Activation Cross Sections for (n, p), $[(n, np)+(n, pn)+(n, d)]$, and (n, α) Reactions in the Region of $Z=40$ to 58 at 14.4 MeV*

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The following activation cross sections (in mb) for the (n, p), $[(n, np)+(n, pn)+(n, d)]$, and (n, α) reactions in the region of $Z=40$–58 have been determined at 14.4±0.3 MeV by using the mixed powder method with Ge(Li) γ-ray detection: $Zr^{90}(n, p)Y^{90m}$ (3.1 h), 12.9±1.0; $Zr^{91}(n, p)Y^{91m}$ (50.3 min), 18.6±1.9; $Zr^{92}(n, p)Y^{92}$ (3.53 h), 18.5±2.7; $Mo^{92}(n, p)Nb^{92m}$ (10.1 day), 62.5±4.0; $Mo^{96}(n, p)Nb^{96}$ (23.35 h), 21.3±1.5; $Mo^{97}(n, p)Nb^{97m}$(1 min), 7.4±0.8; $Mo^{97}(n, p)Nb^{97g}$(72 min), 8.5±1.0; $Mo^{98}(n, p)Nb^{98g}$(51 min), 4.1±0.5; $Ru^{96}(n, p)Tc^{96}$(4.35 day), 146±7; $Rh^{103}(n, p)Ru^{103}$(39.5 day), 16.9±1.5; $Pd^{105}(n, p)Rh^{105}$(35.9 h), 37.6±2.0; $Pd^{106}(n, p)Rh^{106m}$(130 min), 6.0±0.4; $Pd^{106}(n, p)Rh^{106g}$(30 sec), 18±4; $Pd^{108}(n, p)Rh^{108}$(16.8 sec), 8.3±1.5; $Cd^{112}(n, p)Ag^{112}$(3.14 h), 15.0±1.3; $Sn^{116}(n, p)In^{116m}$(54 min), 7.9±0.8; $Sn^{117}(n, p)In^{117m}$(1.93h), 5.7±1.5; $Sn^{117}(n, p)In^{117g}$(45 min), 9.8±1.6; $Ba^{138}(n, p)Cs^{138}$(32.2 min), 3.8±0.6; $Ce^{140}(n, p)La^{140}$(40.22 h), 6.3±0.5; $Zr^{94}(n, \alpha)Sr^{91}$(9.67 h), 5.0±1.0; $Nb^{93}(n, \alpha)Y^{90m}$(3.1 h), 5.3±0.5; $Mo^{92}(n, \alpha)Zr^{89m}$(4.18 min), 9.4±0.9; $Mo^{92}(n, \alpha)Zr^{89g}$(78.4 h), 18.7±1.5; $Mo^{98}(n, \alpha)Zr^{95}$(65.5 day), 8.1±1.0; $Pd^{106}(n, \alpha)Ru^{103}$(39.5 day), 5.6±0.7; $Pd^{108}(n, \alpha)Ru^{105}$(4.44 h), 2.7±0.3; $Cs^{133}(n, \alpha)I^{130}$(12.3 h), 1.96±0.15; $Ba^{138}(n, \alpha)Xe^{135m}$(15.6 min), 0.55±0.05; $Ba^{138}(n, \alpha)Xe^{135g}$(9.14 h), 2.0±0.2; $Ce^{142}(n, \alpha)Ba^{139}$(82.9 min), 6.0±1.0; $Ru^{96}[(n, np)+(n, pn)+(n, d)]Tc^{95m}$(61.0 day), 52±10; and $Ru^{96}[(n, np)+(n, pn)+(n, d)]Tc^{95g}$(20 h), 483±50. The total (n, p) cross sections are compared with Levkovskii's predictions and show good agreement. The relative (n, p) cross sections of Mo and Pd also are compared with Gardner's predictions.

