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Lifetimes of some low-lying levels of ^{55}Co†

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Excitation energies and nuclear lifetimes of levels in ^{55}Co have been measured via the reactions ^{54}Fe(^{3}He, $d\gamma$)^{55}Co induced by 11.0 MeV incident ^{3}He^{++} particles. The Doppler shifted γ-ray spectra, taken in coincidence with the outgoing deuterons, were fitted by a line shape analysis program to determine the lifetimes. Experimental results for excitation energies (±1 keV) and lifetimes (ps) are: 2166, $0.141^{+0.020}_{-0.021}$; 2566, $0.620^{+0.120}_{-0.090}$; 2940, ≥ 0.590; 3324, $0.090^{+0.017}_{-0.012}$; 4166, $0.050^{+0.010}_{-0.005}$.

[NUCLEAR STRUCTURE ^{54}Fe(^{3}He, $d\gamma$), E=11 MeV; measured E_γ, Doppler shifts; ^{55}Co deduced levels, lifetimes.]

I. INTRODUCTION

^{55}Co, with 27 protons and 28 neutrons, has sometimes been described as having a single proton hole in the $1f_{7/2}$ shell and a closed neutron shell. Although both shell model and vibrational model calculations have been made,[1-4] little was known experimentally about this nucleus at the time.

Recently this nucleus has been the subject of several experimental investigations.[5-10] These measurements, together with results presented here, have established the low-lying structure. The present Doppler-shift-attenuation method (DSAM) lifetime measurements, involving several of the low-lying states, should provide a sensitive test for further nuclear structure calculations.

II. EXPERIMENTAL PROCEDURE

In this work the Doppler-shift-attenuation technique was employed in measurements of the line shapes of γ rays emitted from five of the excited states of ^{55}Co. Levels in ^{55}Co were populated via the reaction ^{54}Fe(^{3}He, $d\gamma$)^{55}Co using an 11.0-MeV ^{3}He^{++} beam from the Ohio State University Model CN Van de Graaff accelerator. The line shapes of the Doppler-shifted γ rays in coincidence with the outgoing deuterons were recorded as two-parameter data. Two 1000-μm-thick silicon surface-barrier detectors were positioned at 90° and 270° to the beam, with a 40-cm^3 Ge(Li) detector positioned at 57° to the beam, in order to observe γ rays emitted at an average angle of 90° and 25° to the recoiling ^{55}Co nucleus. The Ge(Li) detector resolution was 2.1 keV at 1332 keV.

The target was a self-supporting 1 mg/cm^2 foil of Fe enriched to 95% in ^{54}Fe. The target was positioned at 45° to the beam axis to allow for deuteron escape with minimal energy loss, while at the same time the ^{55}Co nuclei recoiled nearly in the plane of the target. The deuteron particle resolution achieved with this arrangement was 350 keV.

The coincident deuteron–γ-ray events were sorted and stored on-line by an IBM 1800 computer with magnetic disk memory as two arrays of 102×2048 channels. The advantage of this system is that the two-parameter data are immediately available for inspection and analysis. An example of the experimental data is shown in Fig. 1. The selection of the γ rays and particles associated with the ^{54}Fe(^{3}He, $d\gamma$)^{55}Co reaction was accomplished by choosing appropriate windows for both γ rays and particles to obtain a specific region of the two-parameter data.

Protons and α particle groups from other reactions with the target nuclei appear above the deuteron peaks of interest due to the positive Q values of the reactions involved. As shown in Fig. 1, contaminant γ rays are eliminated by the coincidence requirements.

It is important that only γ rays emitted from directly populated states be considered in the analysis. Due to the particle energy selection and coincidence requirement, γ rays from states populated by deexcitation of higher levels appear in a different region of the two-parameter array.

