branch. A further objection to this decay scheme is that it indicates an energy difference between $I^{131}$ and $Xe^{131}$ nuclei of 1.479 Mev, a value which can be shown to be too great. For, since the dose rate in air produced by a gamma-emitting source is closely proportional to the quantum energy over the range 0.1–1.0 Mev, it follows that a measurement of the gamma-ray ionization from a source of known disintegration rate gives an estimate of the energy emitted per disintegration as gamma-rays; and, since the ratio of mean beta-energy to the maximum does not vary greatly among isotopes of a given atomic number, a measurement of the beta-energy emitted from such a source gives an estimate of the total energy carried by beta-particles and neutrinos. The sum of these two quantities is the total energy difference between parent and daughter nucleus. Such energy measurements have been carried out by Gray,[7] and by comparison with the $I^{131}$ samples of the standard disintegration rate now distributed by the National Bureau of Standards, which are based on $4\pi$ solid angle beta-counting and are therefore independent of the assumed decay scheme, they yield values of the beta- and gamma-energy which are in complete agreement, within experimental error, with either M.D. or K.M.Z., and demonstrate that the total energy of disintegration cannot differ from 0.964 Mev by more than about 10 percent.

It therefore seems reasonable to assume that either the M.D. or K.M.Z. scheme disposes correctly of the radiations with which they both deal, and that the other radiations are to be accounted for by further branching of the spectrum. It is possible to differentiate between these two schemes by measurement of the 80-kev gamma-ray. Both groups detect this gamma-ray by the conversion line in the beta-spectrum, and they are in substantial agreement as to the number of conversion electrons produced; they do, however, differ widely in the values assigned to the conversion coefficient, K.M.Z. giving 15.5 unconverted quanta per 100 disintegrations and M.D. only 3.4. The actual intensity can be conveniently assessed experimentally by measurement of the ionization in a copper chamber. The effect of the 80-kev radiation is greatly enhanced by the photoelectric effect and can be separated out by absorption in tin (Fig. 2). Correction having been made for the relative stopping power of copper and for the effect of secondary electrons arising within the air cavity, it is found that the intensity is 2.6 quanta per 100 disintegrations. So small a value could not occur if the 80-kev line were in cascade with the 637-kev line, and it follows that the M.D. scheme is to be preferred, even though this rules out the tempting hypothesis that the 720-kev gamma-ray arises from the 717-kev level shown in the K.M.Z. scheme.

As regards the presence of further branches in the spectrum, it is probable that one such branch is formed by Zeldes' 810-kev beta-ray leading to the metastable level at 164 kev. The sum of the energies is correct within reasonable experimental error; and, so far as can be judged, the intensities are in agreement. The author has extracted the $Xe^{131}$ from three $I^{131}$ samples, and by estimating the activity by means of a cavity ionization chamber it was found that the frequency of disintegrations leading to the metastable level is $0.8\pm0.1$ percent. This compares reasonably with the statement in Zeldes' paper that the frequency of the beta-ray is "rather less than 1 percent." Another branch might be formed by the 720-kev gamma-ray associated with a 240-kev beta-ray, for the latter could quite easily have escaped detection in the presence of the more intense 315-kev branch. The inclusion of these features leads to the decay scheme given in Fig. 1(b), and it is suggested that this scheme is in reasonable accordance with the known facts concerning the disintegration of $I^{131}$. However, the 177-kev gamma-ray is still not accounted for. Its intensity must be quite small, since there is no sign of it in any of the spectra published by M.D. and K.M.Z.; and moreover, if it occurred in more than 5 percent of disintegrations it would certainly have been apparent in the tin absorption curve (Fig. 2). This gamma-ray might conceivably occur in a separate branch with a weak 787-kev beta-ray; or alternatively, if it were in cascade with the 720-kev line, the associated beta-branch would have an energy of 80 kev, and in this region of the spectrum could easily have escaped detection.

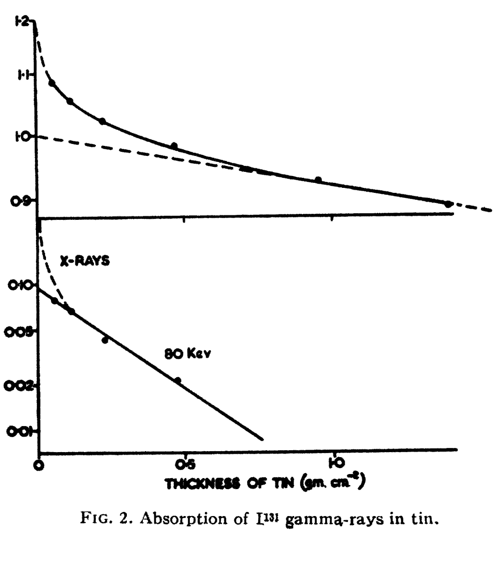


FIG. 2. Absorption of $I^{131}$ gamma-rays in tin.

