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Lifetimes of Excited Nuclear States using Delayed-Reaction Gamma Rays*

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Using the pulsed charged-particle beam from the Livermore variable-energy cyclotron, the delayed reaction gamma rays have been employed for a direct measurement of lifetime of excited nuclear states in the nanosecond region. This technique is particularly useful in the investigation of states not populated (or only weakly populated) by radioactive decay. The mean lives of excited states of several nuclei in the $f_{7/2}$ shell have been measured. Using the $Ti^{48}(p,n\gamma)$ and $Sc^{45}(\alpha,n\gamma)$ reactions the 305-keV state of V^{48} yields (10.9 ± 0.4) nsec. Using the $V^{51}(p,n\gamma)$ and $Ti^{48}(\alpha,n\gamma)$ reactions the 750-keV state of Cr^{51} yields (10.8 ± 0.5) nsec. Considering previously reported level spin and gamma-ray multipolarity assignments, the above reported lifetimes appear to be anomalously long, indicating an extremely high degree of retardation of these electromagnetic transitions within the $f_{7/2}$ neutron and proton shells. These measurements have been confirmed using the delayed gamma-gamma coincidences following the radioactive decays of Cr^{48} and Mn^{51}, respectively.

I. INTRODUCTION

THE conventional methods for the direct measurements of nuclear lifetimes in the nanosecond region are well established. Schwarzschild[1] and Devons[2] in recent reviews have discussed these techniques and their limitations in detail. The standard delayed coincidence methods have been primarily applied to the investigation of excited states which are populated by radioactive decay.

In this paper we discuss a method of lifetime measurements in the nanosecond region with the emphasis on excited nuclear states which are not populated by radioactive decay (see Sec. II). If in a nuclear reaction the product nucleus is formed in an excited state, de-excitation to the ground state usually proceeds by gamma emission. Using a pulsed particle beam, the reaction gamma rays can be investigated as a function of time after formation of the final nuclear state. The long-lived nuclear states are identified by a measurement of the energy of the delayed gamma rays and by varying the nuclear reactions populating the states.

We have used this technique to measure the mean lives of excited states of several nuclei. The results are presented in Sec. III. The lifetimes of the 305-keV state of V^{48} and the 750-keV state of Cr^{51} appear to be anomalously long compared to similar electromagnetic transitions for nuclei in this region of the periodic table, using previously reported[3] level spin and gamma-ray multipolarity assignments. For the two states it was also possible to use the conventional methods of the delayed gamma-gamma coincidences following the beta decay of Cr^{48} and Mn^{51}, respectively (see Sec. IV). The results are found to be in full agreement with the delayed reaction gamma-ray measurements.

II. SURVEY FOR DELAYED REACTION GAMMA RAYS

A. Experimental Techniques

The Livermore 90-in. variable-energy cyclotron was utilized as a source of pulsed charged particles. Proton, deuteron, and alpha beams in energies ranging from about 4 to 12 MeV with a time spread of a few nanoseconds were used in our experiments. The measurements were performed inside the target pit with a geometry similar to the one described previously [see Fig. 1(b) of Anderson, Wong, and McClure[4]]. The diameter of the beam was defined by a $\frac{1}{2}$-in. tantalum collimator located about 1 m in front of the target. The Faraday cup was placed at the end of the beam pipe, about 2 m beyond the target. The cup is lead-lined to prevent the charged particles Coulomb-scattered in the self-supporting targets from striking the stainless-steel beam pipe. Beam currents of the order of 0.5 μA, measured by the cup, were sufficient for our measurements.

About 25 targets were used during the investigations, ranging from $Z=13$ (aluminum) to $Z=46$ (palladium). Some targets were self-supporting metal foils; in other cases it was necessary to use targets prepared by evaporating metals on tantalum or gold backing, or by sedimentation of a suspension of finely divided solids (slurry technique). The target thicknesses ranged from 3 to 15 mg/cm^2.

For the detection of the reaction gamma rays, a scintillation counter was used. The detector was positioned at distances from the target ranging from

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[1] A. Schwarzschild, *Electromagnetic Lifetimes and Properties of Nuclear States*, Nuclear Science Series 37 (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington, D. C., 1962), Publication No. 974.

[2] S. Devons, in *Nuclear Spectroscopy*, edited by F. Ajzenberg-Selove (Academic Press Inc., New York, 1960), Part A, p. 512.

[3] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington, D. C.).

[4] J. D. Anderson, C. Wong, and J. W. McClure, Phys. Rev. **126**, 2170 (1962).

0.6 to 3 m, at right angles with respect to the beam. For an initial survey a 2-in.×2-in. NaI(Tl) crystal mounted on an RCA 6810A photomultiplier was used. The gamma-ray background from the collimator system and the Faraday cup was reduced by surrounding the crystal with lead of at least 4 in. in thickness. Insertion of paraffin and/or boron of thicknesses up to 4 in. between the target and the counter diminished the neutron background.

