Radioactivity of In^{117} and Sb^{117}

CARL L. MCGINNIS
National Bureau of Standards, Washington, D. C. and Nuclear Data Group, National Research Council, Washington, D. C.

(Received September 24, 1954)

The $p_{1/2}$ isomeric level of In^{117} decays with a 1.9-hr half-life 49 percent by a 1.777-Mev β^- to the $s_{1/2}$ ground state of Sn^{117}, 23 percent by a 1.616-Mev β^- to the 0.161-Mev $d_{3/2}$ level of Sn^{117}, and 28 percent by an $M4$ 0.311-Mev γ to the $g_{9/2}$ ground state of In^{117}. The latter decays with a 1.1-hr half-life by a 0.740-Mev β^- to the $g_{7/2}$ level of Sn^{117} which is de-excited by a 0.565-Mev γ and a 0.161-Mev γ in cascade. There is no cross-over γ (<1 percent). Less than 10 percent of the 3.0-hr Cd^{117} decays to the 1.9-hr level. Less than 1 percent of the 1.1-hr ground state populates the 14-day Sn^{117m}. The 2.8-hr Sb^{117} decays to the 0.161-Mev level of Sn^{117} by a 0.61-Mev $\beta^+(\beta^+/\epsilon=0.026)$ but does not decay to the 0.323- or 0.726-Mev levels (<0.5 percent).

I. INTRODUCTION

THE systematics of nuclear energy levels predict that the decay scheme of In^{117} will be similar to that of In^{113} and In^{115}, i.e., will be characterized by an $M4$ isomeric γ ray from the $p_{\frac{1}{2}}$ level to the $g_{9/2}$ ground state. In addition, both levels are expected to decay by β^- emission with accompanying γ rays. The radioactivity of In^{117} has been studied for the purpose of verifying such a decay scheme.

Previous investigations[1] of In^{117} have shown that it decays with a 1.95-hr half-life,[2] a 1.73-Mev β^-,[3,4] and 0.161- and 0.558-Mev γ's.[4] In indium obtained from uranium fission, Coryell and co-workers[5] found half-lives of 70 min and ~2.5 hr, both of which they assigned to In^{117}. It has also been reported[6] that ~0.036 percent of the 3.0-hr Cd^{117} decays to the 14-day Sn. During the course of this work LeBlanc *et al.*[7] published the results of their work on In^{117} giving a 2.3-hr half-life and 0.160-, 0.312-, 0.562-, and 0.725-Mev γ's. The 0.312-Mev γ was assigned to the isomeric transition on account of its high conversion coefficient and because of the absence of coincidences between β's and this γ.

II. EXPERIMENTAL PROCEDURE

Cadmium metal was bombarded with 15-Mev deuterons from the Department of Terrestrial Magnetism, Carnegie Institution of Washington cyclotron. The indium that was formed during the bombardment was first removed by co-precipitation with $Fe(OH)_3$. After allowing 70 minutes for the indium activities, In^{117} plus In^{115}, to grow in from their cadmium parents, indium was again precipitated with $Fe(OH)_3$. The iron was removed with 1.5*M* HCl from a Dowex-2 ion exchange column and then the indium was washed off with 0.1*M* HCl. This procedure removed all silver and cadmium but carried along any tin that might have grown from the indium. The particle spectrum was measured with a magnetic lens spectrograph. The electromagnetic spectrum and coincidences were measured with a NaI scintillation spectrometer. All In^{117} measurements, with the exception of that of the half-life of the ground state, were made with the mixed 1.1-hr and 1.9-hr activities.

III. RESULTS

In^{117}

A value of 1.90±0.05 hours was obtained for the half-life of the isomeric level of In^{117} by observing the decay of 0.804-Mev betas with the lens spectrometer (Fig. 1).

