Radioactive Decay of Lutetium-174

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Ytterbium oxide enriched to 98.4% in the 174 mass number was irradiated with 6-Mev protons. An activity of approximately 165-day half-life was produced and assigned to Lu^{174} by the identification of the ytterbium K x-ray and of the activities produced by similar proton irradiations of the other enriched isotopes of ytterbium. The observed activity of Lu^{174} consists of the L and K x-rays of ytterbium and 76.6- and 1228-kev gamma rays which are in coincidence. Because no beta radiation exists in the activity of Lu^{174}, the mode of decay is solely by electron capture to Yb^{174}. Approximately 31% of the disintegrations of Lu^{174} are to the ground state of Yb^{174}. In addition to the 76.6-kev level of Yb^{174}, there is a 1305-kev level with a spin of 0+. The transitions of Lu^{174} to the 1305-kev level of Yb^{174} are by L capture only and the percentages of electron capture to the 76.6- and 1305-kev levels of Yb^{174} are approximately 59 and 10, respectively. A spin of 1- is assigned to the ground state of Lu^{174}.

INTRODUCTION

AN activity of half-life 165±5 days has been assigned to lutetium-174 and from absorption measurements it was concluded that the mode of decay of this activity is approximately 80% by electron capture and approximately 20% by 0.6-Mev β^- emission.[1] From conversion electron measurements following the proton irradiation of natural ytterbium oxide, a 76.6-kev, E_2 $(2+ \rightarrow 0+)$, transition was assigned to Lu^{174}.[2] In a long half-life activity found in samples of natural lutetium oxide irradiated with 16- and 24-Mev betatron bremsstrahlung, β^- activity of maximum end-point energy 1.2 Mev was found and attributed to Lu^{174} and to the naturally radioactive Lu^{176} existing in the samples.[3] The gamma energies assigned to Lu^{174} were 77, 84, 113, 176, 230, 275, 990, and 1245 kev. The 77- and 1245-kev gamma rays were in coincidence. Gamma energies of 84, 203, and 306 kev were in coincidence with beta energies greater than 250 kev. The 203- and 306-kev gamma rays were attributed to the natural Lu^{176} in the samples and the 84-kev transition was assigned to Hf^{174} as its first excited level populated by the β^- decay of Lu^{174}.

EXPERIMENTAL RESULTS

Ytterbium oxide enriched to 98.4% in the 174 mass number was irradiated with 6-Mev protons. The composition of the remaining portion is as follows in percent: 0.01 Yb^{168}, 0.03 Yb^{170}, 0.13 Yb^{171}, 0.33 Yb^{172}, 0.78 Yb^{173}, and 0.36 Yb^{176}. The atomic number of the activity was determined by the identification of the ytterbium K x-ray which was compared with the known K x-rays of europium, terbium, thullium, ytterbium, lutetium, and tantalum emitted from radioactive Gd^{153}, Dy^{159}, Yb^{169}, Tm^{170}, Hf^{175}, and W^{181}, respectively. Ion-exchange separation was deemed unnecessary.

In order to determine the mass number of the activity, similar proton irradiations were performed on each of the other enriched stable isotopes of ytterbium and the resulting activities intercompared. Because the 165-day activity was not found in any of the other resulting activities, its assignment to the 174 mass number is confirmed. Also observed with the 165-day activity was a very small amount of a longer half-life activity corresponding to the only long half-life activity resulting from the similar proton irradiation of ytterbium oxide enriched in the 173 mass number. This weaker activity is therefore attributed to the small amount of Yb^{173} existing in the enriched Yb^{174}.

L and K x-rays were detected with a Geiger tube used with aluminum and beryllium absorbers. Figure 1 shows the observed gamma-ray spectrum of Lu^{174} which includes 76.6- and 1228±3 kev gamma rays in addition to the previously mentioned ytterbium K

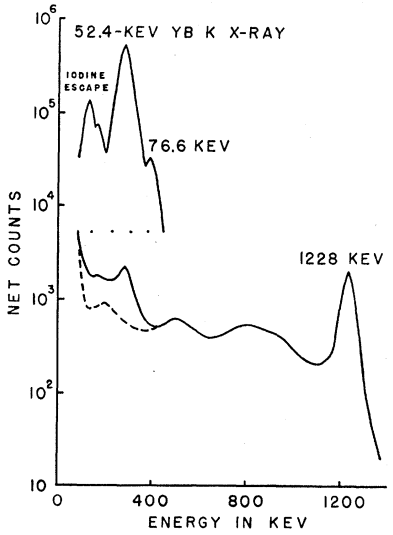

FIG. 1. The gamma-ray spectrum of the activity produced by proton irradiation of ytterbium oxide enriched to 98.4% in the 174 mass number and containing 0.78% of the 173 mass number is shown by the solid line. The dashed line shows the spectrum after subtraction of the activity produced from the 173 mass number.

