Evidence for an Isomeric State of Y^{90}

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The recently reported activity induced by neutron bombardment of niobium has been produced by 14-Mev neutrons and by neutrons of energy less than 6 Mev, on both niobium and zirconium. In each case, chemical separation showed the activity to be due to an isotope of yttrium. Two coincident gamma rays having energies of 0.200 and 0.485 Mev and a half-life of 3.1±0.1 hr were observed; these observations were in agreement with earlier results. The activity appears very similar to that which has been previously attributed to the decay of Y^{92}. However, threshold considerations and the failure to observe by means of a thin-window Geiger counter any beta emission associated with this gamma activity, point to an isomeric state of Y^{90}. Experiments with separated isotopes of Zr^{90} and Zr^{92} support this assignment.

INTRODUCTION

THE recently reported activity[1] induced by bombarding niobium with 14-Mev neutrons has been studied in this laboratory and has been shown to be due to an isotope of yttrium. Two coincident gamma rays having energies of 0.485 and 0.200 Mev decaying with a 3.1±0.1-hr half-life have been observed in agreement with previous measurements. This paper reports experiments[2] indicating that the activity is due to an isomeric state[2a] of Y^{90} arising from $Nb^{93}(n,\alpha)$.

STUDY OF THE INDUCED ACTIVITIES

Samples of niobium, zirconium, zirconium oxide enriched in Zr^{90}, and zirconium oxide enriched in Zr^{92} were bombarded by neutrons produced by 0.3-Mev deuterons incident on a tritium-zirconium target. Niobium metal (99.92% pure) and zirconium hydride (99.8% pure, reactor grade) were obtained from the Kawecki Chemical Company, Inc., and Metal Hydrides Incorporated, respectively. The enriched zirconium isotopes as well as the Zr-T targets used for neutron production were obtained from the Oak Ridge National Laboratory. The enrichments of the Zr^{90} and Zr^{92} samples were 98.66 and 93.22%, respectively. Chemical analyses of the niobium and zirconium hydride samples and spectrographic analyses of the separated isotopes of zirconium were available. This information was carefully considered in eliminating any impurity as the source of the activity under study.

Gamma rays were measured by two NaI(Tl) crystals, $2\frac{1}{2}$ inches in diameter and 2 inches thick, coupled to two Du Mont 6363 photomultiplier tubes, in conjunction with two single-channel analyzers, a coincidence circuit of 0.1-μsec resolving time, and a Radiation Counter Laboratory, Inc., 256-channel analyzer. Na^{22}, Mn^{54}, Co^{60}, Cd^{109}, Ba^{133}, and Cs^{137} sources were used for energy calibration of the gamma detectors. For beta counting, a Geiger counter of window thickness 1.9 mg/cm^2 was used.

Chemical separations[3] were carried out following irradiation of niobium and zirconium targets; however, no chemistry was performed when the separated isotopes were employed. The niobium targets were dissolved in concentrated nitric and hydrofluoric acids; yttrium

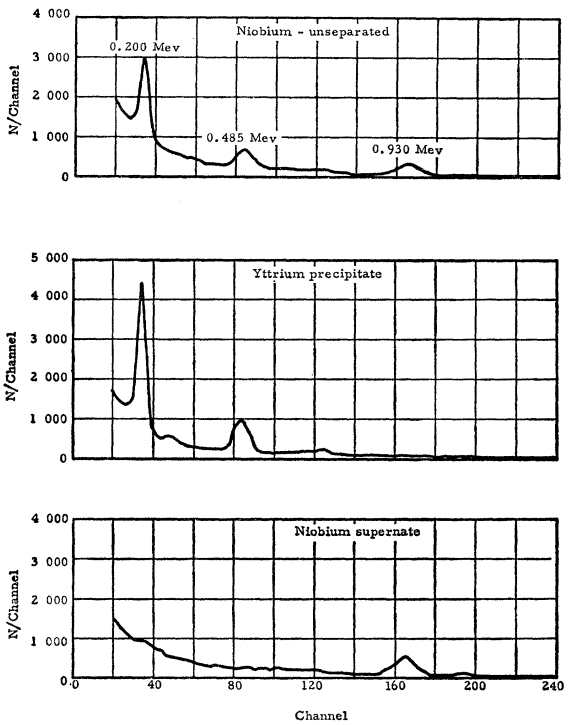

FIG. 1. Gamma-ray spectra resulting from niobium activation with 14.7-Mev neutrons.