To optimize experimental conditions for some of the later measurements, we replaced the above scintillator by the following crystals: (1) a $\frac{1}{4}$-in.-thick×1-in.-diam NaI(Tl) crystal to reduce the high-energy gamma-ray efficiency; (2) a 1-in.×1-in. plastic scintillator to enable a clean separation of the target gamma rays from the reaction neutrons utilizing time-of-flight techniques; and (3) a 1-in.×1-in. stilbene crystal to allow a suppression of the neutron radiation by using a proton-electron discrimination circuit. The latter two crystals, however, do not permit an exact energy determination of any delayed reaction gamma rays observed, but are extremely useful in decay time measurements because of the appreciable reduction in the neutron background.

The electronics circuits consisted of the standard Livermore time-of-flight electronics with the usual single-channel and multichannel pulse-height selectors. As in conventional fast-slow coincidence arrangements, the slow photomultiplier output is used for pulse-height selection and, in the experiments using stilbene scintillators, also for neutron-gamma ray discrimination. The fast detector signal is fed directly to the time-to-pulse-height converter together with the time-reference signal, derived from a pickup loop in the cyclotron and passed through a frequency divider ($f/2$). Details of the converter and pulse-discriminating circuits have been given by Anderson and Wong.[5] The pulse height and time resolution of the equipment is illustrated in Figs. 1 and 2.

An example of a time spectrum resulting from 5.5-MeV proton bombardment of V is shown in Fig. 2. The spectrum was taken with a 1-in.×1-in. plastic scintillator placed at a distance of 1 m from the target. The multichannel analyzer was gated by a differential discriminator accepting pulses corresponding to a Compton electron energy range of about 0.4 to 0.6 MeV (equivalent to an incident maximum gamma-ray energy of 0.6 to 0.8 MeV). The target gamma ray appears twice in the time spectrum, since a double display is used—one time-reference pulse for every two proton pulses. Since increasing time is toward the left in Fig. 2, some of the target gamma rays are clearly delayed. The time between the prompt gamma-ray peaks is equal to the cyclotron period—a very accurately known time interval. The linearity of the time scale is checked by taking a random pulse spectrum. A radioactive source (Na^{22}) is placed near the detector, and the cyclotron beam-extraction deflectors are turned off, maintaining an internal beam, thus insuring the same cyclotron rf conditions. This method of time calibration has previously been described in detail.[6]

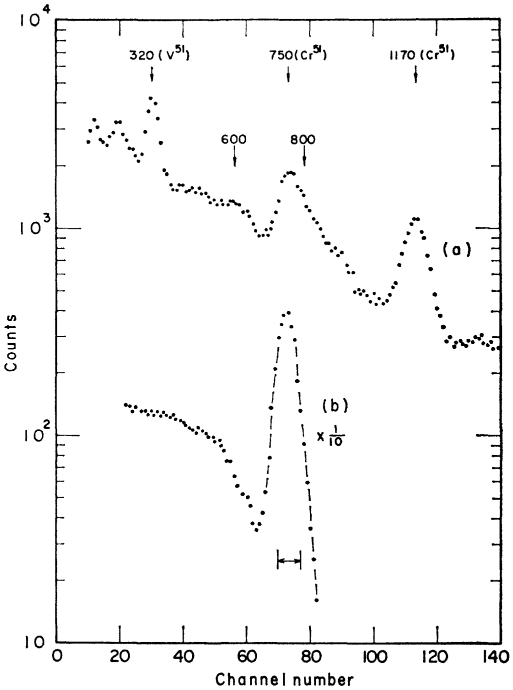

FIG. 1. Gamma-ray pulse-height distributions from 5.5-MeV proton bombardment of V^{51}, taken with a 2-in.×2-in. NaI(Tl) scintillator. The gamma-ray energies are given in keV, together with the nucleus in which the transition occurs. The horizontal arrow indicates the pulse-height interval used for lifetime measurements. (a) Reaction gamma-ray spectrum ungated. (b) Gamma-ray spectrum gated by a 10-nsec time interval selected 20 nsec after the appearance of the prompt gamma-ray peak in the time spectrum. (For an example of a time spectrum see Fig. 2.)

The differential discriminator setting quoted above also corresponds to a proton recoil energy in the plastic scintillator of about 2 MeV; thus neutrons in excess of 2 MeV will be displayed in the time spectrum. By an appropriate choice for the bombarding energy and for the distance between the target and the counter, the neutrons can be moved into a region of the time scale which is beyond the delayed gamma rays (see Fig. 2). However, in some cases it is advantageous to absorb the neutrons in paraffin or boron which, of course, increases the time-independent neutron and gamma-ray backgrounds, or to eliminate, if possible, the neutrons altogether by the proton-electron discrimination circuit. Certain features in the time spectrum, such as collimator gamma rays (see Fig. 2), have to be given special attention in the evaluation of the data.

B. Results

Using the techniques described, a search for delayed reaction gamma rays was carried out. The following

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[6] J. D. Anderson, C. Wong, and J. McClure, Nucl. Phys. **36**, 161 (1962).

