3-yr. isomers are found by capture of slow neutrons in Co^{59}, which has $I=7/2$. The compound nucleus will consequently have $I=3$ or 4, and as pointed out by Deutsch, Elliott and Roberts, if this de-excitation proceeds by an emission of a small number of quanta, the 5-yr. state ($I=4$) should be favored over the 10.7-min. state ($I=1$). Actually, experimental measurements (see Table II) do show a 33 times greater cross section for the formation of the 5-yr. isomer.

[14] Another consistent scheme would give 10.7-min. level $2\pm$, 5.3 yr. $5\mp$, and ground state $0\pm$, all others being the same.

Sb^{124}

A final interesting and puzzling case is that of triple isomerism in Sb^{124} reported by der Mateosian *et al.* (M16). They found three radioactive periods associated with Sb^{124}, all of which are produced by slow neutron capture in samples enriched in Sb^{123}. One period is the well-known 60-day period for which the decay scheme of Scharff-Goldhaber and Meyerhof (M17) is given in Fig. 18. The two additional periods are 21 min. which emits very low energy conversion electrons, corresponding to a γ-ray energy of about 20 kev and β-rays, and 1.3 min. which emits energetic β-rays of upper limit 3.0 Mev and a few low energy conversion electrons. The conversion electrons correspond to a γ-ray energy of 15 kev, and no Sb K x-rays are observed, showing that enough energy for K conversion is not available.

Both the 1.3-min. and the 21-min. states must, since they both emit highly converted γ-rays, be upper states in Sb^{124}. Let us assume they both decay to the 60-day state, which has a total disintegration energy with respect to Te^{124} of $0.6+1.7+0.7=3.0$ Mev. Since the 21-min. transition emits a converted γ-ray of 20-kev energy, we can place it as 3.020 Mev above Te^{124}, and assume the β-rays observed are those of the daughter 60-day period. A spin change of 2 with electric quadrupole radiation forbidden might be sufficient to explain the 21-min. half-life. Theoretically, it gives $\frac{1}{2}$ min. for magnetic quadrupole but only 0.04 sec. for electric 2^3 pole, the conversion coefficient in this latter case being much larger. In any case the β-transition to the ground state of Te^{124} must be highly forbidden. The 1.3-min. state must have a lifetime against transition to the 60-day state fairly long compared to 1.3 min., since its predominant mode of decay is by β-emission directly to the ground state of Te^{124}. Again a spin change of 2 with electric quadrupole radiation forbidden might provide the necessary lifetime. For a pure magnetic quadrupole transition, the calculated half-life is 13 min. The β-transition to the ground state of Te^{124} is probably once forbidden. One can see that a number of possible level schemes would be possible with only this much to work on. The scheme in Fig. 18 is one such scheme. The 0.7-Mev transition from the 60-day level is once forbidden according to the formulas given by Konopinski while the 2.4 Mev is at least twice forbidden. Accordingly the spin assigned to the 60-day state is 3, so that the transition to the

