similar anomaly appears in the total cross section[13] of Li^6, it is unlikely that this hump is due to another state in Li^7. A reasonable explanation is that the sudden decrease of the (n,α) reaction is due to the onset of the competing $Li^6(n,nd)He^4$ reaction which has its threshold at 1.72 Mev. The two-body reactions $Li^6(n,n')Li^{6*}$ and $Li^6(n,d)He^5$ also provide competition above their thresholds at 2.55 and 2.89 Mev.

[13] Johnson, Willard, and Bair, Phys. Rev. 96, 985 (1954).

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the help and advice of Dr. J. H. Coon and Dr. E. R. Graves during the rather long course of this experiment. Indispensible aid was given by Dr. R. H. Henkel and Dr. J. E. Perry at the Los Alamos large Van de Graaff accelerator and by Mr. R. W. Davis at the 250-kev Cockcroft-Walton accelerator.

PHYSICAL REVIEW VOLUME 103, NUMBER 3 AUGUST 1, 1956

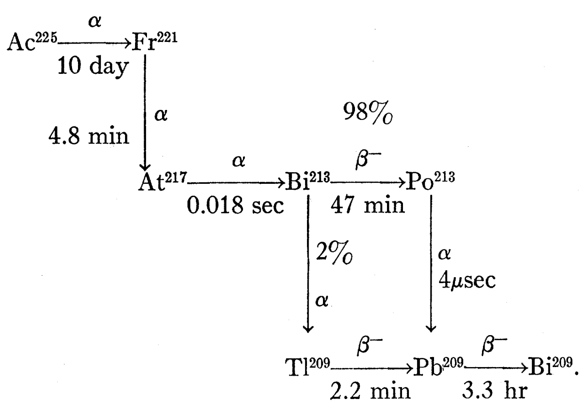
Three-Millimicrosecond Metastable State in Pb^{209}†

D. Strominger, F. S. Stephens, Jr., and J. O. Rasmussen
Radiation Laboratory and Department of Chemistry, University of California, Berkeley, California
(Received April 17, 1956)

Coincidence studies of radioactive isotopes in the Ac^{225} decay chain were made. A metastable state of Pb^{209} with a half-life of (3.1 ± 1.0) millimicroseconds was observed. This delay following beta decay of Tl^{209} to Pb^{209} is exhibited by a 120-kev $E1$ gamma transition and other gamma transitions succeeding the 120-kev gamma transition. Upper limits are set for the lifetimes of several other gamma transitions present in the Ac^{225} chain. An explanation for the delayed nature of this 120-kev $E1$ transition is given in terms of parentage overlap. Some unusual features of the beta decay rates of Tl^{209} to Pb^{209} are discussed.

INTRODUCTION

The 10-day alpha emitter Ac^{225} is followed by a chain of shorter-lived activities.



The decay properties of these activities have been the subject of several previous investigations.[1–4]

The present study was undertaken to investigate the lifetimes of various nuclear excited states by the delayed coincidence method, and γ-γ, β-γ, and α-γ coincidence measurements were made wherever possible.

A sample of Ac^{225} was chemically purified from its Th^{229} and Ra^{225} parents; however, daughter activities of Ac^{225} grow in so rapidly that all of the following measurements were done with a sample in transient equilibrium.

Scintillation detectors with RCA 5819 photomultiplier tubes were used, employing a Lucite disk impregnated with terphenyl, a thin layer of sublimed stilbene, or a sodium-iodide (thallium-activated) crystal as scintillators for beta particles, alpha particles, or electromagnetic radiation, respectively.

Delayed coincidences were measured with fast-slow coincidence pulse-height analysis equipment at resolving

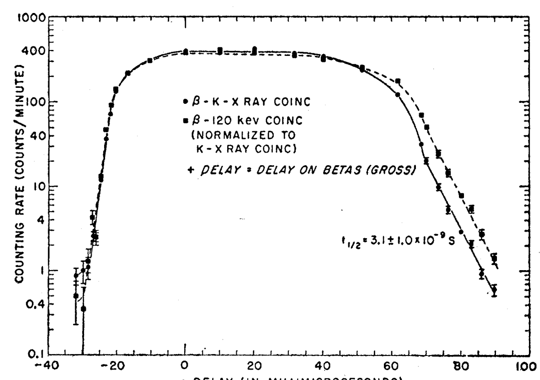


Fig. 1. Delay curves of beta-gamma coincidences. Delay curves of coincident K x-rays and 120-kev gamma rays are shown.