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[1] M. Bocciolini, G. Di Caporiacco, L. Foá, and M. Mandó, Nuovo cimento **16**, 780 (1960).

[2] A preliminary account of the results of this investigation was presented at the twenty-seventh Annual Meeting of the Southeastern Section of the American Physical Society, Louisville, Kentucky, March 30–April 1, 1961. Subsequent to writing this paper it was noted that J. E. Cline, R. L. Heath, C. W. Reich, and E. H. Turk, Bull. Am. Phys. Soc. **6**, 228 (1961) have also reported this isomeric level in Y^{90}. These workers produced the Y^{90m} by thermal neutron irradiation of Y^{89} and obtained results in agreement with those given here.

[2a] *Note added in proof.* A recent report on Y^{90m} has been given by Larry Haskin and Robert Vandenbosch, Phys. Rev. (to be published).

[3] W. A. Cassatt, Jr., and W. W. Meinke, Phys. Rev. **99**, 760 (1955).

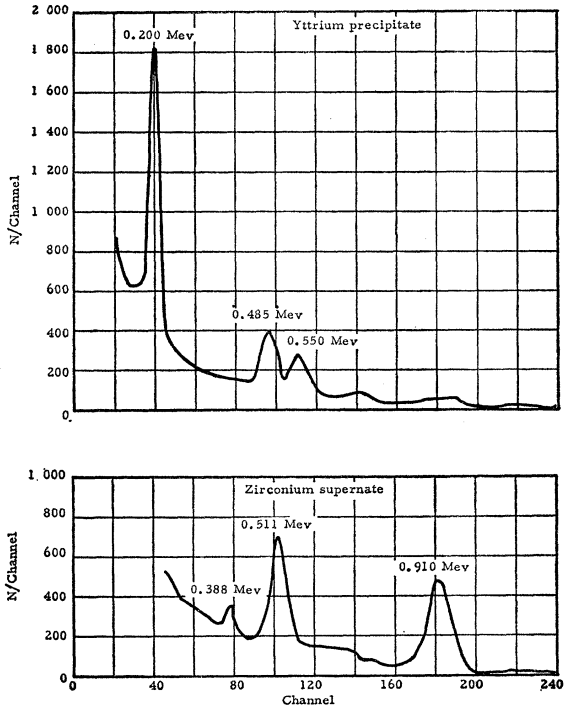

FIG. 2. Gamma-ray spectra resulting from zirconium activation with 14.7-Mev neutrons.

and zirconium carriers were added with the yttrium precipitating as the fluoride. For beta counting under thin-window Geiger counters and for gamma-ray coincidence measurements, the yttrium precipitate was metathesized with 10-molar potassium hydroxide, washed, dissolved in hydrochloric acid, and evaporated to dryness. The irradiated zirconium samples were dissolved in dilute hydrofluoric acid after which the process was the same as for the niobium samples.

The results obtained for 14.7±0.7 Mev neutrons on niobium are shown in Fig. 1. Prior to chemical separation the niobium gamma spectrum showed, in addition to the well-known gamma ray[4] at 0.930 Mev from Nb^{92}, two other gammas at 0.200 and 0.485 Mev. The spectra shown in Fig. 1 for the yttrium fluoride precipitate and for the supernatant solution indicate a satisfactory chemical separation. The decay of both the 0.485- and 0.200-Mev gammas was studied by following the output of single-channel analyzers set to pass pulses occurring within the two photoelectric peaks in two back-to-back NaI crystals. Measurements on both gammas covering a period of about 15 hr gave a value of 3.1±0.1 hours for the half-life of each. The coincidence counting rate was also followed and the same half-life was obtained. Additional gamma spectra were recorded on the multichannel analyzer gated by the output of the coincidence circuit. The gating pulse required coincidence between the outputs of the two NaI crystals and the output of a single-channel analyzer. Spectra were recorded on the multichannel analyzer with the single-channel set at 0.200 Mev and at 0.485 Mev. The spectra showed these gammas to be in coincidence.

The decay of the yttrium fraction was also followed by a thin-window Geiger counter. The sample decayed with a half-life of approximately 65 hr, a value matching that of the beta decay of Y^{90}. Observation of a buildup of the 65-hr decay due to the possible 3.1-hr isomeric state of Y^{90} was unsuccessful; however, the low yield of Y^{90m} and the delay due to chemical separations would make this difficult.

