New Isotope of Manganese; Cross Sections of the Iron Isotopes for 14.8-Mev Neutrons*

D. M. CHITTENDEN, II, D. G. GARDNER, AND R. W. FINK†
Department of Chemistry, University of Arkansas, Fayetteville, Arkansas
(Received October 10, 1960; revised manuscript received February 1, 1961)

Bombardment of iron enriched in Fe^{58} with 14.8-Mev neutrons produces an activity having a half-life of 1.1 ± 0.1 min. On the basis of cross bombardments and the gamma-ray spectrum of the activity, this is assigned to Mn^{58}. In addition, the following cross sections were measured: $Fe^{58}(n,p)$, 23.0 ± 3.5 mb; $Fe^{57}(n,p)$, 71.0 ± 7.0 mb; $Fe^{56}(n,p)$, 128 ± 13 mb; $Fe^{58}(n,\alpha)$, 21.5 ± 2.0 mb; $Fe^{54}(n,\alpha)$, 270 ± 135 mb; $Fe^{57}(n,np)$, 6.1 ± 2.6 mb; $Fe^{54}(n,2n)$, 7.9 ± 0.8 mb; $Fe^{54}(n,t)$, 0.6 ± 0.1 mb.

INTRODUCTION

THE work of Preiss and Fink,[1] of this laboratory, indicates that there is a marked effect of shell structure on the probabilities for the occurrence of 14.8-Mev neutron-induced reactions in the region $Z=28$. Levkovskii[2] has reported that the absolute (n,p) and (n,α) cross sections of various isotopes of an element usually decrease by a factor of 2, 4, or 8 with increasing mass number. This variation is more pronounced in the light elements. The present work was undertaken as part of a program to study 14.8-Mev neutron-induced reactions around the closed 28 neutron shell, and also to examine another region where trends such as noted by Levkovskii might be encountered.

EXPERIMENTAL

Cross sections were measured for 14.8 ± 0.9 Mev neutrons ($10^{10}-10^{11}$ neutrons/sec) from the $T(d,n)He^4$ reaction at 0° to the incident deuteron beam of the University of Arkansas 400-kv Cockcroft-Walton accelerator. Bombardment periods ranged from 30 sec–6 hr.

Enriched Fe^{54}, Fe^{57}, and Fe^{58}, in the form of the powder Fe_2O_3 and natural iron foil (91.6% Fe^{56}) were irradiated. Copper and aluminum foils were used as monitors utilizing the accurately determined cross sections for the $Cu^{63}(n,2n)Cu^{62}$ reaction (556 mb) determined by Yasumi[3] and for the $Al^{27}(n,\alpha)Na^{24}$ reaction (114 mb) determined by Poularikas and Fink.[4] Sample thicknesses were 10–55 mg/cm².

Counting Techniques

Beta counting was performed in a 2π end window, methane-flow proportional counter having an aluminized Mylar window of 0.9-mg/cm² thickness. Samples were counted on a saturation backscattering thickness of either glass or aluminum and the activity was corrected for geometry, self-absorption, and self-scattering as described previously.[5,6]

The probable error limits placed on the cross-section values are based on uncertainties in the monitor cross sections, and uncertainties in resolution of decay curves.

Gamma counting was performed with either a $1\times1\frac{1}{2}$ inch or 3×3 inch NaI(Tl) scintillation spectrometer with a multichannel pulse analyzer. Since gamma-ray spectra were only used as a means of identification, no efficiency corrections were applied.

RESULTS

Samples of Fe_2O_3 enriched to 78.4% in Fe^{58} and weighing about 4 mg were bombarded by 14.8-Mev neutrons, and the gross beta decay was followed. Half-lives of 1.1 ± 0.1 min, 3.5 ± 0.1 min from the $Fe^{58}(n,\alpha)Cr^{55}$ reaction, and 2.56 ± 0.02 hr from the impurity $Fe^{56}(n,p)Mn^{56}$ reaction, were observed.

