Search for Positron Emission in K^{40}†

D. R. TILLEY* AND LEON MADANSKY
Johns Hopkins University, Baltimore, Maryland

(Received May 19, 1958)

A search for positron emission in K^{40} has been made with the use of a triple coincidence technique. An upper limit of $(3.6\pm1.8)\times10^{-4}$ positron per second per gram of natural potassium has been set. A corresponding upper limit of 0.59 ± 0.28 has been computed for the ratio of the squares of the matrix elements, M_+^2/M_-^2, for the K^{40} β^+ and β^- transitions.

INTRODUCTION

THE search for positron emission in K^{40} has been reported by several investigators, and the following upper limits have been set:

$$N_{\beta^+}/N_k<0.01,^1\quad N_{\beta^+}/N_{\beta^-}<2\times10^{-5},^2\quad N_{\beta^+}/N_{\beta^-}<6\times10^{-4},^3$$

and $N_{\beta^+}/N_k<0.01$.[4] These results were obtained by measurements of the intensity of the annihilation radiation from potassium. The upper limits for positron emission were arrived at by calculating the number of annihilation quanta expected from pair production by the 1.46-Mev gamma ray and subtracting it from the number observed.

This experiment distinguishes the sources of the annihilation quanta from one another. The detection efficiency has been measured and, with the use of other known data, an upper limit for the ratio of the matrix elements for the β^+ and β^- transitions has been deduced.

EXPERIMENTAL PROCEDURE

A block diagram of the apparatus is shown in Fig. 1. A 2 in.$\times$2 in.$\times$1 in. KI crystal is mounted on a phototube and placed between two 2 in.$\times$2 in.$\times$2 in. NaI(Tl) scintillation counters. The sensitive volume is surrounded by a set of twelve 1-inch diameter Geiger counters, and the entire assembly is surrounded by an inner shield of three inches of steel, and in addition an outer one of four inches of lead.

The single-channel analyzers are set on the 0.51-Mev annihilation peak obtained by replacing the KI crystal by a Na^{22} source. Coincidences between 0.5-Mev NaI pulses not accompanied by an anticoincidence pulse from the Geiger tubes operate a gate which admits any KI pulse occurring within 1 microsecond to the 20-channel pulse-height analyzer.

The background triples spectrum was obtained by substituting for the KI crystal a $1\frac{5}{8}$ in.$\times1\frac{5}{8}$ in.$\times$1 in. NaI(Tl) crystal. All three counters were calibrated once during each 24-hour run with the annihilation radiation from Na^{22}.

† This work supported by the U. S. Atomic Energy Commission.
* Present address: Duke University, Durham, North Carolina.
[1] P. R. Bell and J. M. Cassidy, Phys. Rev. **77**, 409 (1950).
[2] P. R. Bell and J. M. Cassidy, Phys. Rev. **79**, 173 (1950).
[3] S. A. Colgate, Phys. Rev. **81**, 1063 (1951).
[4] M. L. Good, Phys. Rev. **81**, 1058 (1951).

RESULTS

The KI triples spectrum together with the background NaI spectrum is shown in Fig. 2. The peak centered about channel 15 corresponds to an energy of 0.44 Mev and represents those 1.46-Mev gamma rays which produce pairs in the KI with the annihilation quanta absorbed in the two NaI crystals. Since the $K^{40}-A^{40}$ mass difference is about 1.48 Mev,[5] the positron spectrum would be expected to have a maximum intensity at about 0.26 Mev and would then appear in the region below the gamma-ray peak. On the basis of the total number of counts in channels 1–10, the results are 0.334 ± 0.037 count per hour from KI and 0.276 ± 0.037 count per hour from NaI. If the triples background expected for the KI experiment is computed by correcting the NaI background for the difference in the total number of electrons contained in the crystals, the corrected difference is 0.00 ± 0.059 count/hr. If only the differences in the widths of the two crystals and the number of electrons per cc of the two crystals are considered, the corrected difference is 0.115 ± 0.053 count/hr. An approximate upper limit to the number of counts per hour from positrons is obtained by correcting this figure for the portion of the