The results for 14.7-Mev neutrons on zirconium are shown in Fig. 2. Here again the chemical separation points to an isotope of yttrium as the source of the 0.200- and 0.485-Mev gammas; this result is in agreement with the niobium data. Present in the spectrum from the supernatant solution of zirconium are prominent gamma rays at 0.388, 0.511, and 0.915 Mev. The 0.511- and 0.915-Mev gamma rays are attributed to the decay scheme of Zr^{89} resulting from an $(n,2n)$ reaction in Zr^{90}. The 0.388-Mev gamma ray is expected from the $Zr^{90}(n,\alpha)Sr^{87}$ reaction. The 0.551-Mev gamma which arises from the yttrium fraction, along with the 0.200- and 0.485-Mev gammas, is attributed to Y^{91} formed by $Zr^{91}(n,p)$. The decay of the yttrium fraction was followed by the Geiger counter with a resulting decay curve which could be resolved into 65- and 3.5-hr components. These components could be accounted for by the beta decay of Y^{90} and Y^{92}.

Samples of niobium and zirconium were also bombarded by neutrons of energy less than 6 Mev produced by 1.7-Mev deuterons on a beryllium target; the neutron energy was below the $Nb^{93}(n,2p)$, $Nb^{93}(n,He^3)$, $Zr(n,d)$, and $Zr(n,t)$ thresholds.[5,6] The fact that the activity was still observed in the niobium bombardment indicates either an $Nb^{93}(n,\alpha)Y^{90m}$ or an $Nb^{93}(n,n'\alpha)Y^{89m}$ reaction. The known properties of Y^{89m} essentially eliminate the latter reaction as a possibility. Furthermore, the fact that the activity is produced in the zirconium bombardment completely eliminates Y^{89m} as the responsible activity.

Since gammas similar to those presently considered have been previously attributed[3] to levels in Zr^{92} from the decay of Y^{92}, separated isotopes of Zr^{90} and Zr^{92} were bombarded by 14.7-Mev neutrons. Irradiation of Zr^{90} gives rise to the spectrum of Fig. 3. Apparently present in this spectrum are the 0.388-Mev gamma ray from Sr^{87m}, 0.200- and 0.485-Mev gamma rays from Y^{90m}, and those gammas from the decay of Zr^{89}. The assumption that the peak near 0.5 Mev is due to a mixture of 0.485- and 0.511-Mev gammas appears reasonable from the width of the peak. This spectrum was taken after

[4] D. Strominger, J. M. Hollander, and G. T. Seaborg, Revs. Modern Phys. **30**, 662 (1958). Unless otherwise noted, decay scheme information was taken from this reference.

[5] V. J. Ashby and H. C. Catron, University of California Radiation Laboratory Report UCRL-5419, 1959 (unpublished).

[6] R. J. Howerton, University of California Radiation Laboratory Report UCRL-5351, 1958 (unpublished).

sufficient time had elapsed for the decay of the 4.4-minute Zr^{89m}. A subsequent Geiger count followed a rate of decay which could be attributed to a mixture of Y^{90} (65 hr) and Zr^{89} (79 hr). There was no indication of a 3- to 4-hr component.

As shown in Fig. 3, no gamma photopeaks were clearly evident above background in the reaction products of Zr^{92} plus 14.7-Mev neutrons. Although some low-level gamma activity must certainly be present from the reaction products of other isotopes of zirconium in the separated sample of Zr^{92} and from any branching of the Y^{92} beta decay, it was masked by the background. This Zr^{92} sample, which was also counted under the end-window Geiger counter, showed a 3.5-hour activity as expected from the beta decay of Y^{92}. A comparison of the two parts of Fig. 3 indicates that a reaction involving Zr^{90} is the source of the 0.200- and 0.485-Mev gammas.

The level in Y^{90} at 0.200 Mev has also been reported by Bartholomew.[7] On the basis of angular correlation studies, these workers gave a tentative assignment of 3− to this level. As pointed out by Bocciolini[1] the 3.1-hr activity is consistent with Weisskopf's lifetime formula if the 0.485-Mev gamma results from an $M4$ transition. These considerations would point to an assignment of a 7+ level in Y^{90} at 0.685 Mev.