TABLE III. Table of isomers.*

Z	A	Class	Type of radiation	Half-life	Type of isomer		Energy of radiation particles	Energy of radiation γ-rays	Remarks
20	Ca^{49}	A	$\beta^-,\gamma(e^-?)$	2.5 hr.(W9)	II(?)		2.3(W9) abs.	0.8(W9) abs.	
	Ca^{49}	C	β^-	30 min.(W9)	II(?)				Might be Ca^{41}-(H30) report production by (γ,n).
21	Sc^{44}	A	e^-,γ	2.2 d.(W8)(S19) 2.44 d.(H17)	I	U		*0.269*(S19) spect.	$\alpha=0.08$; $\alpha_K/\alpha_L=8$ but not sensitive to l in this region. Theory gives $\alpha=0.15$, $\tau\sim10$ min. for $E2^4$. $\Lambda=4$ seems preferable.
	Sc^{44}	A	β^+	4.1 hr.(W8)	I	L	1.47(S19) spect.	1.33(H17) abs.	
	Sc^{46}	A	e^-,γ	20 sec.(G22)	I	U		*0.18* abs.(G22)	Both conversion electrons and γ-rays observed. $\Lambda=4$ probable. Theory predicts $\tau\sim1$ hr.
	Sc^{46}	A	β^-,γ,K(W10)	85 d.(W10)	I	L	0.36, 1.49 weak. (P12) spect.	0.88, 1.12(P12)	Probably 0,2,0 cascade in Ti^{46} nucleus (B23).
22	Ti^{51}	A	β^-,γ(W8)	6 min.(S9)	II	U(?)	1.6(S9) abs.		Probably upper state from energies.
	Ti^{51}	A	β^-,γ	72 d.(W10)	II	L(?)	0.36(W10) abs.	1.0(W13) abs.; Lower energy (M8)	β-spectrum probably simple. Sometimes γ's in cascade (M8).
25	Mn^{52}	A	β^+,γ	21 min.(L5)	I, II	U	2.66(O4) spect.	*0.392*, 1.46(O4) spect.	See discussion Section VII.
	Mn^{52}	A	β^+,K,γ(G14)	6.5 d.(L5)	I, II	L	0.58(P13) spect.	0.73, 0.94, 1.46(P13) spect.	
27	Co^{58}	B	e^-	9.3 hr.(S35)	I	U		.023(S35) spect.	$\Lambda=3$ probable
	Co^{58}	A	β^+,γ,K(G14)	72 d.(L14)	I	L	0.47(D23) spect.	0.805(D23) spect.	
	Co^{60}	A	β^-,γ,e^-	10.7 min.(L14)	I, II	U	1.56(P7) spect.	*0.056*, 1.30(D13)(P12) spect.	See discussion Section VII.
	Co^{60}	A	β^-,γ	5.3 yr.(L14)	I, II	L	0.31(D12)	1.16, 1.30(P7)(J1) spect.	
30	Zn^{69}	A	e^-,γ	13.8 hr.(L7)	I	U		*0.439*(H8) spect.	$0.1>\alpha>0.01$ indicates $\Lambda=5$. Theory gives $\tau\sim270$ hr. $E2^5$ or $M2^4$. Spin probably $9/2\pm$.
	Zn^{69}	A	β^-	57 min.(L7)(K3)	I	L	1.0(K3)	No γ(K3)	Spin probably $\frac{1}{2}\mp$.
32	Ge^{71}	A	β^+	40 hr.(S11); 36 hr. (H17)	II	U(?)	1.2(S11) abs.		Energies seem to indicate upper state.
	Ge^{71}	A	K,e^-(S11)β^+(?) (M13)	11 d.(S11)	II	L(?)	0.6(M13) spect.	0.5(M13) spect. 0.6(S23) abs.	This isomer not observed by (γ,n)(H37).
	Ge^{72}	A	e^-	5×10^{-7} sec.(B13)	I	U		*0.70*(B13)	May be 0–0 Transition. See Section IVf.