The gamma-ray spectrum showed rapidly decaying strong gamma rays of energies 0.36, 0.41, 0.52, 0.57, and 0.82 Mev with weak gamma rays of 1.0, 1.25, 1.4, 1.6, 2.2, and 2.8 Mev energy. These gamma rays were attributed to the 1.1 ± 0.1 min activity since Cr^{55} decays without the emission of gamma rays. Rapid chemical separations showed that the 1.1 ± 0.1 min activity appeared in the manganese fraction. On the basis of cross-bombardments utilizing chemical separations and the gamma-ray spectrum (which fits the measured energy level of Fe^{58})[6,7] the activity is assigned to Mn^{58} from the (n,p) reaction of Fe^{58}.

Bombardment of $(Fe^{57})_2O_3$ (76.7% Fe^{57}) gave rise to a 1.5 ± 0.1 min activity assigned to Mn^{57} from the $Fe^{57}(n,p)$ reaction and a 2.55 ± 0.05 hour activity assigned to Mn^{56} from the $Fe^{56}(n,p)$ and $Fe^{57}(n,np)$ reactions.

Activities observed upon irradiation of enriched

* Supported in part by the U. S. Atomic Energy Commission. This work constitutes part of the M.S. thesis of D. M. Chittenden, II at the University of Arkansas.
† Visiting scientist at Gustaf Werner Institute for Nuclear Chemistry, University of Uppsala, Sweden, 1959–1960.
[1] I. L. Preiss and R. W. Fink, Nuclear Phys. **15**, 326 (1960).
[2] V. N. Levkovskii, Soviet Phys.—JETP **6**, 1174 (1958); **4**, 291 (1957).
[3] S. Yasumi, J. Phys. Soc. Japan **12**, 433 (1957).
[4] A. Poularikas and R. W. Fink, Phys. Rev. **115**, 989 (1959).
[5] R. G. Wille and R. W. Fink, Phys. Rev. **118**, 242 (1960); **112**, 1950 (1958).
[6] A. Poularikas and R. W. Fink, Phys. Rev. **115**, 989 (1959).
[6] C. E. McFarland, F. B. Shull, A. J. Elwyn, and B. Zeidman, Phys. Rev. **99**, 655 (1955).
[7] A. Sperduto and W. W. Buechner, Bull. Am. Phys. Soc. **1**, 223 (1956).

TABLE I. Summary of absolute neutron cross sections for iron isotopes.

Reaction	Product	Measured half-life	Measured cross sections (mb) (14.8 Mev) Present work	(14.1–15 Mev) Other work	Q-value (Mev)
$Fe^{54}(n,t)$	Mn^{52m}	21 ± 2 min	0.6 ± 0.1		-11.5
$Fe^{54}(n,2n)$	Fe^{53}	8.4 ± 0.4 min	7.9 ± 0.8	14.9,[a] 16.7,[b] 10,[c] 2,[d] 10.6[e]	-13.6
$Fe^{54}(n,\alpha)$	Cr^{51}	25 ± 5 days	270 ± 135	131 ± 25[e]	$+0.8$
$Fe^{54}(n,p)$	Mn^{54}	(not measured)		460,[c] 376,[f] 395[q]	$+0.2$
$Fe^{56}(n,p)$	Mn^{56}	2.56 ± 0.11 hours	128 ± 13	110,[h] 114,[i] 131 ± 15,[j,k] 144 ± 16,[l] 190,[c] 72,[m] 96.7,[n] 124 ± 12,[o] 105 ± 2,[p] 110,[e] 95,[f] 120[q]	-2.9
$Fe^{57}(n,p)$	Mn^{57}	1.5 ± 0.1 min	71.0 ± 7.0	28[e]	-1.9
$Fe^{57}(n,np)$	Mn^{56}	2.56 ± 0.20 hours	6.1 ± 2.6		-10.5
$Fe^{58}(n,p)$	Mn^{58}	1.1 ± 0.1 min	23.0 ± 3.5		-5.2[r]
$Fe^{58}(n,\alpha)$	Cr^{55}	3.5 ± 0.1 min	21.5 ± 2.0		-1.5