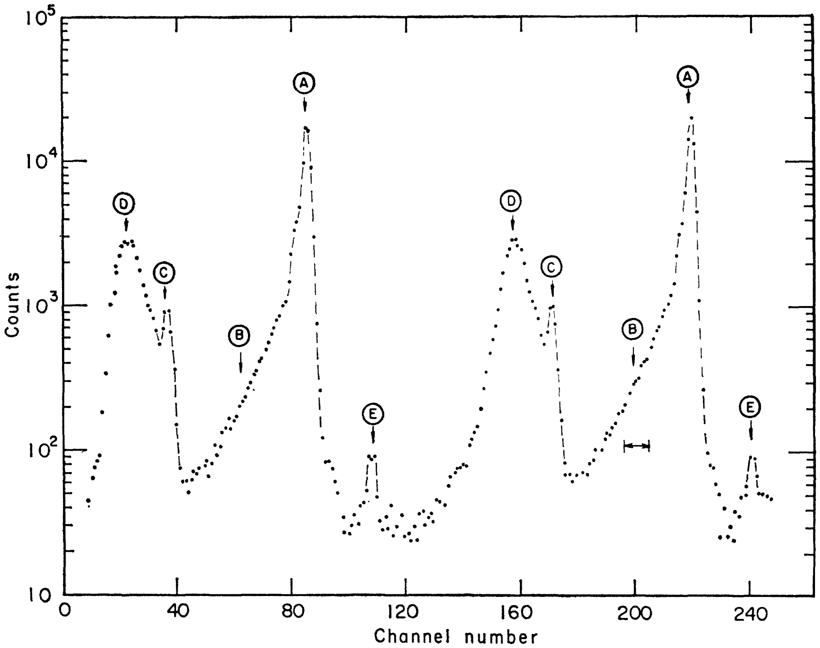

FIG. 2. Time spectrum from 5.5-MeV proton bombardment of V^{51}, taken with a 1-in.×1-in. plastic scintillator, located 1 m from the target. The separation between the prompt target gamma rays *A*, together with the cyclotron frequency of 6.035 Mc/sec, determines the time scale as 1.24 nsec/channel; increasing time is toward the left. The delayed gamma rays *B* are clearly distinguishable. The ground-state neutron group *C* from the $V^{51}(p,n)$ reaction with an energy of about 3.9 MeV are completely separated from the delayed gamma rays, as are the lower energy neutron groups *D*. The time-dependent background *E* from the collimator system is observable. The horizontal arrow indicates the approximate position and width of the time interval used for delayed gamma-ray pulse-height measurements.

targets have been bombarded with protons in the energy range from 5 to 6 MeV: Al, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu^{63}, Cu^{65}, Zn, Ga, Ge, As, Se, Sr, Y, Zr, Nb, Mo, Rh, and Pd, listed in the order of increasing atomic number. Where the mass numbers are given, separated isotopes have been used. In all other cases the natural isotopic abundance applied. Fe and the elements from As to Pd have also been bombarded with protons in the energy range above 7 MeV. The bombarding proton energy was repeatedly adjusted to values which exceed the (p,n) ground-state reaction thresholds and allow appreciable Coulomb barrier penetration, but was kept as low as possible to minimize population of highly excited states.

During this initial survey, using a 2-in.×2-in. NaI(Tl) crystal, with the lower limit of the gamma-ray energy set about 200 keV, the following delayed reaction gamma rays have been found: 305-keV gamma ray produced by proton bombardment on Ti (which consists to about 74% of Ti^{48}), 750-keV gamma ray produced by proton bombardment on V (which consists to about 99.8% of V^{51}). The mean lives for the decay of the two gamma rays were measured to be of the order of 10 nsec. For the other targets, under similar experimental conditions, no delayed gamma rays with energies above 200 keV and with a mean life in the time range from a few nanoseconds to slightly below 1 μsec have been observed. The principal limitations in this survey were the low-energy gamma-ray bias of 200 keV and the requirements on the intensity of the delayed gamma rays.

The search was further concentrated to nuclei with partially filled $f_{7/2}$ proton shells and $f_{7/2}$ neutron shells. The targets Sc, Ti, and V have been bombarded with 6-MeV deuterons, and in a separate experiment with 12-MeV alphas. The following delayed reaction gamma rays have been found: 305-keV gamma ray produced by alpha bombardment on Sc^{45}, 750-keV gamma ray produced by alpha bombardment on Ti. Again the mean lives for the decay of the two delayed gamma rays observed in the alpha-induced reactions were determined to be of the order of 10 nsec, which is a strong indication that the retarded 305-keV gamma rays observed both in $Ti^{48}(p,n)$ and $Sc^{45}(\alpha,n)$ reactions are associated with a decay of an excited state in V^{48}, and the 750-keV gamma rays observed both in $V^{51}(p,n)$ and $Ti^{48}(\alpha,n)$ reactions are due to the decay of an excited state in Cr^{51}. These tentative assignments will be fully confirmed in Secs. III and IV. For the other alpha and the deuteron-induced reactions, no delayed gamma rays have been observed under the same experimental conditions given in the previous paragraph.

