Neutron Reaction Cross Sections of Selenium and Iron at 14.4 MeV*

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Fast-neutron activation cross sections of selenium and iron have been measured with an improved technique that takes advantage of the high resolution of Ge(Li) detectors. Powdered samples, mixed with iron and/or aluminum powders to act as neutron-flux monitors, were irradiated with 14.4±0.3-MeV neutrons, and the decay of gamma spectra was followed with a thin Ge(Li) detector having a resolution of 4 keV (full width at half-maximum). The following cross sections (in millibarns) have been determined: $Se^{74}(n,2n)Se^{73g}$, 293±29; $Se^{74}(n,2n)Se^{73m}$, 65±15; $Se^{74}(n,p)As^{74}$, 107±11; $Se^{76}(n,2n)Se^{75}$, 808±81; $Se^{76}(n,p)As^{76}$, 56±6; $Se^{78}(n,p)As^{78}$, 24±2.4; $Se^{78}(n,\alpha)Ge^{75(m+g)}$, 6±1.0; $Se^{80}(n,2n)Se^{79m}$, 680±100; $Se^{80}(n,\alpha)Ge^{77(m+g)}$, 2–9; $Se^{82}(n,2n)Se^{81m}$, 894±89; $Se^{82}(n,2n)Se^{81g}$, 225±45; $Fe^{54}(n,p)Mn^{54}$, 259±26; and $Fe^{54}(n,\alpha)Cr^{51}$, 90±10. Systematic trends in these cross sections are discussed and compared with the available theoretical computations. The $2p_{3/2,1/2}$ proton subshell-closure effect in the Ga-Ge-As region for (n,α) cross sections suggested by Chatterjee is confirmed. For Se^{81} the spin cutoff parameter is calculated to be 2.9±0.4 from the isomer ratio $\sigma_m/\sigma_g=4.0\pm0.9$, and the ratio of the moment of inertia I associated with the spin distribution to the rigid-body moment of inertia I_R is obtained as $I/I_R\approx1.0$.

INTRODUCTION

RECENT surveys of 14–15-MeV neutron cross sections for $(n,2n)$, (n,α), and (n,p) reactions[1–5] indicate the need for more accurate determination of these cross sections in order to investigate shell-structure effects. The activation technique is the most widely used method of measurement of these cross sections since Paul and Clarke[6] made the first extensive study for a large number of target elements. The activities produced are measured either by absolute beta or gamma counting, often using enriched target isotopes and chemical separation when necessary. The method is severely limited in accuracy when the cross sections are small and the reaction products are long-lived.

An improved technique for the determination of activation cross sections is developed in the present work which takes advantage of the high resolution of Ge(Li) detectors. This permits the identification of very low activities and accurate measurement of their formation cross sections. Another advantage is that natural elements can be used instead of enriched isotopes, since all of the activities can be identified and the half-lives followed simultaneously.

The activity A of a reaction product, present at any time, resulting in a counting rate A' in one of its characteristic gamma photopeaks, is calculated using the relation

$$A=A'/\epsilon f_s f_d, \tag{1}$$

where ϵ, f_s, and f_d are the photopeak detection efficiency, the correction factor for source self-absorption, and the number of gamma quanta emitted per disintegration of the reaction product, respectively. The activity at the end of bombardment A^0 is estimated by following the decay of the gamma spectrum with time using a least-squares method.

If the incident neutron flux f remains constant during the irradiation time T, the cross section σ is determined from the usual relation

$$A^0=\sigma n\lambda f(1-e^{-\lambda T}), \tag{2}$$

where n is the number of target nuclei in the sample and λ is the decay constant of the activity. However, the neutron flux from titanium-tritium targets under constant beam current does not remain constant but decreases essentially exponentially[7,8] as

$$f=f_0e^{-\Delta T}, \tag{3}$$

where f_0 is the flux at the beginning of the bombardment and Δ is the average decay constant during the irradiation time T. The cross section σ is then obtained from the equation

$$A^0=\sigma n f_0\left(\frac{\lambda}{\lambda-\Delta}\right)(e^{-\Delta T}-e^{-\lambda T}). \tag{4}$$

The flux f is determined by measuring simultaneously the activity from a monitoring reaction, the cross section of which is previously known, e.g., the $Fe^{56}(n,p)Mn^{56}$ (2.6 h) or the $Al^{27}(n,\alpha)Na^{24}$ (15 h) reactions. If the cross section of one of the resulting activities in the natural sample under investigation is known, it may be used as an internal flux monitor. Otherwise, the powdered sample may be mixed with aluminum and/or iron powders *of the same grain size.* It is preferable to use a mixture containing *both* iron and aluminum in order to recognize from the Mn^{56}/Na^{24} activity ratio any error arising from possible nonuniform

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mixing of sample and monitor powders. In cases where a stoichiometric chemical compound is available, one of the constituents often can be used as an internal monitor. This procedure of mixing the monitor with the sample will eliminate the geometrical errors present in the normal procedure of sandwiching the sample between foils that act as standards.