[1] F. Metzger and M. Deutsch, Phys. Rev. **74**, 1640 (1948).
[2] Kern, Mitchell, and Zaffarano, Phys. Rev. **76**, 71 (1949).
[3] Brosi, DeWitt, and Zeldes, Phys. Rev. **75**, 1615 (1948).
[4] P. E. Cavanagh, private communication (1949).
[5] Cork, Rutledge, Stoddard, Branyan, and Childs, Phys. Rev. **81**, 482 (1951).
[6] Zeldes, Brosi, and Ketelle, Phys. Rev. **81**, 643 (1951).
[7] L. H. Gray, Brit. J. Radiology **22**, 673 (1949).

## Capture of μ-Mesons in Heavy Elements*

F. B. HARRISON, J. W. KEUFFEL, AND G. T. REYNOLDS
*Palmer Physical Laboratory, Princeton University, Princeton, New Jersey*
(Received June 18, 1951)

We have used large liquid scintillation counters[1] to study the processes associated with the stopping of negative $\mu$-mesons in heavy elements. The reasonable efficiency of the liquid scintillators for gamma-rays and neutrons of a few Mev has permitted us to use the non-ionizing radiations following nuclear capture for mean life measurements in Cu and Sb.

The experimental arrangement is shown in Fig. 1. A coincidence circuit (resolving time 3 $\mu$sec) selects events $(AS_1S_2-X)$; and for each such event the relative lag between $S_1$ and $S_2$ is measured by photographing an oscilloscope trace on which are presented the scintillator pulses and the output of a chronotron timing circuit.[2] Thus we look for events where a penetrating cosmic-ray particle

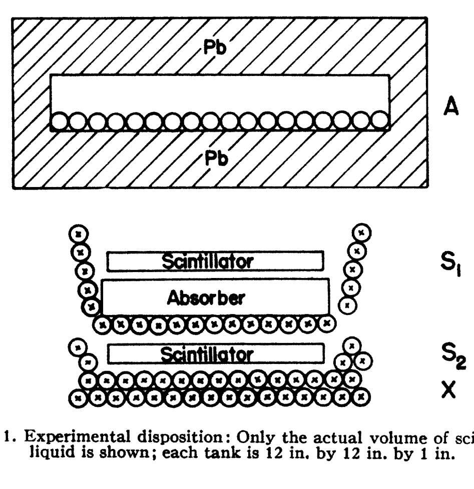


FIG. 1. Experimental disposition: Only the actual volume of scintillator liquid is shown; each tank is 12 in. by 12 in. by 1 in.

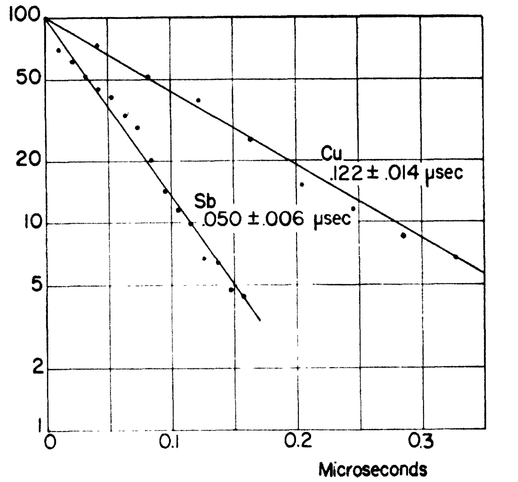


FIG. 2. Integral distributions of delayed counts from the meson capture radiation. The number of counts has been normalized to agree at time zero.

at sea level stops in the absorber, and is followed by a delayed non-ionizing ray which crosses the upper anticoincidence bank and is detected in $S_2$.

The timing uncertainty was measured by selecting events in which $S_1$ and $S_2$ were tripped simultaneously by a fast meson; the resulting lag distribution was approximately gaussian with a mean deviation of 4.5 mμsec. We therefore disregarded events delayed by less than 15 mμsec. Since the total number of instantaneous events selected by our triggering system was only about three times the number of delayed counts, the background due to this source could be ignored.