A value of 1.1±0.1 hours was obtained for the half-life of the ground state by observing the decay of the 0.161- and 0.565-Mev γ's with a scintillation spectrometer (Fig. 1) from a source prepared in the following

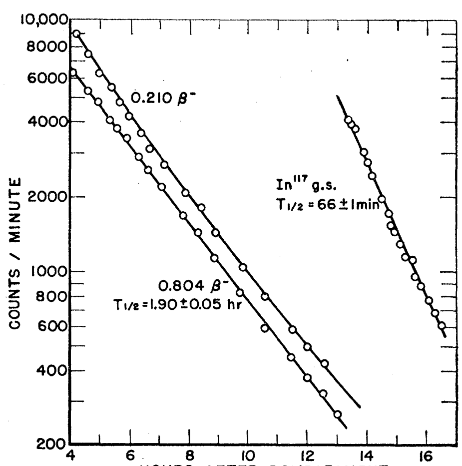

FIG. 1. Decay curves of 0.210- and 0.804-Mev betas of In^{117m} as measured with the lens spectrometer and the decay curve of the 0.161-Mev γ of the In^{117} ground state.

[1] For complete references see K. Way *et al.*; *Nuclear Data*, National Bureau of Standards Circular No. 499 (U. S. Government Printing Office, Washington, D. C., 1950) and Nuclear Science Abstracts **6**, 24B (1952); **7**, 24B (1953).
[2] J. L. Lawson and J. M. Cork, Phys. Rev. **57**, 982 (1940).
[3] J. M. Cork and J. L. Lawson, Phys. Rev. **56**, 291 (1939).
[4] J. D. Knight and G. A. Cowan, quoted by Hollander, Perlman, and Seaborg, Revs. Modern Phys. **25**, 469 (1953).
[5] Coryell, Lévêque, and Richter, Phys. Rev. **89**, 903(A) (1953).
[6] G. A. Cowan, quoted by M. Goldhaber and R. D. Hill, Revs. Modern Phys. **24**, 179 (1952).
[7] LeBlanc, Cork, and Burson, Phys. Rev. **93**, 916(A) (1954).

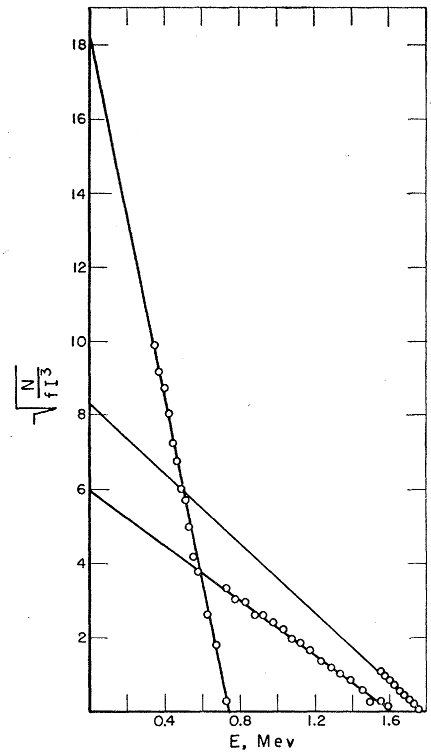

FIG. 2. Fermi-Kurie plot of the In^{117} beta spectra showing the end points of 1.772, 1.616 and 0.740 Mev.

manner. Twelve hours after the bombardment indium was chemically removed from the cadmium, the Cd^{117} was allowed to decay for 70 minutes and indium was again separated. The γ-ray spectrum of this sample was measured with a scintillation spectrometer. The 0.161- and 0.565-Mev γ's decayed with a 1.1 ± 0.1 hour half-life and an 0.333-Mev γ with the expected 4.5-hr half-life of In^{115m}. It was not possible to resolve the 0.311-Mev γ of the 1.9-hr In^{117m} from the 0.333-Mev γ.

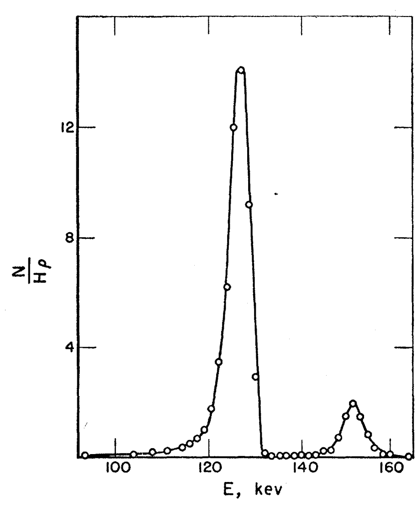

FIG. 3. Conversion electron spectrum of the 0.161-Mev γ of Sb^{117}.