Although only the coincidence selection is shown in Fig. 1, the actual line shapes were obtained by setting a narrow window on the particle peak of interest and selecting a few adjacent channels above and below the peak to allow a background subtraction. The experimental line shape for the

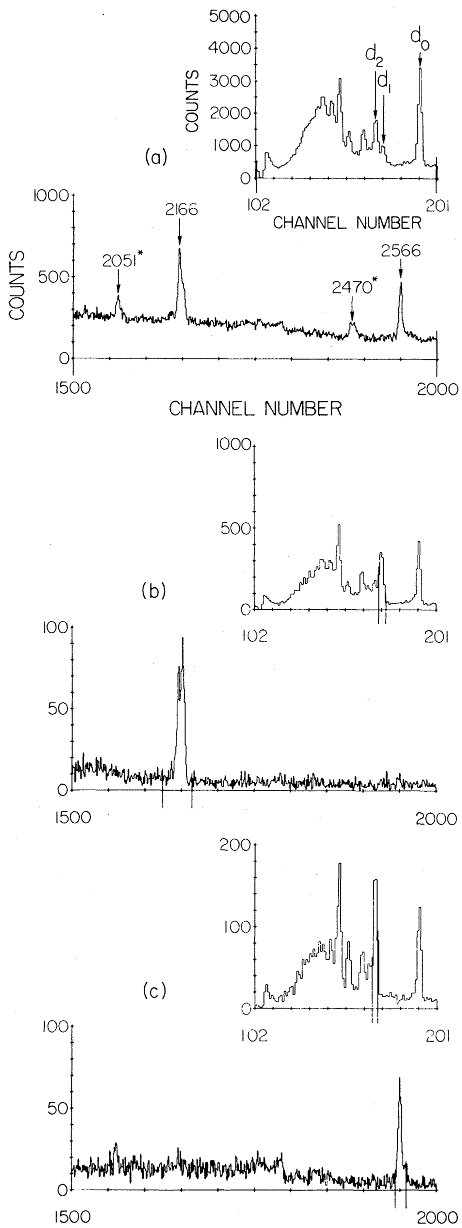

FIG. 1. Examples of the two-parameter data for the ^{54}Fe(^{3}He, $d\gamma$)^{55}Co reaction. In each of the three cases the γ spectrum in coincidence with a selected region of the particle spectrum (taken at 270°) is shown in the lower diagram. The particle spectrum in coincidence with the window set in the γ spectrum appears to the upper right. The spectra displayed are as follows: (a) A portion of the γ rays in coincidence with particles in the approximate energy region 0–10 MeV, showing, in particular, the transitions from the first and second excited states in ^{55}Co. The γ rays labeled with an asterisk (*) are products of the ^{56}Fe(^{3}He, α)^{55}Fe reaction. The particle groups labeled d_0, d_1, and d_2 are deuterons to the ground, first, and second excited states, respectively. (b) These spectra are based on the same data when the windows are narrowed to accept only d_1 and the 2166-keV γ ray. (c) Similar spectra arise when the windows are set on d_2 and the 2566-keV γ transition.

2166→0 keV γ ray observed in coincidence with deuterons of the appropriate energy to populate the first excited state is shown in Fig. 2.

The experimental line shapes were fitted by a computer program, DEWIT.[11] As no experimental information was available on the energy loss for cobalt ions stopping in iron, the stopping power equation of Lindhard, Scharff, and Schiøtt[12] (LSS),

$$d\epsilon/d\rho = f_e\,(d\epsilon/d\rho)_{\text{electronic}} + f_n\,(d\epsilon/d\rho)_{\text{nuclear}}\,,$$

was used. In this equation ϵ and ρ are the dimensionless energy and length as expressed by LSS, and f_e and f_n are corrections to the LSS theory introduced by Blaugrund *et al.*[13] The method developed by Lewis[14] for finding the angular distribution, as a function of path length, of an originally parallel beam of ions scattering in an infinite medium, was also an integral part of the program, as were the effects of target thickness, target angle, and detector resolution.