Integral delay distributions for Cu and Sb are shown in Fig. 2. We have subtracted small backgrounds due to random noise pulses and to the bremsstrahlung of decay positrons from positive mesons stopping in the absorber. The former are due mainly to events where a meson passes obliquely through $A$ and $S_1$ (but misses the anticoincidence counters $X$) and is followed by a random noise pulse in $S_2$. Since noise pulses of this type occur with equal probability before and after the events $AS_1$, a knowledge of the number of negative lags permits us to correct for the number of positive lags due to noise. The bremsstrahlung background was identified by its characteristic 2.1 μsec decay time, at times long compared to the decay of the negative meson capture radiation, and was corrected for by extrapolation back to the shorter times. For Cu, the combined background rate, per hour of counting and per mμsec of delay, was only 1/10 the maximum counting rate due to meson capture, while for Sb it was only 1/20 the maximum rate.

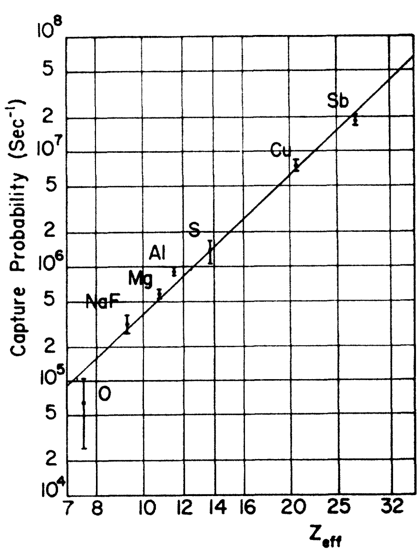


FIG. 3. Capture probability *vs* $Z_{eff}$. The effective atomic numbers are those calculated by Wheeler. Points for the light nuclei are from Ticho, with the result of Valley for Al averaged in. The line is drawn with a slope corresponding to the $Z_{eff}^4$ law.

The mean lives given in Fig. 2 have been computed according to the method of Peierls,[3] and the errors quoted are purely statistical. We believe our instrumental errors are smaller than these.

Wheeler[4] has predicted that the capture probability should go as $Z_{eff}^4$, where $Z_{eff}$ is an effective atomic number defined in his paper. In Fig. 3 we have plotted out values for the capture probability, together with those of Ticho[5] and Valley[6] for the light elements. We find good agreement with the $Z_{eff}^4$ law. While the earlier results could be fitted fairly well with a simple $Z^4$ dependence, our results show the need for using $Z_{eff}$ for the heavy elements, where the effect of the finite nuclear radius becomes important.

A knowledge of the capture probabilities permits one in principle to find the value of the coupling constant for the μ-meson-nucleon interaction. An evaluation of this constant more precise than the estimate given by Wheeler and Tiomno[7] awaits, however, a more detailed theoretical analysis of the nucleonic dynamics involved in the meson capture process.

* Supported by the joint program of the AEC and ONR.
1 Reynolds, Harrison, and Salvini, Phys. Rev. **78**, 488 (1950).
2 J. W. Keuffel, Rev. Sci. Instr. **20**, 197 (1949).
3 R. Peierls, Proc. Roy. Soc. (London) **A149**, 467 (1935).
4 J. A. Wheeler, Revs. Modern Phys. **21**, 133 (1949).
5 H. K. Ticho, Phys. Rev. **74**, 1337 (1948).
6 G. E. Valley, quoted by B. Rossi, *Colston Papers* (Butterworths, London, 1949), p. 55.
7 J. Tiomno and J. A. Wheeler, Revs. Modern Phys. **21**, 153 (1949).

---

## Gamma-Radiation Associated with Radium and Daughter Products*

J. M. CORK, C. E. BRANYAN, A. E. STODDARD, H. B. KELLER, J. M. LEBLANC, AND W. J. CHILDS
*University of Michigan, Ann Arbor, Michigan*
(Received June 14, 1951)

MANY studies have been made of the energies of the gamma-rays emitted by the various decay products of radium. Early spectrometric observations by Ellis[1] and associates and later by Siegbahn[2] have resulted in the correct assignments of many strong, internally converted gamma-rays. Subsequent measurements by various techniques including electron-pair production[3] have shown the existence of additional gamma-rays particularly

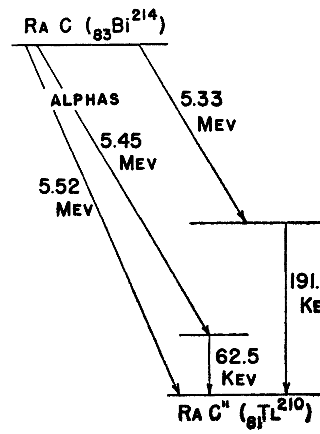


FIG. 1. Decay scheme for RaC to RaC''.