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x-ray. Fortunately, the latter gamma-ray energy lies between the two accurately known gamma-ray energies of Co^{60}, 1332.5±0.3 and 1172.8±0.5 kev.[4] No evidence of beta activity was found in Lu^{174} by the method of plastic scintillation spectrometry nor by the use of Geiger tube with aluminum and beryllium absorbers. No annihilation radiation exists in the gamma-ray spectrum. The 76.6- and 1228-kev gamma rays were shown to be in coincidence by the use of a gamma-gamma coincidence circuit of resolving time $2\tau=1.5$ μsec. Therefore a 1305-kev level exists in Yb^{174}. After correction for crystal counting efficiency, the ratios of the number of radiations emitted by Lu^{174} are K x-ray: 76.6-kev γ: 1228-kev $\gamma=100:6.2:10.7$.

The conversion electron data mentioned in the introduction give the relative number of K, L_1, L_2, L_3, and M conversion electrons resulting from the 76.6-kev transition. The K, L_1, L_2, L_3, and M internal conversion coefficients, 1.52, 0.17, 2.80, 2.87, and 2.71, respectively, for a 76.6-kev E_2 transition in ytterbium were obtained from the internal conversion coefficient data calculated by Rose.[5] The above two sources of information yield a value of 11.2 for the ratio of the number of 76.6-kev transitions to the number of 76.6-kev gamma rays. Therefore the ratio of the number of conversion electrons to the number of gamma rays resulting from the 76.6-kev transition is 10.2. Also obtained is the value of 7.37 for the ratio of the total number of 76.6-kev transition to the number of K-converted transitions.

The ratio of the number of counts under the spectral distribution of the K x-ray in coincidence with the 1228-kev gamma ray to the number of 76.6-kev gamma-ray counts also in coincidence with the 1228-kev gamma ray was 1.5. The theoretical K-conversion coefficient for the 76.6-kev transition is 1.5. There is some error associated with both the experimentally measured and the theoretically calculated ratios but within these errors the two ratios are the same. This implies that no K x-rays precede the 1228-kev transitions and hence that the electron capture transitions of Lu^{174} to the 1305-kev level of Yb^{174} are by L capture only. The above factor 11.2 for the 76.6-kev transition was used to obtain the ratio of the number of K x-rays: 76.6-kev transitions: 1228-kev transitions $=100:69.5:10.7$. Internal conversion of the 1228-kev transition may be considered negligible. If the probability of L capture to the 76.6-kev level of Yb^{174} is considered small relative to K capture, $69.5-10.7=58.8$ K x-rays result from electron capture transitions to this level. The 69.5 76.6-kev transitions yield $69.5/7.37=9.5$ K x-rays from internal conversion. If the probability of L capture to the ground state of Yb^{174} is also considered small relative to K capture, there remain $100-58.8-9.5=31.7$ K x-rays which are attributable to electron capture to the ground state. It follows that the percentages of electron capture are approximately 31 to the ground state, 59 to the 76.6-kev level, and 10 to the 1305-kev level. The ratio of the number of L to K x-rays in the activity of Lu^{174} is approximately 1.4.

DISCUSSION

Because the 1245-kev gamma ray mentioned in the Introduction and the 1228-kev gamma ray observed in this investigation were each in coincidence with the 76.6-kev gamma ray, it seems probable that they are the same gamma ray. As can be seen in Fig. 1, the 84-, 113-, 176-, 230-, 275-, and 990-kev gamma rays mentioned in the Introduction do not appear in the activity of Lu^{174}. The 113-, 176-, and 275-kev gamma rays are best attributed to the activity of Lu^{173}. As also previously mentioned, the 84-kev gamma ray was found along with 203- and 306-kev gamma rays in coincidence with β^- energies greater than 250 kev. The β^- activity and the 203- and 306-kev gamma rays were attributed to the naturally radioactive Lu^{176} which has 89-, 203-, and 306-kev gamma rays in coincidence with a 1.2-Mev β^- activity.[6] Since there is no β^- activity in Lu^{174}, it seems probable that the 84-kev gamma ray also orginates in the Lu^{176} activity.