† This work was performed under the auspices of the U. S. Atomic Energy Commission.

[1] Hollander, Perlman, and Seaborg, Revs. Modern Phys. 25, 469 (1953).

[2] Magnusson, Wagner, Engelkemeir, and Freedman, Argonne National Laboratory Report ANL-5386, January, 1955 (unpublished).

[3] F. S. Stephens, PhD. thesis, University of California Radiation Laboratory Unclassified Report UCRL-2970, June, 1955 (unpublished).

[4] Perlman, Stephens, and Asaro, Phys. Rev. 98, 262(A) (1955).

times of 20 or 80 millimicroseconds. A Los Alamos type single-channel analyzer[5] was used for pulse height analysis of the alpha, beta, or electromagnetic spectra and to set the "gate." A 50-channel differential pulse height analyzer was used to analyze the energy of the coincident electromagnetic radiation. The pulses to the fast coincidence circuit were amplified by wide-band Hewlett-Packard 460A amplifiers,[6] and the coincidence discrimination was achieved by a simple adder circuit using a G7A crystal diode.[7]

No delayed gamma transitions were observed following emission of alpha particles. Limits were set as follows: $t_{\frac{1}{2}}<3$ millimicroseconds for a gamma transition of approximately 100 kev following the alpha decay of Ac^{225} and $t_{\frac{1}{2}}<1$ millimicrosecond for the 220-kev gamma transition following the alpha decay of Fr^{221}.

Beta-gamma coincidences showed coincident electromagnetic radiation at 80 (K x-rays), 120, 450, and 1560 kev as has been reported previously.[2–4] Previous work[2,3] indicates that the coincident 450-kev peak is actually a composite of two gamma rays of energy 434 and 450 kev. The 434-kev gamma transition is associated with the beta decay of Bi^{213}, while the other three gamma rays are associated with the beta decay of Tl^{209}.[4] K x-rays accompany the beta decay of both Bi^{213} and Tl^{209}.

Figure 1 shows the beta-gamma coincidence counting rates of the K x-ray and 120-kev gamma rays as a function of delay. Figure 2 shows the low-energy coincident electromagnetic radiation in both prompt and delayed coincidence. These results clearly indicate that the 120-kev gamma transition is delayed along with some of the K x-rays with the half-life for the metastable state 3.1 ± 1.0 millimicroseconds.

Stephens[3] has proposed a decay scheme for Tl^{209} (Fig. 3). If this decay scheme is correct, both the 450- and 1560-kev gamma transitions should be delayed with respect to the beta particles. The beta–450-kev gamma delay curve showed a prompt component ($t_{\frac{1}{2}}<2$ millimicroseconds) and then a delayed component. The prompt component was thought to be the 434-kev gamma transition of Bi^{213}. To prove this, the single channel discriminator was set above the 1.00-Mev end point of the Bi^{213} beta spectrum but below the 1.99-Mev end point of the Tl^{209} beta spectrum. Under such conditions the delay curve showed no prompt component but only a single delayed 450-kev gamma transition. Figure 4 shows the two different delay curves normalized at their peak coincidence counting rates.

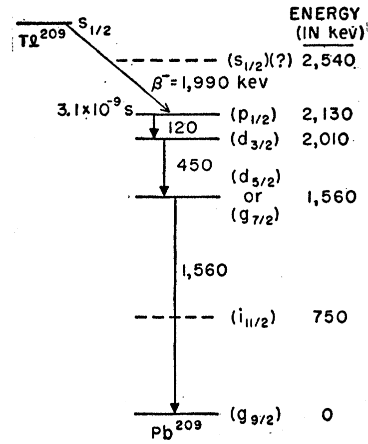


FIG. 3. Proposed decay scheme of Tl^{209}.