If σ_m, A_m^0, λ_m, and n_m are the corresponding quantities for the monitor, the cross section under investigation, σ, is given by

$$\frac{\sigma}{\sigma_m}=\left(\frac{A^0}{A_m^0}\right)\left(\frac{n_m}{n}\right)\left(\frac{\lambda_m}{\lambda}\right)\left(\frac{\lambda-\Delta}{\lambda_m-\Delta}\right)\frac{(e^{-\Delta T}-e^{-\lambda_m T})}{(e^{-\Delta T}-e^{-\lambda T})}. \quad (5)$$

In the special case when the activity observed is not the decay of the reaction product directly, but that of its daughter, the above equation must be suitably modified. The growth of the daughter, which is not directly produced in the reaction except through the decay of the parent, is given by

$$A_2=\sigma f_0 n\left(\frac{\lambda_1\lambda_2}{\lambda_2-\lambda_1}\right)\left[\frac{e^{-\lambda_1 t}(e^{-\Delta T}-e^{-\lambda_1 T})}{\lambda_1-\Delta}-\frac{e^{-\lambda_2 t}(e^{-\Delta T}-e^{-\lambda_2 T})}{\lambda_2-\Delta}\right], \quad (6)$$

where subscripts 1 and 2 correspond respectively to parent and daughter, T is the duration of irradiation, and t is the time after the end of irradiation. The case of particular interest in the present work is Se^{81m} (57 min) which decays almost completely to Se^{81g} (18.6 min). The application of Eq. (6) to this case is described below.

EXPERIMENTAL

Neutrons were obtained from the $H^3(d,n)He^4$ reaction in thick titanium-tritium targets on the Georgia Tech 200-kV accelerator. The samples were of the order of 1 cm^2 in area and were placed about 2 mm behind the Ti-T target, subtending an angle of $\pm 65°$ to the beam direction, so that about 92% of the neutrons irradiating the sample had energies within the range of 14.4±0.2 MeV, the remaining 8% being within ±0.3 MeV. The relative decay of the neutron flux was measured during each bombardment. Typical values for the half-lives range from 18 to 40 min, although half-lives of the order of 2 h also were encountered in irradiations with relatively low beam currents.

A Ge(Li) detector having 1-cm^2 active area and 2-mm depletion depth and a resolution of 4-keV FWHM (full width at half maximum) was used to measure gamma intensities. Its photopeak detection efficiency was calibrated with standard gamma sources relative to a 3-in.×3-in. NaI(Tl) detector. For the geometry used in the present work, the efficiency ϵ varied from 2.65×10^{-2} at 67 keV to 3.65×10^{-5} at 1333 keV.

The primary standard for monitoring the neutron flux was chosen to be $Fe^{56}(n,p)Mn^{56}$ (2.6 h). This reaction is very suitable for detection with a Ge(Li) detector, as almost all of the decay results in gamma emission. The Mn^{56} activity, with a half-life of 2.58 h, was measured by following the 845-keV gamma photopeak intensity. The number of 845-keV gammas per decay, f_d, is 0.989 from *Nuclear Data Sheets*.[9] A value of $\sigma=100\pm6$ mb at 14.4-MeV neutron energy for this reaction was taken from Liskien and Paulsen's[10] absolute measurement. As natural iron samples are being used, the Mn^{56} activity from $Fe^{57}(n,np)Mn^{56}$ reaction also will be included. The cross section for this reaction was measured to be 6.1±2.6 mb by Chittenden, Gardner, and Fink.[11] However, the correction due to this is less than 1%. The other monitor reaction chosen to supplement this standard is $Al^{27}(n,\alpha)Na^{24}$ (15 h) which also results in one gamma per decay. The 1368.5-keV gamma de-exciting the first level in Mg^{24} was used to measure the Na^{24} activity. This reaction has a cross section averaging 114±6 mb at 14.4 MeV from the literature.

TABLE I. Comparison of cross sections at 14.4 MeV determined with mixtures of Fe+Se and with Fe+Al+Se powders.