From the linearity of the decay of this peak it is concluded that less than 10 percent of the 3.0-hr Cd^{117} decays to the isomeric level of In^{117}. The 1.1-hr half-life is in good agreement with the 70-min value found by Coryell *et al.*[5] The previously reported[8] value of 40 min is retracted. When the decay of the In^{117} γ rays was observed several hours after the chemical separation of indium from cadmium, a "half-life" of about 2.3 hours was observed as was expected for the parent-daughter growth and decay.

Figure 2 shows the Fermi-Kurie plot of the beta spectrum. The end-point energies, relative intensities (as determined from the intercepts[9] of the straight lines with the ordinate axis), and logft values[10] are given in Table I. The decay of 0.21-Mev betas, i.e.,

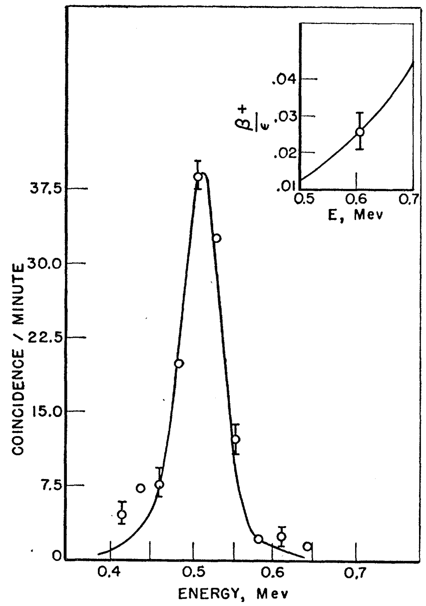

FIG. 4. Spectrum of γ rays in coincidence with the 0.161-Mev γ in the decay of Sb^{117}. The solid curve is the Na^{22} annihilation radiation energy calibration. The insert is a graph of the theoretical β^+/ϵ ratio for Sb with the experimentally measured ratio shown as a point.

about the most probable β's of the 0.74-Mev component, as measured with the β-ray spectrometer, showed little complexity, decaying mainly with a 1.9-hr half-life. If this component had originated solely as a result of the decay of the 1.9-hr isomeric level to the 1.1-hr ground state, the half-life curve would have shown a typical parent-daughter growth and decay. However, the 1.1-hr ground state is also produced directly from the decay of the 3-hr Cd^{117}. The 1.9-hr isomeric level grows from the 50-min Cd.

With these data it was then possible to analyze the decay curve of the 0.21-Mev β's into that portion

[8] C. L. McGinnis, Phys. Rev. **94**, 780(A) (1954).
[9] H. Brown and V. Perez-Mendez, Phys. Rev. **78**, 812 (1950).
[10] Rose, Perry, and Dismuke, Oak Ridge National Laboratory ORNL-1459, 1953 (unpublished); J. R. Reitz, Phys. Rev. **77**, 10 (1950).

which originated directly from the 3-hr Cd and into that portion which grew from the isomeric level of In^{117}. Under the conditions of this experiment 59 percent of the measured 0.740-Mev β^- spectrum was produced directly from the decay of the 3-hr Cd. The percentages of the three modes of decay of the 1.9-hr isomeric level given in Table I have been computed on the assumption that 41 percent of the measured 0.740-Mev beta spectrum originated from the decay of the isomeric level. This correction has not been made in Fig. 2.

The internal conversion coefficients for the three γ rays given in Table II are based on the relative intensities of the beta spectra given in Table I. The conversion electrons of the 0.565-Mev γ were scarcely observable above the β background and therefore the agreement with an $E2$ assignment is quite fortuitous.