	Ge^{72}	A		stable	I	L			
	Ge^{77}	A	β^-(A8)	59 sec.(A8)	II		2.8(A8) abs.		Study of γ-rays necessary to assign U and L.
	Ge^{77}	A	β^-(S17)	12 hr.(S11)	II		1.9 cl. ch.(S17) (S22)		
33	As^{71}	A	K	60 hr.(H32)	II				
	As^{71}	B	β^+	52 min.(H31)	II				
34	Se^{77}	A	e^-	17.5 sec.(G15)	I	U		*0.15*(A8) abs.	Theory predicts $\tau\sim2$ hr. for $\Lambda=4$.
	Se^{77}	A		stable	I	L			
	Se^{81} (L6)	B	e^-(L3)	57 min.(L3)	I	U		*0.99*(H8) spect.	$\Lambda=4$ probable from half-life; $\alpha_K/\alpha_L=4$ indicates 50% $E2^4$, 50% $M2^3$.
	Se^{81}	B	β^-	19 min.(L3)	I	L	1.5(L3) abs.		
	Se^{83}	B	β^-,γ(A8)	67 sec.(A8)	II		3.4(A8) abs.		Transition to ground state of Br^{83} probably allowed.
	Se^{83}	A	β^-,γ	30 min.	II		1.5(G21) abs.	0.17, 0.37, 1.1(G21) abs.	Transition to ground state of Br^{83} highly forbidden.
35	Br^{80}	A	e^-,γ	4.4 hr.(B11)(S5)	I	U		*0.049*, 0.037(V1) spect. (G4) abs.	See discussion Section VII.
	Br^{80}	A	β^-,β^+(B15)	18 min.(S2)(S5)	I	L	β^- 2.0(A10) spect. β^+0.7(B15) abs.	0.5(S2)(B16) abs.	
36	$Kr^{79,81}$	C	e^-,γ, no β^+	13 sec.(C5)	I	U		*0.187*(C5) spect.	Certainly isomeric transition; assignment doubtful. Probably $\Lambda=4$.
	$Kr^{79,81}$	C	e^-,γ, no β^+	55 sec.(C5)	I	U		*0.127*(C5) spect.	Same as 13 sec.
	Kr^{79}	A	β^+(2%),K(98%) (W25)	34 hr.(B17)(C6)	I	L	~.9(30%)~.6(70%) (H34) abs.; 1.0 (W25) abs.	0.2(H34) abs.	Lower state of 13 sec. or 55 sec.
	Kr^{83}	A	e^-	113 min.(L3)	I	U		*0.029* or *0.046*(H8) spect.	Both γ's present. $\alpha K/\alpha_L\sim1$ for 0.046 γ-ray. Assuming this is responsible, $\Lambda=4$ 60% $E2^4$, 40% $M2^3$. Calculated $\tau\sim50$ hr. Spin $3/2\pm$
	Kr^{83}	A		Stable	I	L			Spin $9/2\pm$
	Kr^{85}	A	β^-,γ(H34)	4.5 hr.(H34)(W25)	II	U(?)	1.0(H34) abs.	0.17, 0.37(H34) abs.	Must be upper state from β-energies
	Kr^{85}	B	β^-	~10 yr.(H33)	II	L(?)	0.74(H33) abs.	No γ(H33)	
38	Sr^{85}	A	e^-,γ(D3)	70 min.(D3)	I	U		*0.170*(D3) spect.	$\Lambda=4$ predicts $\tau\sim150$ min. Check of α, α_K/α_L could fix value of l.
	Sr^{85}	A	K, γ(D7)	65 d.(D7)	I	L		0.8(D3) abs.	
	Sr^{87}	A	e^-,γ(D7)(R3)	2.7 hr.	I	U		*0.386*(H8) spect.	$\alpha_K/\alpha_L=6$, $\alpha\sim0.15$, and τ all indicate $\Lambda=5$, $E2^5$. Spin $\frac{1}{2}\pm$.
	Sr^{87}	A		Stable	I	L			Spin $9/2\mp$.