III. IDENTIFICATION OF LONG-LIVED STATES AND MEAN-LIFE MEASUREMENTS USING RETARDED REACTION GAMMA RAYS

A. Experimental Techniques

After the survey described above yielded several nuclear states with lifetimes measurable by the delayed reaction gamma-ray method, in particular for excited states in V^{48} and Cr^{51}, it was important to refine the experimental methods to achieve a unique identification of the long-lived states and to reduce both the time-dependent and the time-independent neutron and gamma-ray backgrounds for a more accurate mean-life measurement. This was achieved by the proper choices of the energy and intensity of the bombarding particles, of the distance between target and counter, of the neutron absorbers used, and of the type and size of scintillator (see Sec. IIA). The electronics and the geometry, in general, were the same as discussed above.

B. Results on Cr^{51}

The level structure of Cr^{51} up to about 2.5 MeV is well established from (p,n) reactions[7–9] and (d,t) reactions.[10] The decay properties of these states have been studied by using the gamma rays following $Ti^{48}(\alpha,n)$ reactions,[11] $V^{51}(p,n)$ reactions,[8,9,12] and thermal neutron capture.[13,14] Relative intensity measurements for weak gamma transitions following the radioactive decay of Mn^{51} have been reported,[15,16] but no coincidence experiments using radioactive sources have been carried out to our knowledge. Presently available information[12,14,16] appears to determine the following decay properties: the first excited state at 750 keV is populated predominantly from the third excited state by means of a 600-keV gamma-ray transition, and from the fifth excited state by means of a 800-keV gamma transition. The second excited state at 1170 keV, decaying via a 1170-keV gamma-ray crossover only, is predominantly populated from the fourth excited state. The third, fourth, and fifth excited states at 1350, 1500, and 1550 keV, respectively, also decay directly to the ground state; the intensity of the crossover transitions, however, is weaker than that of the cascades quoted. The level sequence is given in Fig. 7.

We uniquely identified the state with the mean life of about 10 nsec by the following procedure: Using the 2-in.×2-in. NaI(Tl) crystal referred to in Sec. IIA, with a low-energy limit for gamma rays of about 200 keV, both the pulse-height and time spectra were observed for 5.5-MeV protons bombarding the V target. At this proton energy, states with an excitation up to about 3.5 MeV have been populated in Cr^{51}. The results for the pulse-height distribution measurement are presented in Fig. 1. The de-excitation gamma rays from the first and second excited states in Cr^{51} with energies of 750 and 1170 keV, respectively, are clearly resolved. The delayed gated gamma-ray spectrum [Fig. 1(b)] definitely assigns the 10-nsec mean life to the first excited state of V^{51} at 750 keV, since the 1170-keV gamma ray and the two transitions (600- and 800-keV gamma rays) populating the first excited state are all proven to be *prompt* with respect to the *delayed* 750-keV gamma transition.

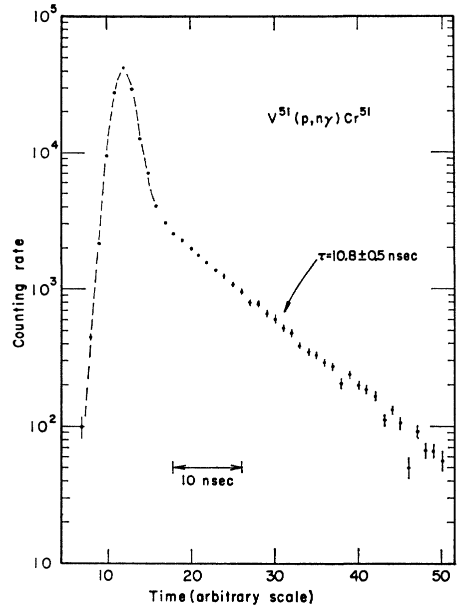

FIG. 3. Corrected time spectrum of the gamma rays from 5.5-MeV proton bombardment on V^{51}. The prompt gamma-ray peak, explained in the text, gives an indication of the time resolution. The exponential decay has been associated with the decay of the 750-keV state of Cr^{51}.

For an accurate time measurement, it was found to be necessary to clearly separate the neutron groups from the delayed gamma rays. This was achieved by using a 1-in.×1-in. plastic scintillator, placed at a distance of 1 m from the V target which was bombarded by 5.5-MeV protons. The uncorrected time spectrum obtained under these conditions, gated by an energy window corresponding to Compton electrons from about 0.4 to 0.6 MeV, is presented in Fig. 2. A discussion of this figure is given in Sec. II A.

A typical time measurement corrected for the time-independent background is shown in Fig. 3. The prompt gamma-ray peak is mainly due to the 600- and 800-keV gamma transitions populating the 750-keV state and, to a lesser degree, to higher energy gamma rays accepted by the Compton electron pulse-height gate from 0.4 to 0.6 MeV. From the exponential tail of the time spectrum, the mean life of the 750-keV state has been determined. The result is 10.8±0.5 nsec. The error quoted includes statistical fluctuations, nonlinearity of the time scale, and uncertainties in the background correction. The latter factor makes the largest contribution to the error.

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[16] K. A. Baskova, S. S. Vasiliev, Ro Song-Chan, and L. Ya. Shavtvalo, Zh. Eksperim. i Teor. Fiz. **42**, 416 (1962) [translation: Soviet Phys.—JETP **15**, 289 (1962)].