The energies of the three gamma rays were measured by the following methods: 0.565±0.007 Mev by scintillation spectrometer studies, 0.311±0.002 Mev by observing the K-conversion electrons with the lens spectrometer (the L electrons were obscured by the more intense K electrons of the 4.5-hr In^{115m} 0.333-Mev γ ray); and 0.161±0.001 Mev by observing the K- and L-conversion electrons from the 2.8-hr Sb^{117}. The scintillation spectrometer showed a peak at 0.726 Mev. However, by varying the geometry of the measurement it was shown that this peak was due to the pile-up of the 0.161- and 0.565-Mev pulses. If a true crossover gamma ray is present, its intensity is less than 1 percent of the 0.565-Mev γ ray.

With a scintillation spectrometer and single channel differential discriminators the following coincidences were measured: $(\beta)(0.161\gamma)$, $(\beta)(0.565\gamma)$, and $(0.161\gamma)(0.565\gamma)$. No coincidences were observed between the 0.311γ and either β's or γ's.

2.8-hr Sb^{117}

Tin was bombarded with 15-Mev deuterons and the electron spectrum of the chemically separated Sb was measured with the lens spectrometer. The energy of the γ ray is 0.161±0.001 Mev. $K/(L+M)=8.3\pm0.1$ (Fig. 3). This result is in agreement with the previous data[11] on the decay of Sb^{117}.

Indium metal was bombarded with 22- to 32-Mev alphas from the Brookhaven 60-inch cyclotron and the following coincidence intensity results were found with a scintillation spectrometer and two single-channel differential discriminators: $(0.161\gamma)(0.511\gamma)/(0.161\gamma)=0.051\pm0.01$, (x-ray)$(0.161\gamma)$/(x-ray)$=0.68\pm0.02$, (x-ray)$(0.565\gamma)$/(x-ray)$<0.005$.

Figure 4 shows the γ-ray spectrum in coincidence with the 0.161γ. The solid curve is the Na^{22} annihilation radiation energy. The geometry for the measurement of the intensity ratio $(0.161\gamma)(0.511\gamma)/(0.161\gamma)$ was calibrated with Na^{22}. Allowance was made for its 10 percent electron capture.[12] On the basis of this calibration the intensity ratio β^+/ϵ is 0.026±0.005. For an allowed decay this ratio is a unique function of the decay energy. The insert in Fig. 4 is a plot of β^+/ϵ *vs* E the positron energy from 0.5- to 0.7-Mev. f_+ was computed from the tables of Rose *et al.*,[10] f_K from the formula given by Moszkowski[13] and the ratio of L_1 capture to K capture from the graph of Rose and Jackson.[14] From the observed ratio of 0.026 the maximum positron energy was then found equal to 0.61±0.03 and the logft for the transition equal to 4.80. The ground-state decay energy of 1.79 Mev is in excellent agreement with the predicted 1.8 Mev of the β-decay systematics.[15]

Te^{123} was used to calibrate the geometry for the (x-ray)(0.161γ)/(x-ray) measurement. If all the electron capture transitions go to the 0.161-Mev level the expected ratio is 0.687 when account has been taken of the previously measured conversion data and the L_1- to K-capture ratio[14] of 0.12. Hence all (≥ 95 percent) of the decays go to this level.

An attempt was made to observe a possible weak transition to the 0.726-Mev level by measuring coincidences between the 0.565γ and either the 0.161γ or x-rays. The greater intensity of the $(0.161\gamma)(0.511\gamma)$ coincidences obscured the possible $(0.161\gamma)(0.565\gamma)$ coincidences. With x-rays the only coincidences observed in the 0.5-Mev energy region were those with the 0.511γ which are expected to occur in 1 percent of the disintegrations. From this negative result if was concluded that <0.5 percent of the decay takes place to the 0.726-Mev level.

TABLE I. 1.1-hr In^{117} and 1.9-hr In^{117m} beta spectra.

Energy (Mev)	Rel. intensity	f	t(sec)	logft
0.740±0.010	22	8.75	3 960	4.54
1.616±0.005	23	166	28 600	6.68
1.772±0.005	55	241	12 450	6.48

IV. DISCUSSION

In^{117}

The measured[1] spin of $\frac{1}{2}$ and magnetic moment of -0.9951 support the shell model designation of $s_{\frac{1}{2}}$ for

TABLE II. Data for the gamma rays of In^{117}.