TABLE III.—*Continued.*

Z	A	Class	Type of radiation	Half-life	Type of isomer		Energy of radiation particles	Energy of radiation γ-rays	Remarks
39	Y^{87}	*B*	e^-,γ(D3)	14 hr.(D3)(S12)	*I*	*U*		*0.5*(D3) abs.	Evidence uncertain.
	Y^{87}	*A*	K(D7)	80 hr.(D7)	*I*	*L*		No γ(?)(D3)	Decays to 2.7-hr. Sr^{87}
	Y^{88}	*A*	K,γ(D3)(H19) β^+,0.19%(P14)	105 d.(D3)	*II*	*U*(?)	0.83(P14) spect.	0.908, 1.89(D14) spect. 2.8(1%)(G16) *D*(γ,*n*)	0.908 and 1.89 in cascade. β^+ transition to Sr^{88} highly forbidden.
	Y^{88}	*A*	β^+	2 hr.(S12)	*II*	*L*(?)	1.65 abs.(O1)		Unless 0.15 Mev in γ-rays present, this must be lower state.
	Y^{91}	*A*	e^-,γ	50 min.(G9)(S18)	*I*	*U*		*0.61*(F19) abs. γ and e^-	Δ=5 probable; theoretical $\tau\sim 2$ hr.
	Y^{91} (H20)	*A*	β^-(B8)	57 d.(G9)(S18) (H10)(G17)	*I*	*L*	1.6(B8) abs.; 1.53 (L4) spect.		
40	Zr^{89}	*A*	e^-,γ or K	4.5 min.(D3)(D7)	*I*(?)			0.555(H38) spect.	Apparently no β^+. Critical absorption of x-rays could differentiate *I* and *II*.
	Zr^{89}	*A*	β^+(S13)	78 hr.(D3)	*L*(?)		1.0(S13) cl. ch(D3) abs.	no γ	
41	Cb^{91}	*A*	e^-,γ(B24)	62 d.	*I*	*U*		*0.13*(?)(M20) abs.	Δ=4 and Δ=5 both off by 10^3. Good value of γ-energy and α_K/α_L needed.
	Cb^{91}			long.					Radioactivity not detected.
	Cb^{92}	*A*	β^-,γ	10.1 d.(K11); 11 d. (S31)	*II*		1.38(S31) cl. ch. 1.38(K11) abs.	1.0(K11) abs.	Accurate measurements on β- and γ-rays needed.
	Cb^{92}	*A*	β^-,γ(W26)	21.6 hr.(W26)	*II*		1.2(W26) abs.	0.6(W26) abs.	
	Cb^{93}	*A*	e^-	42 d.(W15)	*I*	*U*			Produced by x-ray excitation. Other reports of this activity may be of Cb^{95}.
	Cb^{93}	*A*		stable	*I*	*L*			Spin 9/2.
	Cb^{94}	*A*	e^-; β^-(0.01%) (G18)	6.6 min.(G18)	*I*, *II*	*U*	1.3 abs.	*0.058* abs.(G18), 1.0 (C11) abs.	Theory gives $\tau\sim 900$ min. $\alpha_K/\alpha_L=\frac{1}{6}$ for $E2^4$. Probably Δ=4.
	Cb^{94}			>100 yr.	*I*, *II*	*L*			Radioactivity not yet detected.
	Cb^{95}	*A*	e^-	90 hr.(L11)	*I*	*U*		*0.216*(H35) spect.	Δ=4 and Δ=5 both off by large factor. α_K/α_L measurement might decide.
	Cb^{95}	*A*	e^-,γ,β	35 d.	*I*	*L*	0.146(H35) spect.	0.758(H35) spect.	Formed in 98.6% of Zr^{85} decays. $\alpha=2.4\times10^{-3}$ for 0.758-Mev. γ-ray.
43	Tc^{94}	*B*	e^-	53 min.(H28)	*I*	*U*		*0.0334*(H28) spect.	Δ=4. Theory predicts $\tau\sim 20$ hr. α_K/α_L should be very small.
	Tc^{94}	*B*	β^+,K,γ	53 min.(H28)(M4)	*I*	*L*	2.45(H28) spect.	0.38, 0.87, 1.48, 1.85, 2.74(H28) spect.	
	Tc^{95}	*B*	K,γ,e^-(E3) (H29); β^+(1%) (H29)	62 d.(H29); 52 d. (*E*3)	*II*		0.4(H29) cl. ch.	0.201, 0.570, 0.810, 1.017(H29) spect.	Must be 1.4 Mev. above Mo^{95} ground state.
	Tc^{95}	*A*	K,e^-,γ	20 hr.(E5)(M4)	*II*			0.762, 0.932, 1.07 (M21) spect.	Isomerism seems questionable because none of same states observed in Mo^{95}.
	Tc^{97}	*A*	e^-	93 d.(C7)	*I*(M15) (E3)	*U*		*0.097*(H8) spect.	$\alpha_K/\alpha_L\sim 2$. Theoretical τ off by 10^3 for Δ=4 or 5. Probably mixed *E* and *M* radiation (H8).
	Tc^{97}	*A*	β^+, or K		*I*	*L*			Half-life too long to be detected at present.
	Tc^{99}	*A*	e^-,γ(S4)	6.6 hr.(S4)	*I*	*U*		*0.136*(S4) spect.	Experimental evidence uncertain. Δ=4 indicates $\tau\sim 9$ hr. Measurement of α and α_K/α_L needed.
	Tc^{99}	*A*	β^-	9.4×10^5 yr. (M14)	*I*	*L*	0.32(M14) abs.		
45	Rh^{103}	*A*	e^-	45–48 min.(F12) (W14)	*I*	*U*		*0.0942*(F15) abs.; *0.059* or *0.037*(H21) spect.; *0.0659*(G8) spect.	(G8) observe *K* x-rays and only 42.7 kev electrons. α large. Absence of *L* electrons strange. Agreement good with Δ=4, which gives $\tau\sim 20$ hr., except for α_K/α_L.
	Rh^{103}	*A*		stable	*I*	*L*			
	Rh^{104}	*A*	e^-	4.3 min.(A4)(P2) (F12)	*I*	*U*		*0.069*(O3) spect.; *0.087* (F15) abs.; *0.095* or *0.073*(H21) spect.	Apparently either *K* or *L* conversion missing. Measured value of α(A6) indicates $M2^3$. Δ=4 gives $\tau\sim 20$ min. but α_K/α_L should be ~1.
	Rh^{104}	*A*	β^-	44 sec.(A4)(P2)	*I*	*L*	2.3(C8) cl. ch.; 2.6 (H21) spect.		
47	Ag^{106}	*A*	β^+	24.5 min.(D6)(P8)	*II*		2.04(F2) abs.	No γ's(F2)	Need more accurate measurement of β^+- and γ−γ-coincidences. If all γ's in cascade 8.2 d. is *U*.
	Ag^{106}	*A*	K,e^-,γ	8.2 d.(F2)(P8) (H22)	*II*			0.72, 1.06, 1.63(D11) (E1) spect.	
	Ag^{107}	*A*	e^-,γ	40 sec.(A3); 44.3 sec. (B10)	*I*	*U*		*0.093*(H8)(B10) spect.	See discussion Section VII, $I=7/2\pm$.
	Ag^{107}	*A*		stable	*I*	*L*			$I=\frac{1}{2}\pm$.
	Ag^{109}	*A*	e^-,γ	39 sec.(B10)	*I*	*U*		*0.088*(H9)(B10) spect.	$\alpha_K+\alpha_L=19$ indicates $M2^3$; but $\alpha_K/\alpha_L=1$ gives 65% $E2^4$, 35% $M2^3$. Theory predicts $\tau\sim 1$ hr. for Δ=4 $I=7/2\pm$.
	Ag^{109}	*A*		stable	*I*	*L*			$I=\frac{1}{2}\pm$.

