thresholds found in the present experiment, either (1) it was not due to F^{19} or (2) the residual state does not decay by gamma emission principally to the ground state or first excited state of Ne^{20}.

ACKNOWLEDGMENT

The author wishes to express his sincere appreciation to Dr. H. D. Holmgren for his help in the making of the experimental measurements.

PHYSICAL REVIEW VOLUME 118, NUMBER 1 APRIL 1, 1960

Radioactive Decay of Lu^{168}

R. G. WILSON AND M. L. POOL
Department of Physics and Astronomy, Ohio State University, Columbus, Ohio

(Received October 26, 1959)

Ytterbium oxide enriched to 30.9% in the 168 mass number was irradiated with 6-Mev protons. An activity decaying by electron capture with a half-life of 7.1±0.2 minutes was produced and assigned to Lu^{168}. The activity consists of gamma rays with energies of 87±1, 900±7, 987±7, 1410±20, 1800±40, 2130±60 kev in addition to the ytterbium K x ray. An energy level scheme for this decay is presented.

YTTERBIUM oxide enriched to 30.9% in the 168 mass number was irradiated with 6-Mev protons. The initially resulting activity is assigned to Lu^{168} by the identification of the ytterbium K x ray and by comparison with the activities produced by similar proton irradiations of each of the other enriched isotopes of ytterbium. Each of these irradiations produced the well known lutetium activity with the same mass number as the irradiated ytterbium isotope by a (p,n) reaction with no evidence of other reactions. The initial activity observed following the irradiation of Yb^{168} was different from all of the activities produced by the irradiations of the other enriched isotopes of ytterbium. It is assumed that this activity was also produced by a (p,n) reaction.

The observed activity of Lu^{168} consists of the ytterbium K x ray and gamma rays with energies of 87±1, 900±7, 987±7, 1410±20, 1800±60, and 2130±80 kev. From an analysis of the decay of the annihilation radiation in the gamma-ray spectrum of this activity, it is concluded that if positron radiation exists in the activity of Lu^{168}, it results from less than 1% of the disintegrations of Lu^{168} and that the mode of decay of Lu^{168} is therefore essentially by electron capture to Yb^{168}. The half-life of Lu^{168} is 7.1±0.2 minutes as measured by following the decay of the individual gamma rays for over six half-lives with a scintillation spectrometer. The approximate ratios of the relative numbers of the observed radiations in the activity of Lu^{168} after correction for crystal counting efficiency are K x ray : 87-kev γ : 900-kev γ : 987-kev γ = 100 : 7.5 : 10 : 13. The remaining three gamma rays are weak.

The energies of the established first rotational levels of even-even nuclei in the region of Yb^{168} are between 76 and 95 kev; in particular, those of the other even-even nuclei of ytterbium are 84, 79, 77, and 82 kev in order of increasing mass number. It therefore seems probable that the 87-kev transition observed in the activity of Lu^{168} proceeds from the first rotational level to the ground state of Yb^{168}. Thus an 87-kev 2+ level is tentatively assigned to Yb^{168}. Because the energy difference between the 900- and 987-kev gamma rays is the same as that of the now assigned first rotational level of Yb^{168}, a 987-kev level of spin 1 or 2 is tentatively assigned to Yb^{168}.

${}_{71}Lu_{97}{}^{168}$ is in the region of elliptically deformed odd-odd nuclei. Shell theory predicts spins of 1− and 6− for this nucleus using the measured spins of ${}_{71}Lu^{175}$ and ${}_{66}Dy_{97}{}^{163}$ which are 7/2+ and 5/2−, respectively. Because gamma rays corresponding to transitions between rotational levels in Yb^{168} above the first are not observed in the activity of Lu^{168}, the choice of 1− is favored for the ground state of Lu^{168}.

Assuming the 87-kev transition to be E_2, its K, L_1, L_2, L_3, and M internal conversion coefficients are 1.20, 0.13,

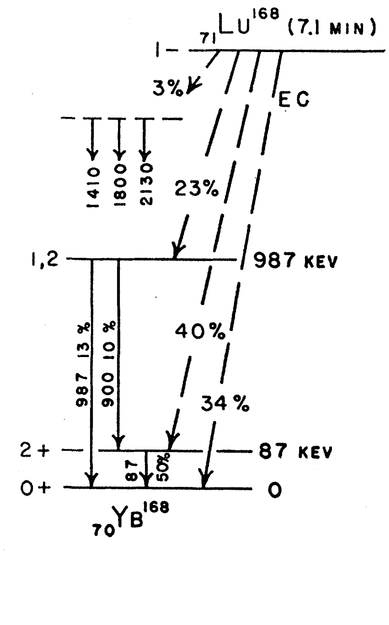

FIG. 1. Proposed energy level scheme for the decay of Lu^{168}.