Energy (Mev)	$K/(L+M)$	α_K(expt)	α_K(theory)[a]
0.161±0.001	8.3±0.1	0.13±0.001	$M1$ 0.14
0.311±0.002	(3.6)[b]	1.3±0.2	$M4$ 1.26
0.565±0.007	(7.8)[b]	~0.005	$E2$ 0.0047

[a] Rose, Goertzel, and Perry, Oak Ridge National Laboratory Report ORNL-1023, 1951 (unpublished).
[b] Interpolated from empirical curves (reference 17).

[11] G. M. Temmer, Phys. Rev. **76**, 424 (1949).

[12] R. Sherr and R. H. Miller, Phys. Rev. **93**, 1076 (1954).
[13] S. A. Moszkowski, Phys. Rev. **82**, 35 (1951).
[14] M. E. Rose and J. L. Jackson, Phys. Rev. **76**, 1540 (1949).
[15] K. Way and M. Wood, Phys. Rev. **94**, 119 (1954).

the ground state of Sn^{117}. The angular correlation[16] between the K-conversion electrons of the 14-day isomeric γ ray and the 0.161-Mev gamma which is in cascade with it show that the latter is $\sim$99.9 percent $M1$. This result identifies the 0.161-Mev level as $d_{3/2}$. The conversion coefficient and $K/(L+M)$ ratio reported here agree with this assignment. The empirical[17] lifetime-energy relationship for $M4$ transitions assign $h_{11/2}$ to the 14-day isomeric level of Sn^{117}. In this region of the periodic table it appears that the simple shell model is particularly applicable. Hence single-particle designations are used for levels.

From the energy difference between the 1.772-Mev β and the 1.616-Mev β it is concluded that the former goes to the ground state and the latter to the 0.161-Mev level of Sn^{117}. The ft values for these two β transitions indicate that both are first forbidden and thus that the isomeric level of In^{117} is the expected $p_{1/2}$ state. The internal conversion coefficient and lifetime of the 0.311-Mev γ show that this is an $M4$ transition and thus that the ground state is $g_{9/2}$. In^{111}, In^{113}, and In^{115} also have $g_{9/2}$ ground states. It is interesting to note the similarity between the indium $M4$ transitions by comparing the ratio of the experimental to the predicted γ-ray lifetimes. For In^{113}, In^{115}, and In^{117} these ratios are 0.41, 0.33, and 0.50 based on the theoretical formula[18] and 1.9, 1.6, and 2.5 based on the empirical relationship.[17]

The 1.1-hr level decays by a 0.740-Mev β followed by 0.565- and 0.161-Mev γ's in cascade. The $\log ft$ of 4.54 for this beta clearly shows that transition is allowed and permits the 0.726-Mev level to have a spin of 11/2, 9/2, or 7/2 with even parity. With either of these first two assignments the predominant mode of decay would be by an $E1$ γ to the 14-day $h_{11/2}$ level rather than by an $E4$ or $M3$ γ to the 0.161-Mev level. Since the observed yield of the 14-day Sn^{117m} from In^{117} is $\sim$0.036 percent,[6] the only assignment for the 0.725-Mev level is $g_{7/2}$. An estimate for the intensity of the possible 1.14-Mev beta from the $g_{9/2}$ ground state of In^{117} to the 14-day $h_{11/2}$ level of Sn^{117} can be obtained by making use of the $\log ft$ of 8.80 for the 1.61-Mev β[1] from the 43-day isomeric $h_{11/2}$ level of Cd^{115} to the $g_{9/2}$ ground state of In^{115} on the assumption that the matrix elements for both transitions are the same. Such an estimate gives a branching of 0.02 percent which agrees with the observed yield of the 14-day Sn^{117m}.