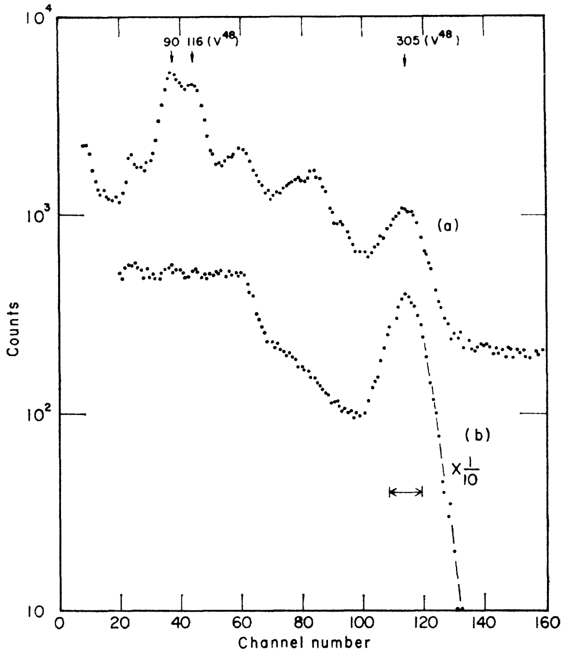

FIG. 4. Gamma-ray pulse-height distribution from 5.5-MeV proton bombardment of Ti, taken with a $\frac{1}{4}$-in.-thick$\times$1-in.-diam NaI(Tl) scintillator. The gamma-ray energies are given in keV, together with the nucleus in which the transition occurs. The horizontal arrow indicates the pulse-height interval used for the lifetime measurements illustrated in Fig. 5. (a) Reaction gamma-ray spectrum ungated. The photopeak near 90 keV is most likely due to transitions in V^{48}, as well as in V^{47}, V^{49}, and V^{50}. (b) Gamma-ray spectrum gated by a 10-nsec time interval selected about 20 nsec after the appearance of the prompt gamma-ray peak in the time spectrum.

C. Results on V^{48}

The level positions and the decay properties of the low-lying excited states of V^{48} are known from radioactivity studies[17,18] and from $Ti^{48}(p,n)$ threshold measurements.[19] The first excited state decays by the emission of a 305-keV gamma ray, while the second excited state at 421 keV decays only by a (116–305)-keV gamma cascade (the crossover is less than 2% compared to the cascade intensity[17]). No gamma rays from higher states have been reported, with the exception of the possible existence of a highly retarded 1-MeV gamma transition with a mean life of the order of several milliseconds.[20]

We uniquely identified the state with a mean-life of about 10 nsec by the following procedure: Using the small NaI(Tl) crystal referred to in Sec. II A, with a low-energy limit for gamma rays of about 50 keV, both the pulse-height and time spectra were observed as a function of the energy of the protons bombarding Ti. At a proton energy of about 5.1 MeV, only the ground state of V^{48} was excited; no 305-keV delayed gamma ray was detected. The latter, however, was clearly observed at a bombarding energy of 5.5 MeV. At this energy states higher than the first excited state are populated. Both the ***prompt*** 116-keV gamma ray populating the first excited state and the ***delayed*** 305-keV gamma ray de-exciting the same state can be identified. The results are presented in Fig. 4. This definitely designates the first excited state of V^{48} as the state in question. This measurement is further supported by the results given in Sec. IV.

The time spectrum was obtained using the same detector at a proton bombarding energy of about 5.5 MeV. The pulse-height gate at 305 keV with a width of about 10% is shown in Fig. 4. A typical decay curve for the 305-keV state is shown in Fig. 5. The curve has been corrected for the time-independent background, which was smaller by about two orders of magnitude compared to the peak counting rate. The mean life of the state is measured as 10.9 ± 0.4 nsec. The error quoted is mostly nonstatistical, but is due to time nonlinearity and to uncertainties in the background correction.

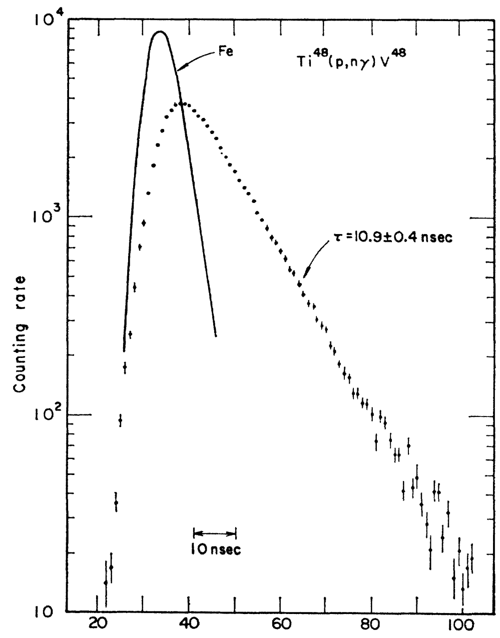

FIG. 5. Decay curve of the 305-keV state in V^{48} observed with the time-to-pulse-height converter using a $\frac{1}{4}$-in.-thick$\times$1-in.-diam NaI(Tl) scintillator, located about 1 m from the target, with 4 in. of borated paraffin between detector and target. The time spectrum was gated by the energy interval indicated by the horizontal arrow in Fig. 4. The solid curve illustrates the time resolution for prompt gamma rays observed with the same gating arrangements, but from proton bombardment on Fe.