1.42, 1.42, and 1.41 as calculated from Rose's data.[1] The ratios of the total number of transitions to the number of gamma rays and the number of K-converted transitions are then 6.6 and 5.5, respectively. Assuming internal conversion of the high-energy transitions of Lu^{168} to be negligible, the ratios of the relative numbers of transitions in Yb^{168} are 49:10:13, respectively. The relative number of K x rays can be corrected for fluorescence by dividing the 100 K x rays observed by the K fluorescence yield in ytterbium which is 0.937.[2] The result is 107. Applying the ratio 5.5 to the 87-kev transitions implies that approximately 9 of the 107 K x rays result from internal conversion of the 87-kev transition and approximately 98 result from K capture to the levels of Yb^{168}.

Figure 1 shows a proposed energy level scheme for the decay of Lu^{168}. The approximate branching ratios of electron capture to the levels of Yb^{168} were obtained by determining the difference between the number of transitions from each level and the number of transitions into the same level. The number of K x rays remaining after correcting for internal conversion and fluorescence was used as the relative number of electron capture transitions to the ground state of Yb^{168}.

There is no information currently available in the literature concerning the radioactive decay of Lu^{168} nor have any energy levels been established in Yb^{168} by Coulomb excitation. The natural abundance of the 168 mass number in ytterbium is only 0.14%.

ACKNOWLEDGMENTS

One of us (R.G.W.) is grateful to the National Science Foundation for the grant of a fellowship which enabled the completion of this research. Appreciation is expressed to R. P. Sullivan of the Department of Physics and Astronomy for assistance in the electronic phases of this research and to the Office of Naval Research for support in obtaining the enriched isotopes.

[1] M. E. Rose, *Internal Conversion Coefficients* (North-Holland Publishing Company, Amsterdam, 1958).
[2] A. H. Wapstra, G. J. Nijgh, and R. Van Lieshout, *Nuclear Spectroscopy Tables* (North-Holland Publishing Company, Amsterdam, 1959).

PHYSICAL REVIEW VOLUME 118, NUMBER 1 APRIL 1, 1960

Cross Sections for the $(n,2n)$ Reaction in N^{14}, P^{31}, Cu^{63}, and Pr^{141}

J. M. Ferguson and W. E. Thompson
U. S. Naval Radiological Defense Laboratory, San Francisco, California
(Received October 12, 1959)

The $(n,2n)$ cross sections have been measured for N^{14}, P^{31}, Cu^{63}, and Pr^{141}, for neutron energies from 12.5 to 18 Mev. The annihilation radiation emitted from the product nuclides was counted with two NaI(Tl) crystals in coincidence. In the energy range measured, the cross sections were found to vary, as follows: N^{14}, 3.03 to 11.67 mb; P^{31}, 0 to 74 mb; Cu^{63}, 186 to 836 mb; Pr^{141}, 1231 to 1737 mb. The results are generally in agreement with those of others. The data are compared with curves plotted from Weisskopf's theoretical expression for $(n,2n)$ cross sections.

INTRODUCTION

Although many $(n,2n)$ cross-section measurements have been made for 14-Mev neutrons,[1–7] relatively few measurements have been made over a range of neutron energies.[8–11] Weisskopf and Ewing presented an approximate theoretical equation for the variation of the $(n,2n)$ cross section for nuclides with $A>50$ as a function of neutron energy as long ago as 1940.[12] However, this equation possesses two parameters (the cross section for the emission of one neutron from the compound nucleus and the nuclear temperature) which in general are not known, and hence it is difficult to compare the theory with experimental data at only one energy.

It was, therefore, decided to take advantage of the unique energy-angle relationship of the neutrons produced by the $T(d,n)He^4$ reaction to measure some $(n,2n)$ reactions in the range from 12 to 18 Mev. Four nuclides were studied: N^{14}, P^{31}, Cu^{63}, and Pr^{141}. These were chosen to give a wide range in atomic weight and for experimental convenience (each of the product nuclides, N^{13}, P^{30}, Cu^{62}, and Pr^{140}, is a positron emitter). The yield of the reaction for a given neutron

[1] B. L. Cohen, Phys. Rev. **81**, 184 (1951).
[2] H. C. Martin and B. C. Diven, Phys. Rev. **86**, 565 (1952).
[3] S. G. Forbes, Phys. Rev. **88**, 1309 (1952).
[4] E. B. Paul and R. L. Clarke, Can. J. Phys. **31**, 267 (1953).
[5] V. J. Ashby, H. C. Catron, L. L. Newkirk, and C. J. Taylor, Phys. Rev. **111**, 616 (1958).
[6] L. A. Rayburn, Bull. Am. Phys. Soc. **3**, 337 (1958); also **4**, 228 (1959); also Report to the Atomic Energy Commission Nuclear Cross-Sections Advisory Group, WASH-1018, 1959 (unpublished).
[7] J. J. Dudley and C. M. Class, Phys. Rev. **94**, 807(A) (1954).
[8] J. L. Fowler and J. M. Slye, Jr., Phys. Rev. **77**, 787 (1950).
[9] J. E. Brolley, Jr., J. L. Fowler, and L. K. Schlacks, Phys. Rev. **88**, 618 (1952).
[10] H. C. Martin and R. F. Taschek, Phys. Rev. **89**, 1302 (1953).
[11] A. V. Cohen and P. H. White, Nuclear Phys. **1**, 73 (1956).
[12] V. F. Weisskopf and D. H. Ewing, Phys. Rev. **57**, 452 (1940).