The decay energy of the ground state of In^{117} of 1.466 Mev is in good agreement with the prediction of the beta decay systematics.[15]

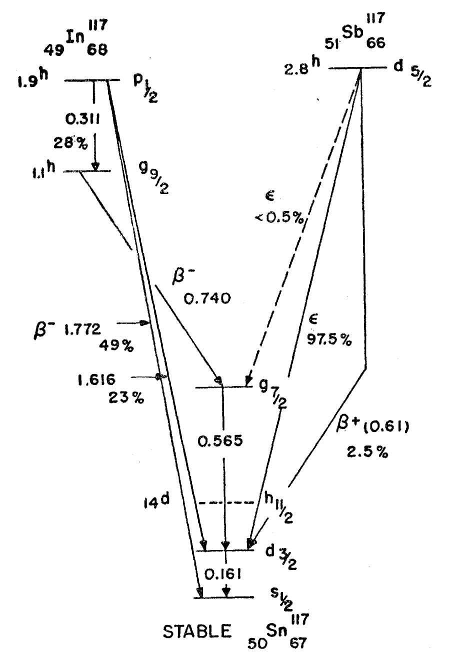

FIG. 5. Decay scheme for In^{117} and Sb^{117}.

Sb^{117}

The $\log ft$ of 4.80 for the decay of the Sb^{117} ground state to the $d_{3/2}$ level of Sn^{117} characterizes this transition as allowed. Hence the ground state of Sb^{117} has even parity and a spin of either 1/2, 3/2 or 5/2. A spin of 1/2 or 3/2 would forbid decay to the 0.726-Mev $g_{7/2}$ level but permit decay to the $s_{1/2}$ ground state, while a spin of 5/2 would do just the reverse. *Neither* decay to the 0.726-Mev level *nor* the ground state was observed. The upper limit for the first is 0.5 percent and for the second 5 percent of the main decay. If either of these transitions were allowed, the branching would be 40 percent or 120 percent respectively of that to the 0.161-Mev level. Thus the first is forbidden by a factor of >80 and the second by one of >20.

Since the experimental data are not sufficient to permit a choice between $1/2^+$, $3/2^+$, and $5/2^+$, other evidence must be considered. It seems possible that l-forbiddenness may play a role here. If it were the controlling factor, no choice would be possible between $3/2^+$ and $5/2^+$ for the Sb^{117} ground state. At present arguments about configuration rearrangements seem to hold more force than do considerations of l-forbiddenness.

The most plausible neutron configuration for Sb^{117} is $(g_{7/2})^8(d_{5/2})^6(h_{11/2})^2$.[19] No rearrangement of this configuration is necessary for the decay of a $d_{3/2}$ or $s_{1/2}$ proton to the $s_{1/2}$ ground state of Sn^{117}, therefore no reduction in the expected branching is to be expected on this account. However, one would expect the decay of a $d_{5/2}$ proton to a $g_{7/2}$ neutron to be very strongly impeded since the $g_{7/2}$ neutron shell is already full. A rearrangement of the neutron configuration to something like $(g_{7/2})^6(d_{5/2})^6(h_{11/2})^4$ is necessary before the decay can take place. A $\log ft$ of 9.2 for an apparently

16 R. K. Golden and S. Frankel, Phys. Rev. **95**, 613(A) (1954).
17 M. Goldhaber and A. W. Sunyar, Phys. Rev. **83**, 906 (1951).
18 V. F. Weisskopf, Phys. Rev. **83**, 1073 (1951).
19 P. F. A. Klinkenberg, Revs. Modern Phys. **24**, 63 (1952).

allowed transition in Kr^{85} has been ascribed[20] to a similar rearrangement. Thus the assignment of $d_{5/2}$ to the ground state of Sb^{117} makes plausible the lack of observed transitions both to the ground state of Sn^{117} and also to the 0.726-Mev level. This is actually the assignment most strongly suggested by the shell model and is consistent with the assignments, from measured spins and moments, of $d_{5/2}$ and $g_{7/2}$ to the ground states of stable Sb^{121} and Sb^{123} respectively.

The proposed decay scheme for In^{117} and Sb^{117} is given in Fig. 5.

[20] Sunyar, Mihelich, Scharff-Goldhaber, Goldhaber, Wall, and Deutsch, Phys. Rev. **86**, 1023 (1952).