Figure 2 is a proposed energy level scheme for the decay of Lu^{174}. This scheme is consistent with all of the experimental data. It accounts for all of the radiations observed in the activity of Lu^{174} and does not imply any radiations which are not observed. The 76.6-kev 2+ level has been designated as the first rotational level of the even-even $_{70}Yb^{174}$ nucleus. Because no decay occurs to higher rotational levels and there is no 1305-kev crossover transition, the assignment of 0+ spin for the 1305-kev level of Yb^{174} is strongly favored. $_{71}Lu_{103}^{174}$ is an odd-odd nucleus in the region of elliptically deformed odd-odd nuclei. Shell theory predicts a doublet state for such a nucleus, one of which is the ground state while the other is usually the first excited state. $_{71}Lu^{175}$ has a measured spin of 7/2+ and Yb_{103}^{173} has one of 5/2−. Therefore $_{71}Lu_{103}^{174}$ would be expected to have spins of 1− and 6−. It is obvious

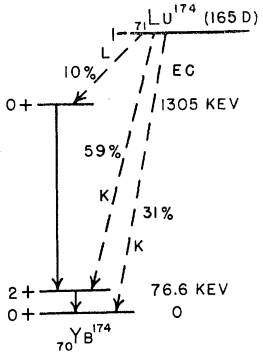

FIG. 2. Proposed energy-level scheme for the decay of Lu^{174}.

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that a spin of 1− should be assigned to the ground state of Lu^{174}.

An isomeric state in Lu^{174} of 75-μsec lifetime and 133 kev above the ground state has been observed.[7] It seems possible that this is the other member of the predicted doublet.

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Nuclear Orientation of Mn^{56}†*

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The angular distribution and circular polarization of the gamma rays emitted from 2.6-hr Mn^{56}, polarized at low temperatures in cerium magnesium nitrate, have been measured. Comparing the angular distribution results with angular correlation data it is possible to establish the spins of the 2.65- and 2.98-Mev excited states of Fe^{56} as 2 uniquely. The amplitude mixing ratios $\delta(E2/M1)$ for the 1.81- and 2.13-Mev γ-rays are shown to be $+0.11\pm0.06$ and -0.27 ± 0.03, respectively. Gamma anisotropies from aligned Mn^{56} in the same cooling salt have been studied; the results are compared with other Mn alignment experiments. From a simultaneous measurement of the angular distribution of the γ-rays from polarized Mn^{52} and Mn^{56}, the ratio of the nuclear g-values $(g_{52}/g_{56})=0.47\pm0.05$ has been determined, giving $\mu_{56}=3.35\pm0.35$ nm. The results of the circular polarization experiment determine μ_{56} to be positive.

I. INTRODUCTION

EXPERIMENTS by the nuclear cryogenics groups in Oxford and Leiden have shown that manganese isotopes incorporated in the lattice of cerium magnesium nitrate crystals can be oriented by the low-temperature method. Grace and co-workers[1] have applied both the Gorter-Rose method of nuclear polarization and the Bleaney method of alignment to the relatively long-lived Mn^{54}; Huiskamp and collaborators[2,3] have used both techniques to orient Mn^{52}. Huiskamp[2] has pointed out that there exists a discrepancy in the alignment data when comparing the results from the two Mn isotopes in the same cooling salt.

The purpose of the present work was to extend the magnetic hfs orientation methods to the investigation of the short-lived 2.6-hr isotope Mn^{56}. The spins of the levels and the multipolarity of the γ rays were determined from the study of the anisotropy of the γ rays emitted, which also yielded information about the magnitude of the magnetic dipole moment of Mn^{56}. The sign of this moment was measured by the observation of the circular polarization of the gamma rays.

II. DECAY SCHEME AND FORMALISM

The principal features of the decay scheme of Mn^{56} are well established (see, for instance, Strominger *et al.*[4]); Fig. 1(a) is based on this together with the results of the present experiment. Investigations of the γ spectrum by Cook[5] revealed additional high-energy γ rays of 2.52 and 3.39 Mev, not shown in the decay scheme.

From Coulomb excitation[6] and angular correlation and polarization correlation experiments[7] the 0.845-Mev state of Fe^{56} has a spin of 2^+. γ-γ angular correlation measurements by Metzger and Todd[8] and by Stimag *et al.*[9] show γ_2 and γ_3 to be mixed dipole-quadrupole transitions, the spin of the 2.98-Mev state being 3 or 2, and that of the 2.65-Mev state being 2.

Childs and Goodman,[10] using the atomic beam magnetic resonance technique, have measured the spin of Mn^{56} to be 3. Thus only Gamow-Teller beta transitions can take place to the excited states of Fe^{56} with

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