[a] V. L. Sailor, Atomic Energy Commission Report WASH-1018, April, 1959 (unpublished).
[b] L. A. Rayburn, Bull. Am. Phys. Soc. **3**, 365 (1958).
[c] D. L. Allen, Proc. Phys. Soc. (London) **A70**, 195 (1957) (emulsion).
[d] B. L. Cohen, Phys. Rev. **81**, 184 (1951).
[e] H. Neuert, University of Hamburg (private communication to R. W. Fink, December, 1960).
[f] P. V. March and W. T. Morton, Phil. Mag. **3**, 143 (1958) (emulsions).
[g] D. L. Allen, Nuclear Phys. **10**, 348 (1959) (emulsions).
[h] R. J. Howerton, University of California Radiation Laboratory Report UCRL-5226, May, 1958 (unpublished), quoted from Atomic Energy Commission Report WASH-160.
[i] C. W. Zabel, Atomic Energy Commission Report WASH-191, 1959 (unpublished).
[j] B. D. Kern, W. E. Thompson, and J. M. Ferguson, Nuclear Phys. **10**, 226 (1959).
[k] J. M. Ferguson, W. E. Thompson, and B. D. Kern, U. S. Navy Research and Development Laboratory Report USNRDL–TR–269, October 10, 1959 (unpublished).
[l] S. Yasumi, J. Phys. Soc. Japan **12**, 443 (1957).
[m] G. W. McClure and D. W. Kent, J. Franklin Inst. **266**, 238 (1955).
[n] E. B. Paul and R. L. Clarke, Can. J. Phys. **31**, 267 (1953).
[o] S. G. Forbes, Phys. Rev. **88**, 1309 (1952).
[p] J. Terrell and D. M. Holm, Phys. Rev. **109**, 2031 (1958).
[q] G. Brown, G. C. Morrison, H. Muirhead, and W. T. Morton, Phil. Mag. **2**, 785 (1957) (emulsions).
[r] Calculated from data of K. Way, R. W. King, C. L. McGinnis, R. van Lieshout, *Nuclear Level Schemes, A =40 − A =92*, Atomic Energy Commission Report TID-5300 (U. S. Government Printing Office, Washington, D. C., 1955).

$(Fe^{54})_2O_3$ (96.66% Fe^{54}) were 8.4 ± 0.4 min Fe^{53} from the $(n,2n)$, 25 ± 5 day Cr^{51} from the (n,α), and 21 ± 2 min Mn^{52m} from the (n,t) reactions. The previously reported 2.1-min activity assigned to Mn^{54m} [8] was not observed.

In Table I a summary of the known reaction cross sections for 14.1–15 Mev neutrons on iron isotopes is presented, together with the present results.

DISCUSSION

The (n,p) reactions were found to exhibit the trend observed by Levkovskii.[2] Thus, the (n,p) cross sections lie in the ratio $Fe^{54}:Fe^{56}:Fe^{57}:Fe^{58}::3.6:1.0:0.55:0.18$ (Table I).

Because of the large uncertainty in the counting efficiency for the Cr^{51} x rays in the counter used here, it is not possible to examine for a Levkovskii trend the ratio of the (n,α) cross sections of iron.

The value for the cross section of the $Fe^{54}(n,2n)$ reaction (7.9 mb) is much lower than those for other $(n,2n)$ reactions in this region; e.g., for Ni^{58} the $(n,2n)$ value is 52 ± 5 mb,[9] for Co^{59}, 149 ± 10 mb [9] or 630 mb,[10] and for Zn^{64}, 245 ± 20 mb.[9] This may be connected in part with the fact that Fe^{54} has a closed neutron shell ($N=28$).

The large cross section for the (n,np) reaction of Fe^{57} and the observation of the (n,t) reaction on Fe^{54} might be explicable on the basis of a nuclear cluster theory as suggested by Wilkinson[11] and others.[12]

ACKNOWLEDGMENT

The authors wish to acknowledge the assistance of Mr. J. E. Wray of the Accelerator Laboratory for the operation of the accelerator.

[8] D. O. Caldwell and H. F. Stoddart, Phys. Rev. **81**, 666 (1951).

[9] I. L. Preiss and R. W. Fink, Nuclear Phys. **15**, 326 (1960).
[10] B. Karlik, Vienna (private communication to R. W. Fink, December, 1960).
[11] D. H. Wilkinson, Phil. Mag. **4**, 215 (1959).
[12] K. Wildemuth and Th. Kanellopoulis, CERN Report No. 59–23, June 5, 1959 (unpublished).