I. INTRODUCTION

THERE have been two approaches to predict (n, p) cross sections at 14 MeV. Levkovskii[1] found that the (n, p) cross sections follow a smooth function of $(N-Z)/A$ and obtained an empirical formula which predicts the (n, p) cross sections quite well. Gardner[2] observed that the (n, p) cross sections of isotopes of a given element decrease with increasing mass number A, and he derived ratio equations based on the statistical evaporation model[3] to predict relative (n, p) cross sections, which were then normalized to experimental values close to the line of stability. However, the (n, p) cross sections used for this normalization procedure were measured by different authors under various experimental conditions and do not agree well with each other. Therefore, more accurately measured cross sections under the same experimental conditions for a wide range of elements should give a better test of the predictions of Levkovskii[1] and of Gardner.[2]

In the present work, the (n, p) cross sections of nuclides from $Z=40$ to 58 were measured with the mixed-powder method[4] and Ge(Li) γ detection. Some (n, α) and $[(n, np)+(n, pn)+(n, d)]$ cross sections are also reported. The large values of the latter cross sections show that the competition of the (n, np) reaction with the $(n, 2n)$ may not be neglected in certain cases when the $(n, 2n)$ reaction is treated with the statistical model.[3]

II. EXPERIMENTAL

A. Irradiation and Detection

Neutrons were produced by the $H^3(d, n)He^4$ reaction in the Georgia Tech 200-kV accelerator. The neutron energy at ±65° to the beam direction is 14.4±0.3 MeV.[4] The neutron yield is about $1–3\times10^{10}$ n/sec, and its decrease during irradiation is monitored by a Si detector at 90° and 100 cm from the beam which counts the associated α particles.

The target material in powder form is mixed with iron and aluminum powders and is contained in a plastic holder with a hole of about 2-cm² area. The target so prepared was irradiated about 5 mm behind the Ti-T neutron source for periods from a few min to 2 h, depending on the half-lives of the product activities of interest. After the end of irradiation, the γ activities were counted with a 16-cm³ coaxial Ge(Li) detector having a resolution of 3.5 keV full width at half-maximum (FWHM) at 1333 keV, and successive γ spectra were recorded by a 400-channel analyzer. The activities were identified both by their γ energies and their half-lives. The relative activity A^0 of a given energy at the end of irradiation was calculated from the

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[3] S. Pearlstein, Nucl. Data **A3**, 327 (1967); Brookhaven National Laboratory Report No. BNL-897(T-365), 1964 (unpublished).

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TABLE I. (n, p) and $[(n, np)+(n, pn)+(n, d)]$ cross sections of nuclides with $Z=40$–58 at 14.4±0.3 MeV from the present work.

Reaction	Half-life	E_γ (keV)	f_d[a]	Measured cross section (mb)
$Zr^{90}(n, p)Y^{90m}$	3.1 h	202	0.97	12.9±1.0
		482	0.91	
$Zr^{91}(n, p)^{91m}$	50.3 min	551	0.95	18.6±1.9
$Zr^{92}(n, p)Y^{92}$	3.53 h	934	0.14	18.5±2.7
$Mo^{92}(n, p)Nb^{92m}$	10.16 day	934	0.99	62.5±4.0
$Mo^{96}(n, p)Nb^{96}$	23.35 h	569	0.59	
		778	0.97	21.3±1.5
		1092	0.49	
		1200	0.21	
$Mo^{97}(n, p)Nb^{97m}$	1 min	747	0.98	7.4±0.8
$Mo^{97}(n, p)Nb^{97g}$	72 min	658	0.98[b]	8.5±1.0
$Mo^{98}(n, p)Nb^{98g}$	51 min	720	0.75	4.1±0.5
		787	1.0	
$Ru^{96}(n, p)Tc^{96}$	4.35 day	778	1.0	
		810	0.84	146±7
		851	1.0	
$Rh^{103}(n, p)Ru^{103}$	39.5 day	497	0.88	16.9±1.5
$Pd^{105}(n, p)Rh^{105}$	35.9 h	319	0.19	37.6±2.0
$Pd^{106}(n, p)Rh^{106m}$	130 min	512	1.0[c]	6.0±0.4
$Pd^{106}(n, p)Rh^{106g}$	30 sec	512	0.097[d]	18±4
$Pd^{108}(n, p)Rh^{108}$	16.8 sec	434	0.43	8.3±1.5
		620	0.22	
$Cd^{112}(n, p)Ag^{112}$	3.14 h	617	0.43[e]	15.0±1.3
$Sn^{116}(n, p)In^{116m}$	54.0 min	417	0.36	7.9±0.8
$Sn^{117}(n, p)In^{117m}$	1.93 h	314	0.31	5.7±1.5
		565	0.47	
$Sn^{117}(n, p)In^{117g}$	45 min	565	1.0	9.8±1.6
$Ba^{138}(n, p)Cs^{138}$	32.2 min	463	0.23	3.8±0.6
$Ce^{140}(n, p)La^{140}$	40.22 h	329	0.21[f]	
		487	0.48[f]	6.3±0.5
		1596	0.96[f]	
$Ru^{96}[(n, np)+(n, pn)+(n, d)]Tc^{95m}$	61.0 day	204	0.835[g]	52±10
$Ru^{96}[(n, np)+(n, pn)+(n, d)]Tc^{95g}$	20.0 h	768	0.94[g]	483±50