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IV. IDENTIFICATION OF LONG-LIVED STATES AND MEAN LIVE MEASUREMENTS USING RADIOACTIVE DECAY

A. Experimental Methods

A further series of experiments has been carried out using conventional gamma-gamma ray delayed coincidence techniques to substantiate our results reported in Sec. III.

Coincidence results for a gamma-gamma cascade with the 305-keV state in V^{48} as the intermediate level have been reported by van Lieshout *et al.*[17] in their radioactive decay study of Cr^{48}. The resolving time of the circuitry, however, indicated the lifetime of the state to be less than 0.1 μsec. With similar resolution, coincidence results for gamma-gamma cascades through the 750-keV state in Cr^{51} have been published by Lobkowicz *et al.*[12] and Kane *et al.*,[14] in their study of reaction gamma rays. We have repeated these coincidence measurements with nanosecond resolving times using the gamma cascade following the radioactive decay of Cr^{48} (see Fig. 6), and the coincidences between the positron annihilation radiation and the 750-keV gamma ray following the radioactive decay of Mn^{51} (see Fig. 7).

The electronic circuits consisted of a generally conventional fast-slow coincidence arrangement with the usual pulse-height selectors. A time-to-pulse-height converter based on the design of Bell *et al.*[21] was used for the decay-time measurements. The detectors consisted of two 2-in.×2-in. NaI(Tl) scintillators mounted on RCA 6810A photomultipliers. The finite time resolution of the circuit was slightly below 4 nsec as determined from (511–511)-keV annihilation coincidences, and had about twice that value for a (116–305)-keV prompt cascade. These resolving times were sufficiently low for our measurements of the 10-nsec states in V^{48} and Cr^{51}.

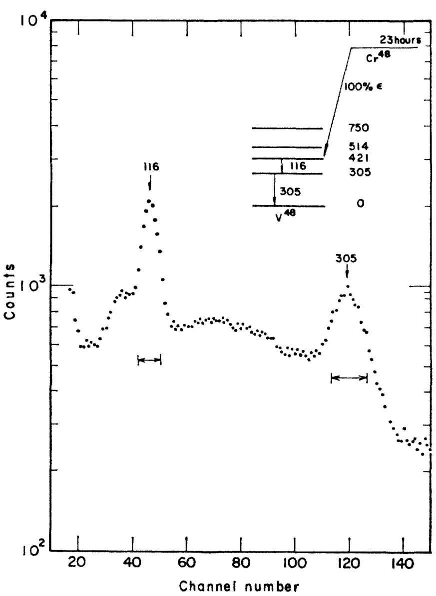

FIG. 6. Gamma-ray pulse-height distribution from the radioactive decay of Cr^{48}, taken with a 2-in.×2-in. NaI(Tl) scintillator. The gamma-ray energies are given in keV. The horizontal arrows indicate the pulse-height intervals selected for the lifetime measurements. The insert shows the relevant level structure of V^{48} and the decay of Cr^{48} (from reference 3).

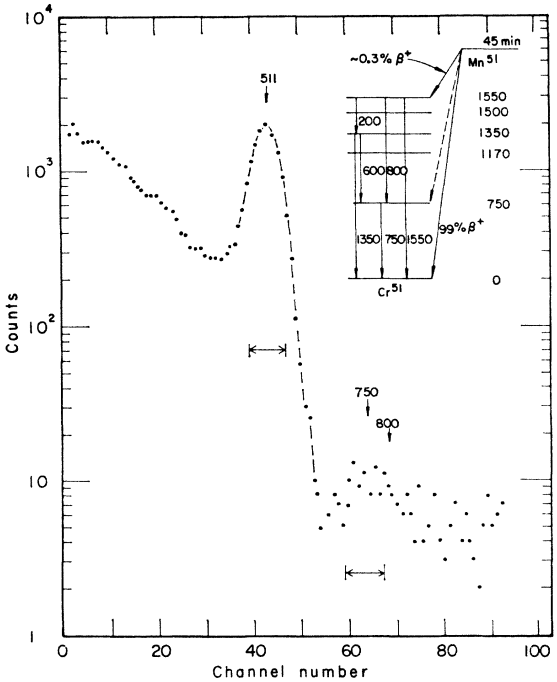

FIG. 7. Gamma-ray pulse-height distribution from the radioactive decay of Mn^{51}, taken with a 2-in.×2-in. NaI(Tl) scintillator. The gamma-ray energies are in keV. The horizontal arrows indicate the pulse-height intervals selected for the lifetime measurements. The insert shows the level structure of Cr^{51} and the portions of the decay scheme of Mn^{51} relevant to our investigations. The decay properties have been deduced from references 12, 14, and 16.