In addition to the lifetime information, excitation energies and the decay scheme for several of the levels up to 4.166 MeV have been derived from single and coincident Ge(Li) spectra. Singles runs were made with the Ge(Li) detector at 90° to the beam and γ-ray calibration sources placed to yield comparable counting rates as γ rays from the reactions occurring in the target. The γ rays from the ^{54}Fe(^{3}He, p)^{56}Co provided additional calibration lines.

III. RESULTS

The experimental level structure of ^{55}Co and the γ rays pertinent to this experiment are shown in

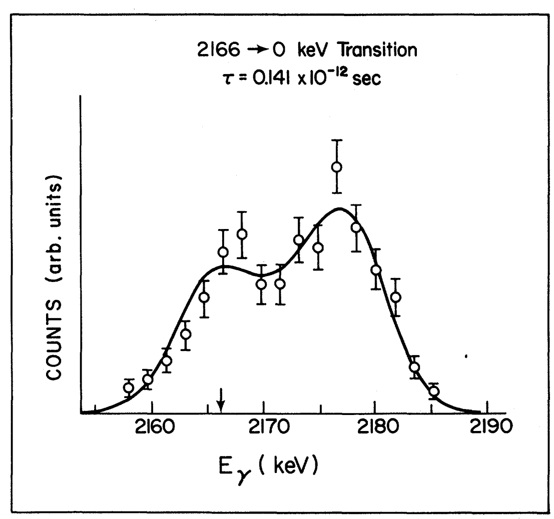

FIG. 2. Comparison of the calculated line shape (solid curve) to the experimental data for the 2166 → 0 keV transition. The arrow indicates the energy of the unshifted γ ray.

Fig. 3. The energies shown are from the present work and differ only slightly from the results reported by Goss *et al.*[10] and Martin *et al.*[8] The experimental information on nuclear lifetimes is summarized in Table I. In the lifetime analysis f_e and f_n were found to be $f_e = 1.0$ and $f_n = 1.2$, by determination of the best line shape fits for all the measured states. Since the uncertainty in f_e and f_n provide the greatest contribution to the uncertainty in the lifetimes, the errors assigned to the measured lifetimes were obtained by varying f_e from 0.9 to 1.1 and f_n from 1.0 to 1.4.

2166 keV level. The first excited state is at 2166 keV. An l value of 1 has been measured for the transfer in the ^{54}Fe(d, n) or ^{54}Fe(^{3}He, d) reaction leading to this state,[6,15-17] which limits the possible J^π's to $\frac{1}{2}^-$ or $\frac{3}{2}^-$. Based on the short lifetime of this state, $\tau < 1$ μs, previous workers[5,18] have assigned a J^π of $\frac{3}{2}^-$. The measured lifetime of this state is $0.141^{+0.020}_{-0.021}$ ps. Comparison of the experimental transition rate with the Weisskopf estimate for a pure $E2$ transition of this energy gives an $E2$ enhancement of 9.5 Weisskopf units (W.u.).

2566 keV level. The second excited state at 2566 keV is also limited to a J^π of $\frac{1}{2}^-$ or $\frac{3}{2}^-$ from an l value of 1 measured for the transfer in the ^{54}Fe(d, n) or ^{54}Fe(^{3}He, d) reaction leading to this state.[6,15-17] A previous assignment of a J^π of $\frac{3}{2}^-$ to this state was based on the absence of a transition to the first excited state and the presence of a transition of the $\frac{7}{2}^-$ ground state. Martin *et al.*,[8] using a Litherland and Ferguson Method II analysis,[19] have also determined the spin of this state to be $\frac{3}{2}$. The measured lifetime for this state is $0.620^{+0.120}_{-0.090}$ ps, which represents an $E2$ enhancement of 0.95 W.u. This is consistent with the $\frac{3}{2}^-$ assignment.