[a] All of the f_d values, unless otherwise stated, were taken from C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes* (John Wiley & Sons, Inc., New York, 1967), 6th ed.

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equation

$$A^0 = Ce^{\lambda t}/\epsilon f_s f_d, \quad (1)$$

where C is the counting rate of a given activity at a particular energy in the middle of a counting period between t_a and t_b measured from the end of irradiation; ϵ is the γ-detection efficiency for the full-energy peak, as calibrated with IAEA standard sources; f_s is the correction factor for self-absorption in the source and is calculated from the equation

$$f_s = (1-e^{-\mu x})/\mu x, \quad (2)$$

where x is the source thickness in g/cm^2, and μ is the mass absorption coefficient of the source material taken from Davisson's tables[5] or by interpolation, a weighted average being taken in the case of mixtures; and f_d is the number of γ photons of given energy emitted per decay of the product nucleus and is calculated from the decay scheme. Cross sections were computed from the equation given in Ref. 4.

Tables I and II summarize the cross sections measured in the present work. The values reported are averaged from at least two separate runs. The $Fe^{56}(n, p)Mn^{56}$ (2.58 h) reaction with cross section[6] of

[5] *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Co., Amsterdam, 1965), Vol. 1, Appendix 1.

[6] H. Liskien and A. Paulsen, J. Nucl. Energy **19**, 73 (1965).

TABLE II. (n, α) cross sections of nuclides from $Z=40$–58 at 14.4±0.3 MeV from the present work and from the literature.

Reaction	Half-life	E_γ (keV)	f_d [a]	Cross sections (mb) Present work	Literature [b]
$Zr^{94}(n, \alpha)Sr^{91}$	9.67 h	1025	0.3	5.0±1.0	5.5, 4.9, 4.7, 4.3, 3.6
$Nb^{93}(n, \alpha)Y^{90m}$	3.1 h	482	0.91	5.3±0.5	5±2
$Mo^{92}(n, \alpha)Zr^{89m}$	4.18 min	588	0.87	9.4±0.9	
$Mo^{92}(n, \alpha)Zr^{89g}$	78.4 h	910	0.99	18.7±1.5	20±8
$Mo^{98}(n, \alpha)Zr^{95}$	65.5 day	758	0.54[c]	8.1±1.0	
$Pd^{106}(n, \alpha)Ru^{103}$	39.5 day	497	0.88	5.6±0.7	
$Pd^{108}(n, \alpha)Ru^{105}$	4.44 h	470	0.19[d]	2.7±0.3	2.3, 1.9, 1.0
$Cs^{133}(n, \alpha)I^{130}$	12.3 h	538	0.99	1.96±0.15	1.0±0.3
$Ba^{138}(n, \alpha)Xe^{135m}$	15.6 min	527	0.8	0.55±0.05	13±2
$Ba^{138}(n, \alpha)Xe^{135g}$	9.14 h	250	0.97[e]	2.0±0.2	3.6, 13
$Ce^{142}(n, \alpha)Ba^{139}$	82.9 min	166	0.266[f]	6.0±1.0	8, 7.0