The isotope Cr^{48} was produced using the Livermore cyclotron by a 22-MeV alpha bombardment on 83% enriched Ti^{46} by an $(\alpha,2n)$ reaction. At a beam current of about 1 μA on 20 mg of target material, about 100 μC of Cr^{48} were produced during a 1-h bombardment, sufficient for our coincidence experiments. Figure 6 shows a gamma-ray pulse-height distribution, taken about 10 h after bombardment, after short-lived isotopes had decayed. The 320-keV gamma rays from the decay of Cr^{51} were not yet detectable, nor was the Compton background from the higher energy gamma rays from the decay of V^{48} high enough to require a chemical separation. Both gamma rays required for the delayed coincidence experiment are clearly observable in the singles spectrum of Fig. 6. The time measurement was carried out about 10 h after bombardment.

The isotope Mn^{51} was produced using the Livermore cyclotron by a 5-MeV deuteron bombardment on 98% enriched Cr^{50} by a (d,n) reaction. At a beam current of

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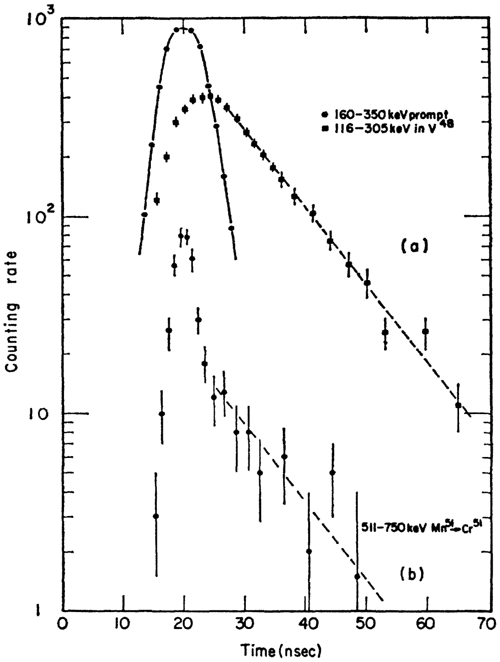

FIG. 8. Time spectra observed with the time-to-pulse-height converter using the following gamma-gamma cascades: (a) (116–305)-keV cascade in V^{48} [together with a prompt curve obtained for (160–350)-keV coincidences resulting from the scattering of 511-keV gamma rays from one counter to the other]; (b) 511-keV annihilation radiation and 750-keV gamma ray in the decay $Mn^{51} \rightarrow Cr^{51}$, measured at a 90° geometry for the two counters. The pulse-height intervals used for the decay curve measurements are indicated in Figs. 6 and 7. The dashed lines indicate a mean life of 11 nsec as reported in Sec. III.

about 2 μA on about 10 mg of target material, about 250 μC of Mn^{51} were produced during a 15-min bombardment. Figure 7 shows a gamma-ray pulse-height distribution taken about 30 min after bombardment. The 511-keV annihilation peak decayed with about a 45-min half-life, characteristic for Mn^{51}. No chemical separation was performed. Both the singles and the coincidence gamma spectra, the latter gated by the 511-keV peak and taken at a 90° geometry for the two counters to suppress annihilation coincidences, did not show a clean 750-keV photopeak. This is most likely due to the fact that in the decay of Mn^{51} the 750-keV state is predominantly populated by a 800-keV gamma transition and possibly by a less intense 600-keV transition, as deduced from coincidence measurements by Lobkowicz *et al.*[12] and recent positron investigations by Baskova *et al.*[16] (see insert Fig. 7). This is in disagreement with earlier decay schemes proposed.[3] The present experiment indicates that of the order of 0.1% of the positrons are in coincidence with the 750-keV gamma transitions. The low intensity of this coincidence rate will make a lifetime measurement extremely difficult due to the short half-life of Mn^{51}, but is found to be sufficient for an identification of the long-lived state in Cr^{51}.

B. Results

The results of the delayed coincidence measurements are presented in Fig. 8. For the case of the (116–305)-keV gamma cascade in V^{48} (curve *a*), the 305-keV gamma ray is found to be delayed, thus uniquely determining the first excited state in V^{48} at 305 keV to be the level with the lifetime of about 10 nsec. This measurement gives a result for the mean life as 11 ± 1 nsec, where the error is mostly due to statistics and nonlinearity of the time scale. This value is in agreement with the more accurate result reported in Sec. III C.

For the case of the (511–750)-keV gamma cascade in the decay of Mn^{51} to Cr^{51} (curve *b* of Fig. 8), a large portion of the gamma rays is found to be delayed by the right order of magnitude of 10 nsec. The delayed gamma rays are due to the 750-keV transition as inferred from the partial decay scheme shown in Fig. 7. The prompt peak appearing in the time spectrum, with an intensity about equal to that of the delayed gamma rays, is due to the 600- and 800-keV gamma transitions in agreement with the decay scheme. These transitions, in particular the latter one, were partially included in our pulse-height intervals used for gating (see Fig. 7). Our results determine the 750-keV state to be the level with the lifetime of about 10 nsec, in agreement with the results reported in Sec. III B. Our coincidence measurement yields a mean life of 10_{-5}^{+10} nsec. The large uncertainty is mainly due to statistics. The results fully support the identification of the state and agree with the more accurate lifetime measurement reported in Sec. III B.