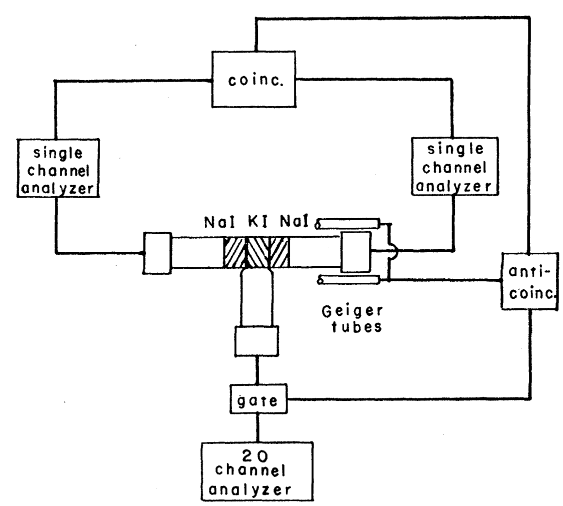

FIG. 1. Block diagram of triple coincidence system.

[5] P. M. Endt and C. M. Braams, Revs. Modern Phys. **29**, 683 (1957).

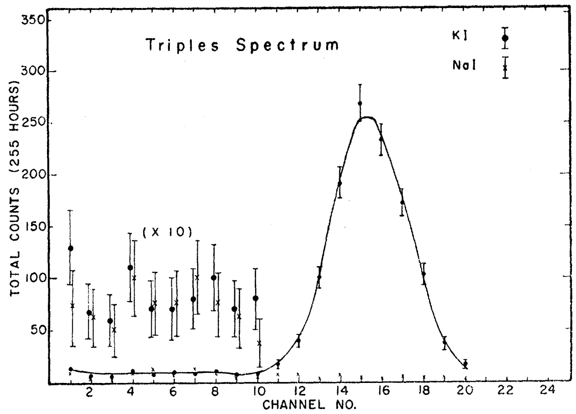

FIG. 2. Spectrum of triple-coincidence pulses from KI and NaI. The peak centered at channel 15 is due to pair production by the 1.46-Mev gamma ray.

beta spectrum above channel 10 by a factor of 1.51 ± 0.11 from the computed shape of the spectrum for an assumed $K^{40}-A^{40}$ mass difference of 1.46 Mev. The result is 0.174 ± 0.082 count/hr.

The efficiency of the system is simply the probability that a positron produced in the KI crystal will cause a double coincidence in the two NaI counters. For a direct measurement of this efficiency, a Lucite container equivalent to the KI crystal mounting was packed with enough CuO to duplicate the 0.51-Mev gamma-ray absorption coefficient of KI, and irradiated with thermal neutrons. The Cu^{64} positron activity produced thereby was measured by comparison with a calibrated Na^{22} source. Point source geometry was approximated by putting the source at 14 inches from the counter. Appropriate absorption corrections were made. The double coincidence rate obtained with the CuO source in the system then furnished directly the efficiency $\epsilon=(2.8\pm0.4)\times10^{-3}$ coincidence per positron.

The system efficiency together with the upper limit of 0.174 ± 0.082 count/hr gives an upper limit for the number of positrons emitted per second per gram of natural potassium of $(3.6\pm1.8)\times10^{-4}$. If the number of β^- per second per gram of natural potassium is taken to be 27.50 ± 0.25,[6] an upper limit of $(1.3\pm0.7)\times10^{-5}$ is obtained for the β^+/β^- ratio.

CONCLUSIONS

The decay scheme of K^{40} is shown in Fig. 3.[5] Both the β^+ and β^- transitions are unique third forbidden. The decay constant for a unique nth forbidden beta transition is given by[7]

$$\lambda_\pm=\frac{g^2}{2\pi^3}\int_1^{W_0} dW\, F_0(\mp Z,W)pW(W_0-W)^2 \times S_n^{(n+1)}(q,p,\mp Z), \quad (1)$$

where

$$S_n^{(n+1)}(q,p,\mp Z)=C_{T(A)}{}^2\frac{4\pi(n+1)!}{(2n+3)!!} \times\frac{2^n}{(2n+1)!}M^2a_n(q,p,\mp Z), \quad (2)$$

$$(2n+3)!!=1\times3\times5\times\cdots(2n+3),$$

$$a_n(q,p,\mp Z)=\sum_{\nu=0}^{n}\frac{(2n+1)!(2\nu+1)!}{2^{2\nu}(\nu!)^2(2n-2\nu+1)!} \times q^{2(n-\nu)}L_\nu(p,\mp Z). \quad (3)$$