[a] All of the f_d values, unless otherwise stated, were obtained from C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes* (John Wiley & Sons, Inc., New York, 1967), 6th ed.
[b] Reference 9(b).
[c] L. Foin, J. Oms, J. Blachet, and J. Crancon, Nucl. Phys. **A123**, 513 (1969).
[d] S. O. Schriber and M. W. Johns, Nucl. Phys. **A96**, 337 (1967).
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100±6 mb was used as the primary monitor, and the reaction $Al^{27}(n, \alpha)Na^{24}$ (15 h) with a cross section of 114±7 mb was used to check the completeness of the mixing from the ratio of the 847-keV (Mn^{56}) and 1369-keV (Na^{24}) γ intensities.[4] The standard error quoted includes errors due to detection efficiency, counting statistics, and self-absorption correction, but does not include errors in f_d due to the decay schemes, since the cross sections may be rapidly revised whenever the decay scheme is revised to give a different value of f_d.

For product nuclides with short half-lives, a fast-transfer rabbit system combined with a magnetic digital tape recorder–data manipulator was used. The cross sections of the reactions $Mo^{92}(n, \alpha)Zr^{89m}$ (4.18 min), $Mo^{97}(n, p)Nb^{97m}$ (1 min), $Pd^{106}(n, p)Rh^{106g}$ (30 sec), and $Pd^{108}(n, p)Rh^{108}$ (16.7 sec) were measured with this system. The reactions $Mo^{92}(n, 2n)Mo^{91m}$ (64 sec) with $\sigma=16.2\pm1.2$ mb[7] and $Pd^{110}(n, 2n)Pd^{109m}$ (4.67 min) with $\sigma=510\pm35$ mb[7] were used as internal monitors, respectively, for these Mo and Pd cross sections.

The ground-state cross section of the $Ru^{96}[(n, np)+(n, pn)+(n, d)]Tc^{95g}$ (20 h) reaction was measured by following the growth of the 20-h Tc^{95g} activity. The contribution from the decay of 1.65-h Ru^{95}, which is the product of the $Ru^{96}(n, 2n)$ reaction is then resolved from their difference in half-lives. The method is similar

TABLE III. Comparison of present total (n, p) cross sections with Levkovskii's predictions and with previous values.

Reaction	Cross section present work (mb)	Predicted from Levkovskii's Eq. (3) in text	Previous values from the literature[a] (mb)
$Zr^{92}(n, p)Y^{92}$	18.5±1.7	18.6	76, 25, 22, 20.7
$Mo^{96}(n, p)Nb^{96}$	21.3±1.5	22.7	37, 21, 16
$Mo^{97}(n, p)Nb^{97}$	15.9±1.3	17.0	110, 108, 68, 17.7
$Ru^{96}(n, p)Tc^{96}$	146±7	89.9	170±30
$Rh^{103}(n, p)Ru^{103}$	16.9±1.5	22.7	
$Pd^{105}(n, p)Rh^{105}$	37.6±2.0	24.8	743±500
$Pd^{106}(n, p)Rh^{106}$	24±4	19.0	
$Pd^{108}(n, p)Rh^{108}$	8.3±1.5	11.3	
$Cd^{112}(n, p)Ag^{112}$	15.0±1.3	13.7	11, 11
$Sn^{117}(n, p)In^{117}$	15.5±2.1	13.0	23, 12
$Ba^{138}(n, p)Cs^{138}$	3.8±0.6	3.43	6.3, 3.1, 2.5, 2.2, 1.9
$Ce^{140}(n, p)La^{140}$	6.3±0.5	6.05	12.1, 10, 7.7

[a] Reference 9(a).