V. DISCUSSION OF RESULTS

The 305-keV excited state of V^{48} with a mean life of 10.9 ± 0.4 nsec is known to decay by an $E2$-transition. The internal conversion measurements by van Lieshout *et al.*,[17] compatible only with this type of transition, together with the beta decay properties of Cr^{48} and V^{48}, suggest a spin and parity assignment for the 305-keV excited state of 2^+, and for the ground state 4^+. Though the $E2$-transition rates in this portion of the periodic table have been found to be higher than the extreme single-particle estimate, our result of about 10^{-8} sec for the 305-keV transition is of the same order of magnitude as the Weisskopf estimate.[22]

The 750-keV state of Cr^{51} decays with a mean life of 10.8 ± 0.5 nsec to the ground state; the spin and parity of the latter have been determined uniquely as $7/2^-$ (see reference 3) as expected from shell-model assignments. The assignment for the 750-keV state is less certain: A strong 8.499-MeV gamma ray, most probably of $E1$ character, from thermal neutron capture[13,14] suggests the assignments $1/2^-$ or $3/2^-$. Measurements of partial cross sections[12,23] in $V^{51}(p,n)$ reactions and a comparison

[22] V. F. Weisskopf, Phys. Rev. **83**, 1073 (1951).

[23] A. T. G. Ferguson and G. C. Morrison, Proceedings of the International Conference on Neutron Interactions, Columbia University, Sept. 1957, p. 178 [Atomic Energy Commission Report TID-7547 (unpublished)].

with the statistical theory by Hauser and Feshbach[24] suggest the assignment $3/2^-$, with $5/2^-$ not completely excluded. Assuming the assignment for the 750-keV state to be $3/2^-$, which is in agreement with the two independent experiments, we again have a retarded $E2$ transition in Cr^{51}, its transition rate reduced by more than a factor of 10 compared to the extreme single-particle estimate. If, however, one considers Cr^{51} as resulting from a neutron hole in Cr^{52}, the ground state is then expected to have a reasonable amplitude of $\{[p(7/2)^4]_0, [n(7/2)^7]_{7/2}\}_{7/2}$, and the $3/2^-$ state should have a reasonable amplitude of $\{[p(7/2)^4]_2, [n(7/2)^7]_{7/2}\}_{3/2}$. The $E2$ transition between the two components as suggested by de-Shalit (private communication) should proceed at essentially the same reduced rate as the 1.45-MeV transition in Cr^{52}. That would lead to a lifetime of the order of 10^{-11} sec, a value about 1000 times smaller than our result, which apparently indicates that either the above expected components may not be present, or that some strange cancellations may take place among contributions from various components. It has also been suggested that a strong coupling of the valence neutrons and protons which are observed in the cases of Ti^{47} and Mn^{55} nuclei[25] may account for the retardation of the observed transitions.

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Low-Energy Σ^-–p and Σ^-–d Interactions and the Pion-Hyperon Coupling Constants*

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Using a static hyperon-nucleon potential, we calculate the fraction, $\Sigma^0/(\Sigma^0+\Lambda)$, for the low-energy reactions: $\Sigma^-+p\rightarrow n+\Sigma^0$ or Λ and $\Sigma^-+d\rightarrow 2n+\Sigma^0$ or Λ. The parameters in this potential are the pion-hyperon coupling constants, $f_{\Lambda\Sigma}$ and $f_{\Sigma\Sigma}$, and the cores in the $^3S_1$ and $^1S_0$ states. We restrict these parameters to values which will reproduce the ΛN scattering lengths. Both even and odd Σ parity are considered. We cannot find agreement for global symmetry, but small $f_{\Sigma\Sigma}$ ($\lesssim 0.1$), in particular unitary symmetry, agrees very well with experiment. Solutions can also be found for the case of odd Σ parity.

1. INTRODUCTION AND DISCUSSION

IN a previous paper[1] we considered the low-energy ΛN interactions for either Σ parity. We tried to see to what extent the pion-hyperon coupling constants are determined by the Λ-N scattering lengths. These scattering lengths are estimated[2] from analyses[3,4] of hyperfragment data. We used static hyperon-nucleon potentials which took account of one- and two-pion exchange only. Thus, the exchange of K mesons and higher mass bosons is neglected. Since there are two pion-hyperon coupling constants,[5] $f_{\Lambda\Sigma}$ and $f_{\Sigma\Sigma}$, and two ΛN scattering lengths (for the $^1S_0$ and $^3S_1$ states), it would appear that a solution is always possible. Complications arise because phenomenological hard cores must be included in the potential. We require the cores to be of the same order of magnitude as the nucleon-nucleon cores. This still allows a rather large region of possible solutions for the coupling constants. For example, with even parity, global symmetry,[6] as well as unitary symmetry,[7] are both possible solutions. Global symmetry was favored over unitary symmetry because it required the same cores in singlet and triplet states while for unitary symmetry ($f_{\Sigma\Sigma}=0$), the cores differed by 0.08 μ^{-1}, the triplet core being the larger.

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[5] For the correct definition of the different coupling constants used, see A, Eq. (22).

[6] M. Gell-Mann, Phys. Rev. **106**, 1296 (1957).

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