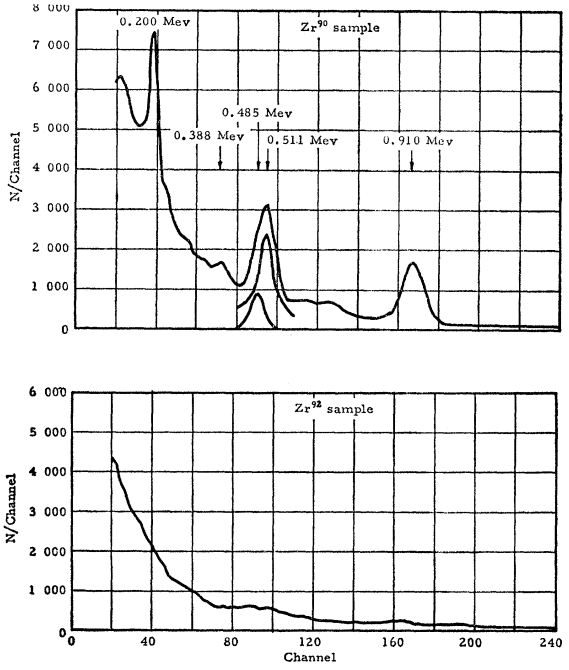

FIG. 3. Gamma-ray spectra resulting from 14.7-Mev neutron activation of Zr^{90} and Zr^{92}. The structure of the peak near 0.500 Mev in the Zr^{90} spectrum was deduced by observing the 0.511-Mev peak of the 79-hr Zr^{89} after the 3.1-hr activity had decayed away.

[7] G. A. Bartholomew, P. J. Campion, J. W. Knowles, and G. Manning, Nuclear Phys. **10**, 590 (1959).

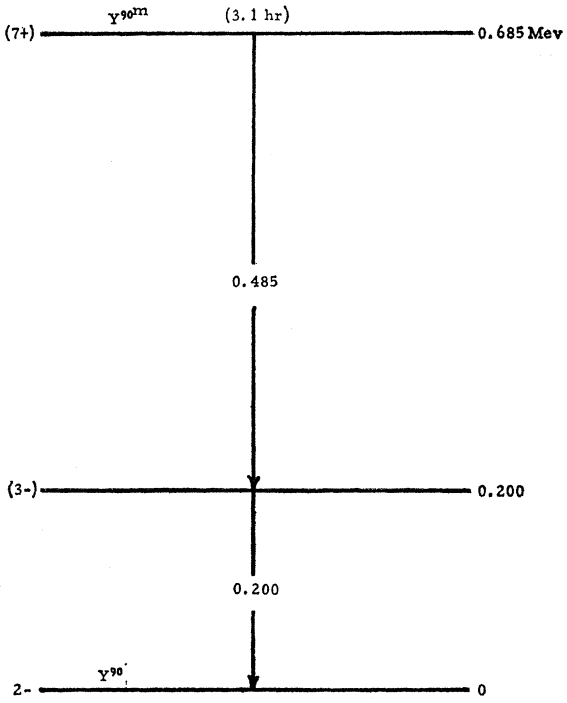

FIG. 4. Decay of Y^{90m}.

CROSS SECTIONS

The $Nb^{93}(n,\alpha)Y^{90m}$ and $Zr^{90}(n,p)Y^{90m}$ cross sections at 14.7 Mev were found to be 5±2 and 12±4 mb, respectively. The $Zr^{90}(n,p)Y^{90m}$ cross section was determined by comparing the total counts under the 0.200- and 0.485-Mev photopeaks from Y^{90m} and the 0.915-Mev photopeak from Zr^{89}. The value[8] of 822 mb was used for the $Zr^{90}(n,2n)$ cross section at 14.7 Mev. For the $Nb^{93}(n,\alpha)Y^{90m}$ cross-section measurement, the niobium sample was sandwiched between disks of copper foil and activated. A comparison was made of the yield of the 0.200- and 0.485-Mev gammas from Y^{90m} and the annihilation gammas from Cu^{62}. The absolute cross section obtained for $Nb^{93}(n,\alpha)Y^{90m}$ was based on a $Cu^{63}(n,2n)Cu^{62}$ cross section[9] of 610 mb at 14.7 Mev. In making the cross-section determinations, corrections were included for crystal efficiency, saturation factors, internal conversion coefficients,[10] and decay factors. It was found that, within the uncertainties in the crystal efficiencies and the internal conversion coefficients, the number of 0.485-Mev gamma rays was equal to the number of the 0.200-Mev gamma rays. No measurements of the cross section were made at the lower neutron energies; however, the yields were

[8] R. J. Prestwood and B. P. Bayhurst, Phys. Rev. **121**, 1438 (1961).

[9] J. L. Fowler and John E. Brolley, Jr., Revs. Modern Phys. **28**, 103 (1956).