TABLE III.—*Continued.*

Z	A	Class	Type of radiation	Half-life	Type of isomer		Energy of radiation: particles	Energy of radiation: γ-rays	Remarks
	Ag^{110}	A	β^-,γ	22 sec.(A4); 24 sec. (H23); 28 sec. (F12)(P8)	*II*		2.6(H23) abs. 2.8 (G6) cl.ch.		From σ of (Table II), probably has small spin. Not enough known to assign *U* and *L*.
	Ag^{110}	A	K,ϵ^-	225 d.(L8)(R4)	*II*			0.65, 0.925, 1.51(D11) spect.	From σ of table II, probably has large spin.
48	Cd^{111}	A	ϵ^-,γ	48.7 min.(G15) (W17)(D8)	*I*	*U''*		*0.149*, 0.247(H24) (H18) spect.	0.149 γ-ray is Λ=4. 0.247 γ-ray follows.
	Cd^{111}	A	ϵ^-,γ	8×10^{-8} sec.(D20)	*I*	*U'*		*0.247*	Probably $E2^2$.
	Cd^{111}	A		stable	*I*	*L*			
	Cd^{113}	A		2.3 min.(H25)(T5)	*I*	*U*			
	Cd^{113}	A		stable					
	Cd^{115}	A	β^-,γ	43 d.(S23)	*II*	*U*	1.67(H16) spect.	0.5(S23) abs.	β^- goes to ground state of In^{115}. Transition to In^{115} isomer very weak. Transition to ground state of Cd^{115} not observed. Probably Λ=6.
	Cd^{115}	A	β^-,γ	2.33 d.(L1); 2.5 d. (G3)	*II*	*L*	1.10(H16) spect.; 1.13, 0.6(L1) spect.	0.52(H16) spect.; 0.65 (M9) spect.	β^- goes to isomeric state of In^{115}.
49	In^{112}	B	ϵ^-	23 min.(B18)(S29)	*I*	*U*		*0.16*(B18)	Λ=4 gives $\tau\sim15$ min., $\alpha_K/\alpha_L=2$ and $\alpha=6$ for $E2^4$. Measurement of α_K/α_L would determine whether *E* or *M*. Spin 4 or 5.
	In^{112}	B	β^+,β^-,K	9 min.(B18)(S29)	*I*	*L*	β^+ 1.7(L1) cl.ch. β^-1.		Spin probably 1.
	In^{113}	A	ϵ^-,γ	105 min.(L1)	*I*	*U*		*0.393*(L1) spect.	$\alpha_K/\alpha_L=5.4$, $\alpha=0.7$. Probably mostly $M2^4$. Theory predicts $\alpha_K/\alpha_L=6$, $\alpha=0.3$; $\tau\sim140$ hr. Spin $\frac{1}{2}\pm$.
	In^{113}	A		stable	*I*	*L*			Spin 9/2∓.
	In^{114}	A	ϵ^-	48 d.(L1)	*I*	*U*		*0.192*(L1) spect.	$\alpha_K/\alpha_L=1$, $\alpha\sim100$. Theory predicts for Λ=5, 5/6 $E2^5$, 1/6 $M2^4$, $\alpha=12$, and $\tau\sim$ 1600 d. Spin probably 5±.
	In^{114}	A	β^-	72 sec.(L1)(B6) (L9)(L10)	*I*	*L*	1.98(L1) spect.		Spin probably 1∓.
	In^{115}	A	ϵ^-,γ	4.5 hr.(L1), 4.1 hr. (B4)(G3)	*I*	*U*		*0.338*(L1) spect.	$\alpha_K/\alpha_L=4.8$–5.3, $\alpha\simeq1$. $M2^4$ predicts $\tau\sim500$ hr., $\alpha_K/\alpha_L=5.75$, $\alpha=0.6$. Spin probably $\frac{1}{2}\pm$.
	In^{115}	A		stable					Spin 9/2∓.
	In^{116}	A	β^-	13 sec.(A4)(C9)	*II*		2.8(C9) cl.ch.	No γ(M5)	Both allowed transitions; need more investigation. 54 min. seems *U*.
	In^{116}	A	B^-,γ	54 min.(A4)(C9) (L9)	*II*		0.85(C10) spect.	0.428, 1.12, 1.31, 2.32 (D11) spect.	
50	Sn^{119}	C	ϵ^-,γ	13 d.(L19)	*I*	*U*		∼0.250(L19) abs. ϵ^-,γ	Assignment to 119 doubtful, but is certainly an isomer, since emits Sn x-rays; $l=5$ probable.
	Sn^{119}	A		stable	*I*	*L*			
	Sn^{121}	B	β^-	36 min.(N2)	*II*		2.5–3.0(N2) abs.	No γ(?)(N2)	
	Sn^{121}	A	β^-	28 hr.(L18)	*II*		0.4(L18) abs.	No γ(L18)	
51	Sb^{120}	B	K,ϵ^-,γ	6.0 d.(L18)	*II*			1.1(L18) abs.	
	Sb^{120}	B	β^+	17 min.(L15)	*II*		1.53(A9) cl.ch.		
	Sb^{122}	A	ϵ^-	3.5 min.(M16)	*I*	*U*		*0.140*(M16) abs	Theory predicts $\tau\sim12$ sec. for Λ=4. α should be ∼12.
	Sb^{122}	A	$\beta^-,\gamma,\epsilon^-$	2.8 d.	*I*	*L*	1.94, 1.36(M13) spect.	0.58(R6) spect.; 0.80 (M9) spect.	
	Sb^{124}	A	ϵ^-	21 min.(M16)	*I*	*U''*		*0.02*(M16) abs.	See discussion Section VII.
	Sb^{124}	A	β^-,ϵ^-	1.3 min.(M16)	*I, II*	*U'*	3.2(M16) abs.	*0.015* abs.	
	Sb^{124}	A	β^-,γ	60 d.(L15)	*I, II*	*L*	2.4, .7(M17)	1.7(M17)	Decay scheme probably much more complicated. For example (K5).
52	Te^{121}	A	ϵ^-,γ	143 d.(P10); 125 d. (S7)(B19)	*I*	*U''*		*0.082*(H36) spect.	α_K/α_L for 0.082 indicates Λ=3. Half-life requires at least Λ=4.
	Te^{121}	A	ϵ^-,γ	5×10^{-8} sec.(B20)	*I*	*U'*		*0.213*(H36) spect.	α_K/α_L indicates Λ=3. Λ=2 predicts $\tau\sim10^{-9}$ sec.
	Te^{121}	A	K,γ	17 d.(P10)	*I*	*L*		0.61(P10) abs.	
	Te^{125}	A	ϵ^-	∼60 d.(F20)	*I*	*U*		*0.125* abs.(F20)	Λ=5 predicts $\tau\sim4000$ d., $\alpha_K/\alpha_L\sim0.2$. Energy of γ-ray obtained by assuming absorption curve corresponds to *L* electrons.

ground state of Te^{124} is three times forbidden. In addition, if the 1.3-min. level has 0 spin with parity opposite to that of Te^{124}, the β-transition is twice forbidden and the γ-transition goes with Λ=4 instead of the Λ=3 mentioned as possible above. Some experiments in unraveling this case are suggested by attempts to make up level schemes. For example, the directional correlation of the 1.7- and 0.6-Mev γ-rays in the 60-day case might tell about the spins of these states. More data on selection rules in β-decay will also be a great help. The conversion coefficients in the isomeric γ-rays are so large that there is little chance to measure them.