[7] W. Lu, N. RanaKumar, and R. W. Fink, preceding paper, Phys. Rev. C **1**, 350 (1970).

to that described in Ref. 8 for the case of the $Cd^{106}(n, np)+\cdots Ag^{105}$ cross section, except that chemical separation of Tc^{95} was not required. The results obtained were

$$\sigma_{[(n,pn)+\cdots]}/\sigma_{(n,2n)}=0.82\pm0.13,$$

$$\sigma_{[(n,pn)+\cdots]}=483\pm50 \text{ mb},$$

$$\sigma_{(n,2n)}=590\pm70 \text{ mb}$$

for Ru^{96}. It is important to note that the cross-section ratio $\sigma_{[(n,np)+\cdots]}/\sigma_{(n,2n)}$ is independent of detection efficiency, self-absorption correction, and the decay scheme of Tc^{95g}, because it is obtained from the same measured activity (Tc^{95g}, $E_\gamma=768$ keV). The $(n, 2n)$ cross section has been measured previously for Ru^{96}, by measuring Ru^{95} activity, and a value was found of 569 ± 30 mb.[7] The good agreement of these two values for the $(n, 2n)$ cross section confirms the present value of the $Ru^{96}[(n, np)+(n, pn)+(n, d)]Tc^{95g}$ (20 h) cross section.

III. DISCUSSION

In Table III, the total (n, p) cross sections measured in the present work are compared with Levkovskii's predictions from the empirical equation[1]

$$\sigma_{(n,p)}=45.2(A^{1/3}+1)^2\exp[-33(N-Z)/A]. \quad (3)$$

Previously reported experimental values also are listed for comparison, and are taken from the compilation in Ref. 9. It is seen that Levkovskii's predictions agree fairly well with present results except for two cases, $Ru^{96}(n, p)Tc^{96}$ and $Pd^{105}(n, p)Rh^{105}$. In the latter case, there is a possible contribution from $(n, np)+(n, pn)+(n, d)$ reactions from the neighboring stable nuclide Pd^{106}, since natural Pd was used in the experiment.

In Table IV, the relative (n, p) cross sections of Mo and Pd are compared with Gardner's predictions.[2] Again the cross section of $Pd^{105}(n, p)Rh^{105}$ shows a large discrepancy, but the deviation is just opposite to that from Levkovskii's prediction.

The statistical model also has been applied to (n, α) cross sections.[10,11] For low-Z nuclides there has been some success, but for medium- and high-Z nuclides the results are unsatisfactory; the results being generally far too small compared with the experimental values.[10] The excess emission of α particles is thought to arise from direct interactions with virtual preformed α clusters in the nuclear surface.

TABLE IV. Comparison of relative (n, p) cross sections with Gardner's predictions.

Reaction	Relative cross section: Present work	Relative cross section: Gardner's prediction[a]
$Mo^{96}(n, p)Nb^{96}$	1.0	1.0
$Mo^{97}(n, p)Nb^{97}$	0.75	0.71
$Pd^{105}(n, p)Rh^{105}$	1.57	2.70
$Pd^{106}(n, p)Rh^{106}$	1.0	1.0
$Pd^{108}(n, p)Rh^{108}$	0.35	0.46

[a] Reference 2.

The large $[(n, np)+(n, pn)+(n, d)]$ cross section of Ru^{96} suggests that the competition of the (n, np) with the $(n, 2n)$ reaction may not be negligible in the statistical model treatment of $(n, 2n)$ reactions as has been assumed.[3] If the $Ru^{96}[(n, np)+(n, pn)+(n, d)]$ reaction arises mainly from the (n, np) component, the small $(n, 2n)$ cross section[7] of Ru^{96} (569 ± 30 mb), as compared with Pearlstein's[3] prediction (932 mb) can be explained by the competition from the (n, np) reaction. Since the activation method can not distinguish the (n, np) (n, pn), and (n, d) reactions, this question remains open for investigation by emitted-particle methods which distinguish the $[(n, p)+(n, pn)]$ reaction group from (n, np) and (n, d) reactions. Moreover, the existence of a large $Ru^{96}(n, p)Tc^{96}$ cross section (compared with Levkovskii's prediction) suggests that the contribution of the $Ru^{96}(n, pn)Tc^{95}$ reaction may be small, as otherwise it would compete with the $Ru^{96}(n, p)Tc^{96}$ reaction.

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