In the above expression, the upper sign refers to positron emission, the lower to electron emission. $F_0(\mp Z,W)$ and $L_\nu(p,\mp Z)$ are functions tabulated in Appendices II and III of reference 7. The squared matrix element, M^2, is

$$M^2=\sum_m\left|\int\beta\mathcal{Y}_{n+1,\,m}(\boldsymbol{\sigma})\right|^2, \quad (4)$$

where

$$\mathcal{Y}_{l,m}(\boldsymbol{\sigma})=(i/l\hbar)\boldsymbol{\sigma}\cdot\mathbf{p}r^lY_{l,m}(\theta,\varphi), \quad (5)$$

and

$$\mathbf{p}=(\hbar/i)\nabla.$$

Since the squared matrix element, M^2, enters the expression for $\lambda_\pm$ only as a proportionality constant, the β^+/β^- ratio for K^{40} should depend only on the

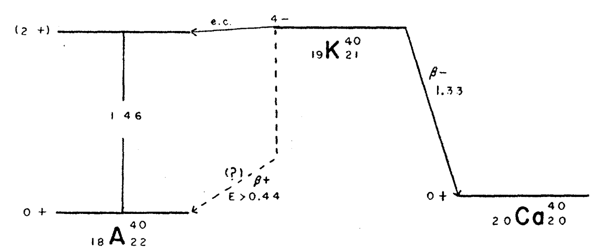

FIG. 3. Decay scheme of K^{40}.

available energies and the ratio of the matrix elements for the two transitions. A lower limit for λ_+/λ_- can be computed in terms of the ratio of the matrix elements by using the known β^- transition energy for W_0 in the expression for λ_-, and the lower limit for W_0 (corresponding to zero energy for the electron capture transition to the 1.46-Mev excited state of A^{40}) in the expression for λ_+. The result of the numerical integration is

$$\lambda_+/\lambda_- > (2.21\pm0.16)\times10^{-5}M_+{}^2/M_-{}^2,$$

where M_+ and M_- are the matrix elements for the positron transition to A^{40} and the electron transition to Ca^{40}, respectively.

[6] McNair, Glover, and Wilson, Phil. Mag. 1, 199 (1956).
[7] E. Konopinski, in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (Interscience Publishers, Inc., New York, 1955), p. 304.

Then from the experimental upper limit and the calculated lower limit, one has

$$(1.3\pm0.7)\times10^{-5} > \lambda_+/\lambda_- > (2.21\pm0.16)\times10^{-5}M_+^2/M_-^2, \quad (6)$$

and

$$M_+^2/M_-^2 < 0.59\pm0.28. \quad (7)$$

On the basis of the shell model the β^+ and β^- transitions can be represented, respectively, by $(d_{3/2})^p \rightarrow (f_{7/2})^n$ and $(f_{7/2})^n \rightarrow (d_{3/2})^p$.[8] It is expected therefore that $M_+^2 \cong M_-^2$.

The upper limit obtained for M_+^2/M_-^2 is not surprising, however. As an indication of values to be expected, Feenberg[9] has pointed out that the squares of the matrix elements for unique first forbidden transitions spread over a range of 10 according to the empirical evidence. For example, in ${}_{33}As_{41}{}^{74}$, $(f_1t)_+/(f_1t)_- = 0.63$,[10] $[f_1 = (1/20)(W_0^2-1)f]$; and in ${}_{53}I^{126}$, $(f_1t)_+/(f_1t)_- = 0.12$.[11]

We would like to thank Professor F. Rasetti for many helpful discussions.

[8] P. Morrison, Phys. Rev. **82**, 209 (1951).

[9] E. Feenberg (private communication).

[10] E. Feenberg, *Shell Theory of the Nucleus* (Princeton University Press, Princeton, 1955), p. 89.

[11] Koerts, Macklin, Farrelly, van Lieshout, and Wu, Phys. Rev. **98**, 1230 (1955).