Table III is a table of isomers, which, it is hoped, is complete to Jan. 1, 1949. The arrangement of the table is that originally used by Bethe, and re-

TABLE III.—*Continued.*

Z	A	Class	Type of radiation	Half-life	Type of isomer		Energy of radiation particles	Energy of radiation γ-rays	Remarks
	Te^{125}	*A*		stable	*I*	*L*			
	Te^{127}	*A*	e^-	90 d.(S7)	*I*	*U*		*0.086*(H8) spect.	$\alpha_K/\alpha_L \sim 0.75$; $\Lambda=5$ gives slightly better agreement. α_K/α_L suggests 50% *E*, 50% *M*.
	Te^{127}	*A*	β^-	9.3 hr.(S7)	*I*	*L*	0.76(S7) abs.	No γ	
	Te^{129}	*A*	e^-	32 d.(S7)	*I*	*U*		*0.102*(H8) spect.	$\alpha_K/\alpha_L \sim 1$. Probably *E* and *M*. $\Lambda=5$ gives better agreement than $\Lambda=4$.
	Te^{129}	*A*	β^-	72 min.(S7)(A5)	*I*	*L*	1.8(R6) spect.		
	Te^{131}	*A*	e^-	30 hr.(S7)(A5)	*I*	*U*		*0.177*(H8) spect.	$\alpha_K/\alpha_L \sim 2$. Probably *E* and *M*. $l=4$ or 5.
	Te^{131}	*A*	β^-	25 min.(S7)(A5)	*I*	*L*			
54	Xe^{127}	*B*	e^-,γ	75 sec.(C5)	*I*	*U*		*0.175* or *0.125*(C5) spect.	No *L* conversion of 0.125 γ observed; 0.175 γ probably responsible; $\Lambda=4$ gives $\tau \sim 500$ sec.
	Xe^{127}	*B*	$e^-,\gamma,K(?)$	34 d.(C5)	*I*	*L*		0.9(C5) abs. e^-	
	Xe^{135}	*A*	e^-,γ	10 min.(W22); 15.6 min.(R7); 12 min.(G7)	*I*	*U*		0.52(P4) spect.; 0.6(S24) abs.	$\Lambda=5$ probable; theory predicts $\tau \sim 4$ hr.
	Xe^{135}	*A*	β^-,γ	9.4 hr.(S15)(W22)	*I*	*L*	0.93(P4)	0.247(P4) spect.	
55	Cs^{134}	*A*	β^-,e^-,γ	3.15 hr.(S25)(K5)	*I, II*	*U*	2.4(S25) abs.	*0.150*(P7) spect.; 0.7 (S25) abs.	$\Lambda=4$ probable. Need to know branching ratio.
	Cs^{134}	*A*	β^-,γ	1.7 yr.(K5)	*I, II*	*L*	0.09(25%), 0.65 (75%)(E4)(D15) spect.	0.568 25%, 0.602, 0.794(E4)(D15) spect.	
56	Ba^{133}	*A*	e^-	38–39 hr.(K9) (W18)(Y1)	*I*	*U*		*0.276*(C12) spect.	$\alpha_K/\alpha_L=3.2$. $\Lambda=5$ predicts $\tau \sim 100$ d. Formulas for α and α_K/α_L not good in this range.
	Ba^{133}	*A*	e^-,K,γ	20 yr.(K9)	*I*	*L*		0.32, 0.085(Y1) abs.	
	Ba^{135}	*C*	e^-,γ	28.7 yr.(Y2)	*I*	*U*		0.29(Y2) abs.	Isotope assignment uncertain. Assume *L* electrons observed $\Lambda=5$ probable.
	Ba^{135}	*A*		stable	*I*	*L*			
	Ba^{137}	*A*	e^-,γ	158 sec.(T9); 156 sec.(M18)	*I*	*U*		*0.663*(T4)(M18) spect.	$\alpha=0.14$; $\Lambda=5$ predicts 1200 sec. Spin probably $11/2\pm$. (M18) point out β-theory difficulties in Cs^{137} decay.
	Ba^{137}	*A*		stable	*I*	*L*			Spin $3/2\mp$.
63	Eu^{152}	*A*	$\beta^-,\gamma,e^-,K(R8)$	9.2 hr.(P9)	*II*		1.88(T6) spect.	0.123, 0.163, 0.925(T6) spect.	
	Eu^{152}	*A*	$\beta^-,\gamma,e^-(S32)$	~5 yr.(I2)	*II*		0.751(S32) spect.	several (S32)	Known to be isomeric with 9 hr. from mass spectrograph assignment(I2). γ-rays difficult to assign because of Eu^{154} activity.
65	Tb^{160}	*A*	β^-	3.9 hr.(H12)(M7)	*II*				
	Tb^{160}	*A*	β^-,γ	72–73.5 d.(B9) (B21)(I2)	*II*		0.546, 0.882(C18) spect.	0.086, 0.195, 0.212, 0.297, 1.15(C18) spect.	Assignment of γ-rays doubtful.
66	Dy^{165}	*B*	e^-	1.25 min.(I3)(F11)	*I*	*U*		*0.102*(H38) spect.	Mass probable from mass spectrograph work. $\alpha K/\alpha L$ small. $\Lambda=4$ probable.
	Dy^{165}	*A*	β^-,γ	2.5 hr.(P9)(H13) (M7)	*I*	*L*	1.18(D16) spect.; 0.42, 0.88, 1.25 (S27) spect.	1.0, 0.37(M13) spect.; 0.091, 0.37, 0.78 (S27) spect.	
68	Er	*C*	e^-	2.5 sec.(D18)	*I*	*U*		*0.2*(D18) abs.	$\Lambda=4$ probable.
69	Tm^{169}	*A*	e^-,γ	1×10^{-6} sec.(D22)	*I*	*U*		*0.19*(D22) abs.	$\Lambda=2$ and $\Lambda=3$ both give values of τ off by 10^3. Need good value of energy and α.
	Tm^{169}	*A*		stable					
	Tm^{171}	*B*	e^-,γ	2.5×10^{-6} sec. (D22)	*I*	*U*		*0.113*(K10) spect.	$\alpha=1.3$; $\Lambda=2$ gives $\tau \sim 10^{-8}$ sec.
	Tm^{171}	*B*		~500 d.(K10)	*I*	*L*	0.1 abs.		
70	Yb	*C*	e^-	6 sec.(D18)	*I*	*U*		*0.23* abs.(D18)	Produced by (n,γ)
	Yb	*C*	e^-	50 sec.(D18)	*I*	*U*		*0.02* abs.(D18)	Produced by (n,γ)
71	Lu^{176}	*A*	β^-	3.4 hr.(D17)(F9)	*II*	*U*	1.15 abs.	No γ	Produced by x-ray excitation (D17).
	Lu^{176}	*A*	β^-,γ	7.3×10^{10} yr. (N14) (L13)	*II*	*L*	0.215(L13) abs. 0.40(F9) abs.	0.260(F9) abs.	