Reaction	σ (mb) Fe+Se	σ (mb) Fe+Al+Se
$Se^{74}(n,2n)Se^{73g}$ (7.0 h)	290±29	296±30
$Se^{76}(n,2n)Se^{75}$ (120 days)	796±80	813±81
$Al^{27}(n,\alpha)Na^{24}$ (15 h)		107±11

Table I shows the results obtained by using mixtures of Fe+Se and Fe+Se+Al powders. The consistency in the two sets of values for $(n,2n)$ reactions on Se^{74} and Se^{76} assures that the activation of carefully mixed powdered samples can be reliably employed for cross-section measurements. The threefold mixture of Fe+Se+Al powders assures consistency, since the known ratio of iron and aluminum cross sections serves as a check. An averaged value of 293±29 mb for the $Se^{74}(n,2n)Se^{73g}$ (7.0 h) reaction was used as an internal monitor in bombardments of natural, spectroscopically pure elemental selenium samples which were not mixed with iron or aluminum.

Eleven bombardments were made to measure the various cross sections, with and without cadmium wrapping of samples. No large differences were observed in cross sections values between wrapped and unwrapped samples, indicating that the (n,γ) reaction with thermal neutrons was not significant. Table II summarizes the cross sections obtained in the present work on $Se^{74,76,80,82}$ and Fe^{54}, together with the values of half-lives and gammas used for measurement and

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TABLE II. Summary of neutron cross sections at 14.4±0.3 MeV from present work.

Reaction	Half-life	Gamma measured (keV)	f_d	σ (mb)
$Se^{74}(n,2n)Se^{73g}$	7.0 h	360	0.99	293±29
$Se^{74}(n,2n)Se^{73m}$	42 min	annihilation	1.70	65±15
$Se^{76}(n,2n)Se^{75}$	120 days	280 401	0.25 0.12	808±81
$Se^{80}(n,2n)Se^{79m}$	3.9 min	96	0.078	680±100
$Se^{82}(n,2n)Se^{81g}$	18.6 min	276+290	0.014	225±45
$Se^{82}(n,2n)Se^{81m}$	57 min	103	0.119	894±89
$Se^{74}(n,p)As^{74}$	18.7 days	596	0.612	107±11
$Se^{76}(n,p)As^{76}$	26.4 h	559	0.392	56±5.6
$Se^{78}(n,p)As^{78}$	90 min	615	0.42	24±2.4
$Se^{78}(n,\alpha)Ge^{75(m+g)}$	82 min	265	0.111	6±1
$Se^{80}(n,\alpha)Ge^{77(m+g)}$	54 sec+ 11.3 h	210+215	0.14–0.60	2–9[a]
$Fe^{54}(n,p)Mn^{54}$	313.5 days	835	1.0	259±26
$Fe^{54}(n,\alpha)Cr^{51}$	27.8 days	320	0.09	90±10

[a] See discussion of these limiting values in the text.

the f_d values used in the calculations. The error limits quoted include those in statistics (<1%), source self-absorption, which is important only for low-energy gammas, half-lives, and cross sections of the monitor reaction, but do not include those in decay schemes (f_d) taken from the literature.

RESULTS

Se(n,2n) Reactions

$Se^{82}(n,2n)Se^{81m}$ (*57* min.) The cross section for this reaction was previously measured by beta counting by Paul and Clarke[6] to be 1500±500 mb at 14.5 MeV and by Mangal and Khurana[12] to be 1600±160 mb at 14.8 MeV. In the present work, the 102.5-keV gamma from the isomeric transition was used to measure Se^{81m} activity. This isomeric transition is of the *E*3 type ($\frac{7}{2}+\rightarrow\frac{1}{2}-$), and the total internal conversion coefficient, $\alpha_{tot}=7.07$, was taken from Rose's tables.[13] It has been shown in a recent survey by Geiger[14] that the most accurately known experimental *E*3 conversion coefficients agree very well with the theoretical values listed by Rose. Samples of reduced thicknesses have been used to reduce the source self-absorption of the 102.5-keV gammas to less than 5%.

$Se^{82}(n,2n)Se^{81g}$ (*18.6* min). The 276+290-keV gammas from the 276- and 566-keV levels in Br^{81} were used to calculate the activity of Se^{81g} relative to that of Se^{81m} (Ref. 15). The counting rate of the 276+290-keV peaks was plotted versus time for several hours until the initially produced 18.6-min Se^{81g} completely decayed, after which only the 57-min half-life of Se^{81m} was observed. Fitting Eq. (6) to the 57-min portion of the decay curve, the contribution to the total Se^{81g} present, due to decay of the 57-min metastable state, was obtained, and the ratio of Se^{81m}/Se^{81g} activities *directly produced* in the reaction was evaluated. The cross section for the $Se^{82}(n,2n)Se^{81g}$ (18.6 min) reaction was previously estimated to be less than 100 mb,[12] in gross disagreement with the present value of 225±45 mb.