The counting efficiency of the 1560-kev gamma transition is too low to permit a direct beta—1560-kev gamma delay curve to be run, but a delay curve integrating all gamma-ray counts above 500 kev showed that essentially everything higher than 500 kev was delayed.

By gating on the 120-kev gamma ray, we were able to set upper limits for the half-lives of the 450- and 1560-kev gamma transitions at 1.5 millimicroseconds.

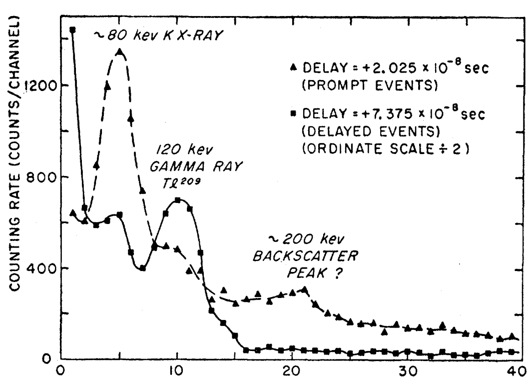


FIG. 2. Low-energy electromagnetic radiation coincident with beta particles.

DISCUSSION

Stephens[3,4] has assigned the 120-kev gamma transition as $E1$ on the basis of K and L conversion coefficients. Thus this transition is 3.6×10^4 times slower than a simple single-neutron ($p_{\frac{1}{2}}\xrightarrow{E1}d_{\frac{3}{2}}$) transition should be (where we have used formulas VII-1 and VII-7 of Bohr and Mottelson[8] for the single-neutron lifetime).

The delayed nature of this transition can be explained in terms of parentage overlap.[9] We can make a plausible set of spin assignments as shown in Fig. 3 from consideration of the shell model, from spins of neighboring nuclei, and from the observed gamma radiations in the Tl^{209} beta decay. The assignments of Fig. 3 are slightly different from those of Harvey.[10] The level at 750 kev was seen by Harvey[10] in the (d,p) reaction on Pb^{208},

---

[5] C. W. Johnstone, Nucleonics **11**, 36 (1953).
[6] Hewlett-Packard Company, Palo Alto, California.
[7] General Electric Company, Schenectady, New York.
[8] A. Bohr and B. R. Mottelson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **27**, No. 16 (1953).
[9] A. M. Lane and D. H. Wilkinson, Phys. Rev. **97**, 1199 (1955).
[10] J. A. Harvey, Can. J. Phys. **31**, 278 (1953).

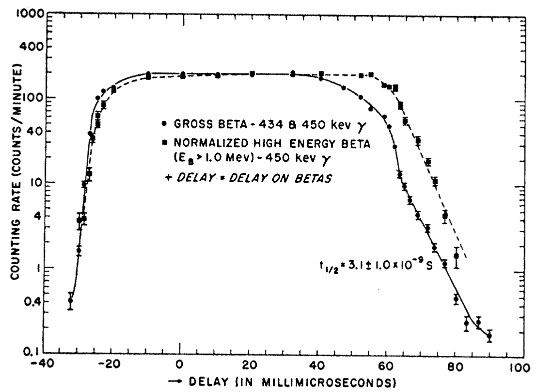


FIG. 4. Delay curves of beta-gamma coincidences. Delay curves of coincident 434- and 450-kev gamma rays are shown.

but this level is not populated in the beta decay of Tl^{209}. Note that the $\frac{1}{2}-$ level can only be formed by breaking the closed shell of 126 neutrons. This particular level however, is more than 2 Mev above the ground state, so it seems reasonable to make the assignment of principle neutron configuration as $(g_{9/2})^2(p_{\frac{1}{2}})^1$ plus 124 filled orbitals below the $p_{\frac{1}{2}}$.

The $\frac{3}{2}+$ level has as its principal configuration $(p_{\frac{1}{2}})^2(d_{\frac{3}{2}})^1$ with a small admixture of $(g_{9/2})^2(d_{\frac{3}{2}})^1$. The schematic representation of the nucleons involved in the $E1$ transition is given in Fig. 5.