cently by Seaborg (S20). The first two columns are self-explanatory. In the third column under "Class," the notation is also the same as that used by Seaborg.

A = isotope certain (mass number and element certain),

B = isotope probable, element certain,

C = one of few isotopes, element certain.

However, isotopes of classification *D*, *E*, *F*, *G* have been omitted, with one or two exceptions. These few cases are those in which the evidence for isomerism seems very good, but the isotopic assign-

TABLE III.—*Continued.*

Z	A	Class	Type of radiation	Half-life	Type of isomer		Energy of radiation particles	Energy of radiation γ-rays	Remarks
72	$Hf^{177,179}$	C	e^-	19 sec.(F11)	*I*	*U*		*0.20*(F11) abs.	Must be isomer. Isotope assigned by Mattauch's Rule (F11). Λ=4 gives $\tau\sim50$ sec.
	$Hf^{177,179}$	A		stable					
73	Ta^{181}	A	e^-,γ	2.2×10^{-5} sec. (D22)(B22); 2.0×10^{-5} sec. (B5)	*I*	*U*		*0.133*, 0.345, 0.478 (C17) spect.; *0.128* 0.472(B22) spect.	(B22) report 0.342 γ precedes isomeric γ. $\alpha\sim0.6$. Probably Λ=2. (B5) report Λ=3, with 0.478 γ, Λ=2. Their scheme does not forbid transition to ground state.
	Ta^{181}	A		stable	*I*	*L*			
	Ta^{182}	A	e^-,γ	16.2 min.(S14)	*I*	*U*		*0.22*(S14) abs.	0.22 obtained by assuming (S14) observed *L* electrons Λ probably 4.
	Ta^{182}	A	β^-,γ,e^-	117 d.(Z1)	*I*	*L*	0.499(J2) spect.	0.15, 0.22, 1.13, 1.22 (R6) spect.	
74	W^{183}	D	e^-(D18)	5.5 sec.(D18)	*I*	*U*		*0.100* abs.(D18)	Electrons have maximum energy 0.08. Assume *L* electrons. Λ probably 4.
	W^{183}			stable	*I*	*L*			
75	Re^{187}	A	e^-,γ	0.65×10^{-6} sec. (D19)(D22)	*I*	*U*		*0.135*, 0.086, 0.101(V3) spect.	0.135 γ-ray is most converted, hence probably responsible. Other 2 γ-rays may not be involved. Λ=2 or Λ=3. Spin probably ½.
	Re^{187}	A		stable					Spin 5/2.
77	Ir^{192}	A	e^-,γ	1.5 min.(G19)	*I*	*U*		*0.06*(G19)	Converted only in *L* shell. Λ=3 or 4.
	Ir^{192}	A	β^-,γ	75 d.(G20); 60 d. (M6)(F4)	*I*	*L*	0.59(G20) abs.	0.307, 0.467, 0.603 (D10) spect.	(L16) observes more γ's.
78	Pt^{197}	B	β^-	18 hr.(M6)	*II*		0.65(S16) abs.; 0.72 (K7) abs.		
	Pt^{197}	B	β^-,γ(K7)	3.3 d.(M6)	*II*				
79	Au^{196}	B	β^-(30%), K(70%), γ,e^-(S33)	5.55 d.(W27)(S33)	*II*(?)		~0.27, ~0.43(S33) spect.	0.139, 0.358 with *K*, 0.173, 0.334 with β^- (S33)spect.	
	Au^{196}	B	β^-, K or I.T. (W28)	14.0 hr.(W28) (M6)	*II*(?)				
	Au^{197}	A	e^-	7.4 sec.(F16) (W15)	*I*	*U*		*0.250*(F16) abs.; 0.077 (F16) abs.	γ's in cascade. 0.07 γ has $\tau<10^{-6}$. Λ=4 gives $\tau\sim10$ sec.
	Au^{197}	A		stable	*I*	*L*			
80	Hg^{197}	A	K,γ,e^-	23 hr.(F17)(F16) (W12)	*II*	*U*		0.125, 0.157(V2) spect.	Half-life of 0.157 γ-ray $<10^{-7}$ sec.(F16).
	Hg^{197}	A	K,γ,e^-	64 hr.(W12)	*II*	*L*		0.075(H26) spect.; 0.077(F16) abs.	
	Hg*	C	e^-	43 min.(M6)(F17)	*I*	*U*		*0.222* or *0.362*(H24) spect.	Both highly converted γ-rays. Λ probably 5. Isomer of a stable Hg.
82	Pb^{204}	B	e^-,γ	65–68 min.(M3) (F18)(T7)	*I*	*U*		*1.1*(F18) abs. e^-,γ; *0.9*(M3) abs.	Exception to "Mattauch's Rule."
	Pb^{204}	A		stable	*I*	*L*			
	Pb*	C	e^-	1.6 min.(W11)	*I*	*U*		*0.15–0.25*(W11)	Λ=4 probable. Isomer of a stable Pb isotope.
91	UX_2^{231}	A	β^-,γ(M10)	1.14 min.(C14)	*I, II*	*U*	2.32(98%), 1.4 (1.7%)(B7) spect.	*0.394*, 0.822, 0.782 0.95(B7) spect.	Λ=5 from lifetime and α of γ-ray(B7). Isomeric γ-ray occurs in only 0.12% of cases.
	UZ^{231}	A	β^-,γ	6.7 hr.(C14)(F2)	*I, II*	*L*	0.45(90%), 1.2(10%) (B7) spect.	0.85(B7) spect.	
93	Am^{242}	A	β^-	16 hr.(S26)	*II*		1.0(S26) abs.		
	Am^{242}	A	$\beta^-\alpha$,(.2%)	400 yr.(S26)	*II*		0.5(S26) abs.		