[10] M. E. Rose, in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1955), p. 905.

markedly reduced from those at 14.7-Mev neutron energy.

CONCLUSION

The experimental results obtained in the present work support those findings previously reported[1] with the additional result that the 3.1-hr activity is associated with yttrium. Threshold considerations and the absence of a detectable beta particle associated with the 0.200- and 0.485-Mev gammas indicate an isomeric state of Y^{90}. The information on the decay of Y^{90m} is summarized in Fig. 4.

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Excitation Functions for Lithium-6 Induced Reactions on Aluminum-27†

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Excitation functions for a number of Li^6-induced reactions on Al^{27} have been studied using stacked foil techniques and the Li^6 ion beam from the Yale Heavy Ion Accelerator. Excitation functions corresponding to radioactive residual nuclei P^{32}, P^{30}, Si^{31}, Al^{29}, Al^{28}, Mg^{27}, Na^{24}, and Na^{22} have been measured in the Li^6 energy range from 1 to 63.3 Mev. The data strongly suggest that the P^{32}, P^{30}, and Si^{31} result from compound system processes and the Na^{22} and Na^{24} from a predominant direct knockout process. In the cases of Al^{28} and Al^{29} both compound system and direct pickup reaction amplitudes contribute to the reaction yield.

INTRODUCTION

SEVERAL laboratories[1–6] have reported results of the study of the interactions of accelerated Li^6 ions with various target materials. However, these data are limited either by very low Li^6 ion energies or by detection of the fragments resulting primarily from Li^6 ion breakup. The availability of a Li^6 ion beam of high intensity (3×10^{12} Li^6 ions/min) and energy (10.55 Mev/nucleon) from the Yale Heavy Ion Accelerator has facilitated more extensive studies, using activation methods, of excitation functions for several residual nuclei.

Reactions of particular interest are those, where the target nucleus—Li^6 ion interactions lead to products formed via nucleon pickup or charge exchange and those in which the target nucleus is depleted by one or more nucleons or nucleon-clusters as a result of a direct pickup or knockout reactions. In the present work Al^{27} foils were used as the target material because of the ease of identification of many of the residual nuclei in question (P^{32}, P^{30}, Si^{31}, Al^{28}, Al^{29}, Mg^{27}, Na^{22}, and Na^{24}) by observing either gamma-ray decay, beta decay, or both. In addition, the availability of very thin Al foils with uniform thickness and high purity permits the use of the normal stacked-foil technique.

EXPERIMENTAL

Foil stacks, each consisting of 27 foils of 99.9% Al^{27}, 4.65 mg/cm² in superficial density, were irradiated for periods ranging from 20 min to 1 hr with Li^6 ion beams having an incident energy of 10.55 ± 0.2 Mev per nucleon. In all bombardments the beam intensities were measured using a Faraday cup and a Cary electrometer. Following the bombardment the foils were separated, mounted on aluminum disks and the gamma-ray decay followed using a 3×3 in. NaI(Tl) crystal and a 400-channel pulse-height analyzer (Fig. 1; tables). The foils were counted with a gas-flow end-window beta proportional counter and the beta decay of P^{32}, Si^{31}, Na^{22}, and Na^{24} followed for times sufficient to establish accurate half lives.

The energy calibrations for the gamma-ray spectra were accomplished with several standard sources (i.e., Cs^{137}, Na^{22}, Mn^{54}, etc.). The gamma-ray spectra were normalized in the standard manner, corrections for background and efficiency[7] were applied, and the total disintegration rates established by observing the decay of the integrated areas of the gamma-ray peaks of interest. The gross beta-decay curves were resolved

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[1] G. C. Morrison, Phys. Rev. **121**, 182 (1961).
[2] E. Norbeck and C. S. L. Littlejohn, Phys. Rev. **108**, 754 (1957).
[3] E. Norbeck, *Proceedings of the Second Conference on Reactions between Complex Nuclei, Gatlinburg, Tennessee* (John Wiley & Sons, Inc., New York, 1960), p. 236.
[4] C. E. Anderson, *Proceeding of the Second Conference on Reactions between Complex Nuclei, Gatlinburg, Tennessee* (John Wiley & Sons, Inc., New York, 1960), p. 67.
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[6] E. Norbeck, J. M. Blair, L. Pinsouneault, and R. J. Gerbracht, Phys. Rev. **116**, 1560 (1959).
[7] R. L. Heath, Atomic Energy Commission Report, IDO-16408, 1957 (unpublished).