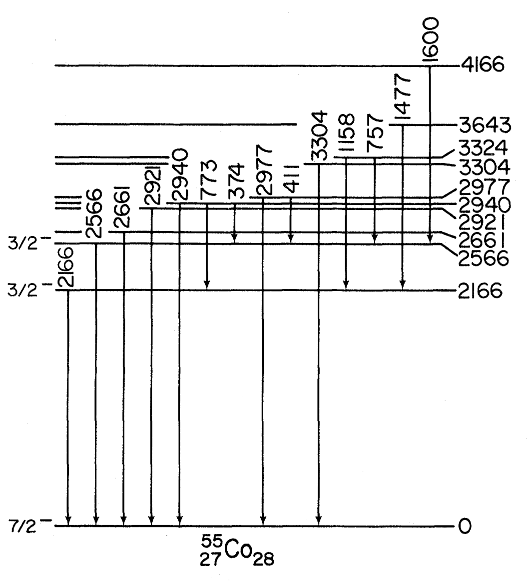

FIG. 3. Partial level scheme of ^{55}Co showing the major transitions studied in the present work. The energies shown result from the present singles and coincidence measurements and carry an uncertainty of ±1 keV. Above 3324 keV there are additional levels which are not shown here.

2940 keV level. The observed decay to the ground state represents a difference between the present work and previous work.[7,8] This decay is weak and was measured to be 5 ± 2%. Martin *et al.*,[8] using the reaction ^{54}Fe(p, γ), placed an upper limit of 1% for the decay to the ground state. Hagan *et al.*[6] using the reaction ^{54}Fe(d, n) find an $l = 1, 3$ doublet in this region. The $l = 3$ components is most likely the 2921-keV state observed to decay exclusively to the ground state in both the present work and that of Martin *et al.*[8] The presence of the ground state transition would indicate a tentative assignment of $\frac{3}{2}^-$ for the 2940-keV level. The measured lifetime of this level is > 0.590 ps.

3324 keV level. The 3324-keV level decays to the 2166-keV state and to the 2566-keV state. The lifetime found from each of these transitions must agree since they are both measures of the same state. The experimental values for the 1158-and 757-keV lines were found to be $0.093^{+0.017}_{-0.012}$ ps and $0.086^{+0.014}_{-0.012}$ ps, respectively.

4166 keV level. The measured lifetime of the 4166 keV state is $0.050^{+0.010}_{-0.005}$ ps.

The level structure of ^{55}Co has been calculated by Ram, Rustgi, and Singh[4] (quasiparticle method), by Lips and McEllistrem[2] (mixed-configuration shell model), and Stewart, Castel, and Singh[3]

TABLE I. Results of Doppler-shift-attenuation method lifetime measurements as determined by line shape analysis. Relative intensities were measured with a Ge(Li) detector at 90° with respect to the incoming beam; uncertainties are statistical only and do not include angular distribution effects.

Initial level (keV)	Final level (keV)	Branching ratio (%)	τ (ps)
2166	0	100	$0.141^{+0.020}_{-0.021}$
2566	0	(100)	$0.620^{+0.120}_{-0.090}$
2940	0	5 ± 2	
	2166	70 ± 2	≥0.590
	2566	25 ± 2	
3324	2166	77 ± 5	$0.093^{+0.017}_{-0.012}$
	2566	23 ± 5	$0.086^{+0.014}_{-0.012}$
4166	2566	(100)	$0.050^{+0.010}_{-0.005}$

(unified vibrational model). Stewart *et al.*[3] also predicted the lifetime of the first excited state and their value (0.281 ps) is to be compared with the measured value of $0.141^{+0.20}_{-0.21}$ ps.

None of the calculated level schemes bears much resemblance to the observed levels. Moreover, all three approaches predict high spin states ($\frac{9}{2}$ and $\frac{11}{2}$) between 2 and 4 MeV, whereas none have been observed to date in ^{55}Co. It is possible that high spin states have not been excited in the available experimental studies. It will be interesting to learn whether this lack of correspondence between the calculations and experiment is due to the paucity of the experimental information or to the failure of the assumptions on which the calculations were based. It is clear that meaningful comparisons must await further calculations.

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