V. ACKNOWLEDGMENT

I wish to express my appreciation to R. W. Hayward for his generosity in placing the facilities of his laboratory at my disposal, to D. Hoppes for his cooperation in the experiments, to D. Cowie, N. Heydenburg, and S. Buynitzky of the Department of Terrestrial Magnetism for the cyclotron bombardments, to G. Scharff-Goldhaber, and A. W. Sunyar for their cooperation in making it possible for me to do part of the experimental work at Brookhaven, and to K. Way and R. W. King for their helpful discussions throughout the course of this work.

PHYSICAL REVIEW VOLUME 97, NUMBER 1 JANUARY 1, 1955

Decay Scheme of the Mirror Nucleus P^{29} and Related Results*†

H. RODERICK, O. LÖNSJÖ,‡ AND W. E. MEYERHOF
Stanford University, Stanford, California
(Received September 27, 1954)

The decay of P^{29} has been investigated with scintillation spectrometers, single and in coincidence. Positron emission (3.945±0.005 Mev end-point energy for the most energetic spectrum) occurs with a half-life of 4.45±0.05 sec to the ground state and to excited levels of Si^{29} at 1.28, 2.43, and possibly 2.03 Mev. Branching ratios (in percent) of 98.8±0.4 (ground state), 0.8±0.2 (1.28-Mev level), <0.15 (2.03-Mev level), and $0.24_{-0.08}^{+0.26}$ (2.43-Mev level) were measured. A study of γ rays from the decay of Al^{29} to Si^{29} led to branching ratios (in percent) of 15±9 (1.28-Mev level), <4 (2.03-Mev level), and 85±9 (2.43-Mev level). The intensity of a 1.15-Mev γ ray (cascading from the 2.43-Mev level) has been set at <11 percent of the total Al^{29} decays. Spin and parity assignments of the Si^{29} levels are discussed and compared with the results of other experiments. The *ft* values of the P^{29} decay are shown to agree with values calculated from the coupling constants of β decay if the theories of Feenberg and Bohr are used.

I. INTRODUCTION

PHOSPHORUS-29 had previously been found to decay to Si^{29} with a half-life of 4.6±0.2 sec by emitting positrons of 3.67±0.07 Mev.[1] The positron transition was presumed to be an image transition. The present work shows that the disintegration of P^{29} proceeds by two, or possibly three, alternative positron transitions to the low excited states of Si^{29} in competition with the image transition.[2]

II. METHOD

The method used to study the weak modes of β^+ decay in competition with the intense β^+ transition to the ground state was to search in the radioactivity for γ rays from the excited states to which the lower energy positrons decayed. Such a method is suitable even if the branching ratio to the excited state is quite small, because any low-intensity γ rays produced are of discrete energy. Hence the gamma rays can be detected relatively free of background, and can be identified.[3] The success of this method depends entirely on the use of NaI scintillation counters with their high sensitivity to and selectivity of γ rays. The apparatus used in this work for selecting, analyzing and presenting the pulse energy distribution produced in the NaI scintillation counter has been described in the literature.[4]

III. PRODUCTION AND HALF-LIFE OF P^{29}

P^{29} was produced by the $Si^{28}(d,n)$ reaction by bombarding Si crystals with 2.8-Mev deuterons from the Stanford cyclotron. The half-life of P^{29} was determined by measuring the activity of annihilation radiation (detected by the photoelectric peak in a NaI scintillation spectrometer) as a function of time. A scaler

* Condensation of a dissertation submitted by H. Roderick to the Department of Physics and the Committee on Graduate Study at Stanford University in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

† Supported in part by the joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.

‡ Fulbright Travel Fellow. Present address: Physics Department, University of Oslo, Blindern, Norway.

[1] White, Creutz, Delsasso, and Wilson, Phys. Rev. **59**, 63 (1941).

[2] A preliminary report of this work has been given earlier: Roderick, Lönsjö, and Meyerhof, Phys. Rev. **90**, 371(A) (1953).

[3] The intense β^+ ray transition to the ground state, of course, produced no discrete γ ray, except annihilation quanta, although, as shown below, bremsstrahlung and annihilation in flight gave disturbing background effects.

[4] H. I. West, Jr., and L. G. Mann, Rev. Sci. Instr. **25**, 129 (1954).