PHYSICAL REVIEW VOLUME 116, NUMBER 2 OCTOBER 15, 1959

Reactions of Alpha Particles with Germanium-70 and Zinc-70*

SAADIA AMIEL†
Chemistry Department, Brookhaven National Laboratory, Upton, New York
(Received May 21, 1959)

The reactions $Ge^{70}(\alpha,2n)Se^{72}$, $Ge^{70}(\alpha,pn)As^{72}$, $Zn^{70}(\alpha,pn)Ga^{72}$, and $Zn^{70}(\alpha,2p)Zn^{72}$ were studied with alpha particles of 20–40 Mev, and their excitation functions were measured. The results are compared with evaporation calculations based on the assumption of compound-nucleus formation.

INTRODUCTION

THE mechanisms of nuclear reactions at moderate energies, 20 to 40 Mev, have long been the subject of discussion and much contradictory evidence has been presented.[1] In particular, the fact that (α,pn) and (p,pn) cross sections are often larger than the cross sections of competing $(\alpha,2n)$ and $(p,2n)$ reactions has, on the one hand, been cited[2] as supporting evidence for a direct-interaction mechanism, and has, on the other hand, been interpreted[3–6] in terms of level density effects in the framework of compound-nucleus theory.

It seemed of interest to investigate comparable α-induced reactions with two isobaric target nuclei, and to see whether the measured cross sections and their energy dependence could be accounted for by the statistical theory. The target nuclei chosen were Zn^{70} and Ge^{70} and the reactions studied were $Zn^{70}(\alpha,2p)Zn^{72}$, $Zn^{70}(\alpha,pn)Ga^{72}$, $Ge^{70}(\alpha,pn)As^{72}$, and $Ge^{70}(\alpha,2n)Se^{72}$. Figure 1 shows in detail the evaporation paths which can lead to these products under the assumption of a compound-nucleus mechanism.

EXPERIMENTAL

Targets.—Natural germanium was used for the study of $Ge^{70}(\alpha,2n)Se^{72}$ and $Ge^{70}(\alpha,pn)As^{72}$ reactions. The targets were prepared by evaporation of metallic germanium in a high vacuum onto 0.001-inch gold foils to thicknesses of 0.151 ± 0.002 and 0.85 ± 0.04 mg/cm². The reactions $Zn^{70}(\alpha,pn)Ga^{72}$ and $Zn^{70}(\alpha,2p)Zn^{72}$ were studied with targets of enriched zinc-70 (48 and 59 atom-percent Zn^{70}) electroplated on 0.001-inch gold foils to thicknesses in the range of 0.20 to 0.85 mg/cm².

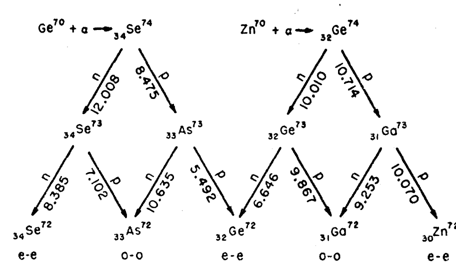

FIG. 1. Evaporation paths leading from the compound nuclei Se^{74} and Ge^{74} to the product nuclei of $A=72$. The neutron and proton separation energies[13,14] (in Mev) are shown. The even-even (*e-e*) and odd-odd (*o-o*) character of the product nuclei is indicated.

* Research performed under the auspices of the U. S. Atomic Energy Commission.

† Present address: Israel Atomic Energy Commission, at the Weizmann Institute of Science, Rehovoth, Israel.

[1] See, e.g., Conference on the Statistical Aspects of the Compound Nucleus, Eisberg, Gugelot and Porter, Brookhaven National Laboratory Report BNL-331, 1955 (unpublished).

[2] B. L. Cohen and E. Newman, Phys. Rev. **99**, 718 (1955).

[3] S. N. Goshal, Phys. Rev. **80**, 939 (1950).

[4] Miller, Friedlander, and Markowitz, Phys. Rev. **98**, 1197 (A) (1955).

[5] J. Miller and F. S. Houck, Bull. Am. Phys. Soc. Ser. II, **2**, 60 (1957).

[6] J. Meadows, Phys. Rev. **91**, 885 (1953); **98**, 744 (1955).