It seems reasonable that the transition proceeds only by virtue of the small admixture of the neutron configuration $(g_{9/2})^2(d_{\frac{3}{2}})^1$ in the final state. The large hindrance indicates a very small configuration mixing. This type of reasoning is similar to that used by Sunyar *et al.*[11] in explaining some features of the beta decay of Kr^{85} to Rb^{85}. In the language of fractional parentage theory, we may say that the principal configurations of the $\frac{1}{2}-$ and the $\frac{3}{2}+$ levels have no common parents.[9]

Another interesting feature is the $\log ft$ value of 5.5 for the beta decay of Tl^{209}, which we assume to have an $s_{\frac{1}{2}}$ proton hole in the 82-proton structure, like Tl^{205} and Tl^{207}. With our spin and parity assignments this beta decay would be first forbidden because of parity change (Fig. 3). De-Shalit and Goldhaber[12] and also King and Peaslee[13] have discussed several similar cases in this region. The $\log ft$ value of 5.5 fits within King and Peaslee's group of "favored" first forbidden beta transitions ($\Delta j = \Delta I = 0$, yes, not $0 \to 0$). With our proposed principal configurations the beta transition involves transformation of the $p_{\frac{1}{2}}$ neutron to an $s_{\frac{1}{2}}$ proton, entirely analogous to the beta decay of Tl^{207}, a "favored" first forbidden transition with a $\log ft$ value of 5.2.[12,13]

For the decay scheme and level assignments of Fig. 3 ordinary beta selection rules would give an allowed transition ($\frac{1}{2}+ \to \frac{3}{2}+$) to the 2.01-Mev level. Experimentally we can say, from comparison of intensities of 450-kev and 120-kev gamma radiation, that a direct beta transition to the $\frac{3}{2}+$ level must be less than 10% as intense as the main beta group, and hence its $\log ft > 6.4$. This slowness may be simply explained, since the transition is both l forbidden ($\Delta l = 2$) and has unfavorable parentage overlap.

The 220-kev gamma transition following the alpha decay of Fr^{221} has been assigned as an $E2$ transition.[2,3] Thus, with its half-life of less than one millimicrosecond,

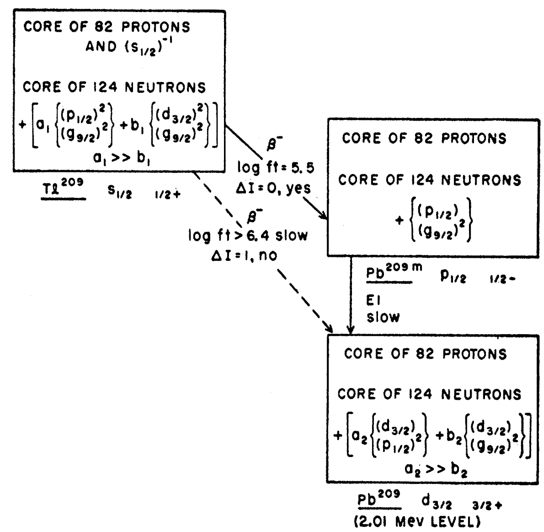


FIG. 5. Schematic representation of principal nucleon configurations involved in gamma and beta transitions in the decay of Tl^{209} and Pb^{209m}.

this transition is faster than that calculated from the simple Weisskopf[14] formula by at least a factor of three.

ACKNOWLEDGMENTS

We wish to express our appreciation to Dr. F. K. McGowan of the Oak Ridge National Laboratory for helpful suggestions concerning the fast-coincidence circuitry and to Dr. C. W. Johnstone of the Los Alamos National Laboratory for supplying detailed photographs and information on construction of the single-channel pulse-height analyzer.

[11] Sunyar, Mihelich, Scharff-Goldhaber, Goldhaber, Wall, and Deutsch, Phys. Rev. **86**, 1023 (1952).
[12] A. de-Shalit and M. Goldhaber, Phys. Rev. **92**, 1211 (1953).
[13] R. W. King and D. C. Peaslee, Phys. Rev. **94**, 1284 (1954).
[14] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952), p. 627.