* Footnotes that appear in parentheses refer to the Bibliography.

ment is lacking. Such cases arise, for example, when isomers are formed by x-ray excitation. Because of this selection, some bona fide cases of isomerism have undoubtedly been omitted, but we believe them to be few in number.

The fourth column lists the type of radiation, with the following symbols.

β^- = negative beta-particles,
β^+ = positive beta-particles (positrons),
γ = gamma-rays,
e^- = internal conversion electrons,
α = alpha-particles,
K = K electron capture (or in more general terms, orbital electron capture).

Annihilation radiation and x-rays following internal conversion are not listed.

Under half-life, no attempt has been made to include all the measured values, though in some cases, several are included. In a few cases the limits of the measured values are given. The refer-

ences are by no means exhaustive; but the most recent references to work on an isotope are given, and further references can be obtained from them or from the table of Seaborg and Perlman in the Review of Modern Physics, (October 1948 issue).

In the column "Type of isomer," the classification Type *I*, decay of the metastable state to the ground state by γ-radiation or internal conversion, and Type *II*, decay of both isomeric states to the neighboring element by a β^--, β^+-, or *K* process (see Section IIIb) is used. In addition the letter *U* indicates the upper of the isomeric states, *L* the lower. In case of triple isomerism U'' is used for the highest state, U' for the middle state. When this is doubtful, a question mark has been included. Where there is not sufficient evidence to make an assignment, the letters have been omitted. In cases of isomers of stable elements, the stable isotope has also been included.

Under "Energy of radiation" no attempt at completeness in recording all references to energy measurement has been made. Rather, the most recent or what is considered the most accurate measurement is included. The column "Particles" includes only β^-- and β^+-particles. Under γ-rays, the energy of the transition from upper to lower isomeric state is italicized for emphasis. In cases in which there is some doubt, this has been indicated under "Remarks." The symbols used have the following meaning.

abs. = absorption,
cl. ch. = cloud chamber (with magnetic field in case of beta-particles),
spect. = magnetic deflection (magnetic spectrograph or spectrometer or counter with magnetic field). No differentiation of conversion electrons and secondary photoelectrons has been made.
$D-\gamma-n$ reaction = measurement of neutron energy from $D-\gamma-n$ reaction.

When a semicolon is used, it means that the values listed on each side of it are independent determinations of the same item, e.g., independent determinations of the half-life or of the energy of the radiation of a radioactivity. In another usage the semicolon separates the symbols in the "Type of radiation" columns when there is more than one type of decay (β^-, β^+, α, or *K*) for the radioactivity.

Under "Remarks" is included pertinent information about α, α_K/α_L, etc. (references are given under "energy of radiation") plus indicated Λ values. As pointed out previously, $\Lambda = 4$, for example, may mean Electric 2^4 pole ($E2^4$) or magnetic 2^3 pole ($M2^3$) radiation or both. τ is used for half-life. In some cases spins of states have been given followed by parity. For example, $7/2\pm$ and $1/2\mp$ indicate spins of $7/2\hbar$ and $1/2\hbar$ and opposite parities.

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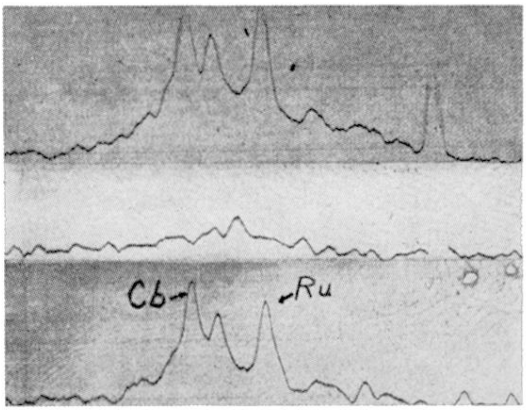

FIG. 2. A microphotometer trace of the K_α line of Tc. The three peaks of the upper and lower calibration traces correspond to the Cb, Mo, and Ru K_α doublet. The main peak of the center trace is due to the K_α of Tc. The peak to the left is due to Mo K_α which arises from a two-day Tc activity. *Note:* This figure is taken from Phys. Rev. **56**, 753 (1939).