$Se^{80}(n,2n)Se^{79m}$ (*3.9* min). Mangal and Khurana[12] determined this cross section to be 125±12.5 mb, which disagrees strongly with the present value of 680±90 mb. The 96-keV gamma from the *E*3 isomeric transition to the ground state of Se^{79} was used to determine the activity, taking the total conversion coefficient from Rose.[13]

$Se^{76}(n,2n)Se^{75}$ (*120* days). No previous cross section data are available for this reaction. Owing to the long half-life of Se^{75}, the yield of this activity is relatively low. However, the complete spectrum of gammas in Se^{75} decay up to 400.7 keV was observed after all short-lived activities decayed completely. The activity was measured by following the 136-, 265-, 280-, and 400-keV gammas and employing the decay scheme from recent literature.[16] The total conversion coefficients for these transitions were taken as weighted averages of available experimental values.

$Se^{74}(n,2n)Se^{73m,g}$. Two previous measurements are reported for the cross sections leading to this isomeric

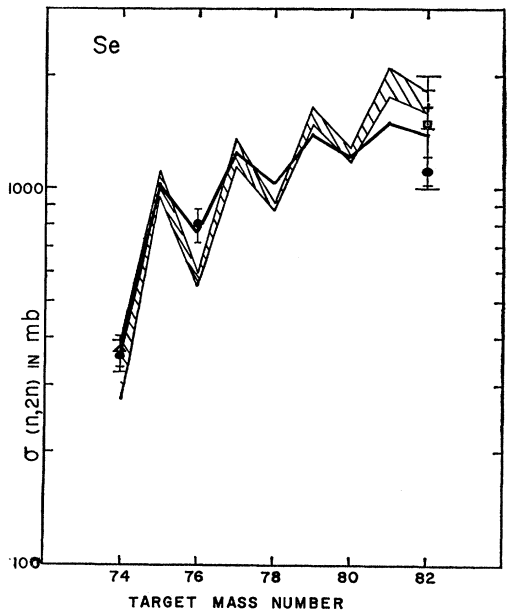

FIG. 1. Calculated (*n*,2*n*) cross sections at 14.4 MeV for all selenium isotopes, based on Gardner (Ref. 22) (cross-hatched band) and on Pearlstein (Ref. 21) (solid line). All available experimental points are plotted for comparison. ●: present work; △: Bormann; +: Mangal and Khurana; ⊡: Paul and Clarke.

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pair. Rayburn[17] obtained 383±29 mb to Se^{73g} (7.0 h) and 49±8 mb to Se^{73m} (42 min) at 14.4 MeV. Bormann *et al.*[18] have determined the cross sections for neutron energies 12.95 to 19.6 MeV. At 14.1 MeV, their values are 258±21 mb for Se^{73g} and 41.7±4.6 mb for Se^{73m}. The present values are in good agreement with these and fit with the cross section versus neutron energy excitation function obtained by Bormann *et al.*[18] The yield of Se^{73g} was measured by following the 360 keV and annihilation gammas. Almost all of the decays result in emission of a 360-keV gamma, since the conversion coefficient for this transition is very small. The yield of Se^{73m} was obtained by comparing annihilation radiation resulting from the complete stopping of the positrons from the decay of 42 min and 7.0 h Se^{73m} and Se^{73g} activities, respectively. The cross sections also were measured in a separate experiment in which the 511+511-keV sum-coincidence peak was followed in an integral-bias sum-coincidence spectrometer.[19] The decay scheme information was obtained from recent work on these isomers.[15]

Theoretical Calculation of Se$(n,2n)$ Cross Sections

A statistical-model approach has been developed recently by Barr *et al.*,[20] and Pearlstein[21] for calculating $(n,2n)$ cross sections, which agrees excellently with available experimental data in most cases. Following the computational procedure outlined by Pearlstein,[21] the predicted $(n,2n)$ cross sections at 14.4 MeV were calculated for selenium isotopes ($A=73$ to 82) and are plotted in Fig. 1. More recently, Gardner[22] has attempted to estimate $(n,2n)$ cross sections by relating them to charged-particle-reaction cross sections, such as $(p,2n)$ and $(\alpha,2n)$. If a compound system is formed either by an $(X+\alpha)$ or $(Y+n)$ reaction and the probability that it emits two neutrons is independent of the mode of formation, then

$$\frac{\sigma_{(n,2n)}(E_n)}{\sigma_{(\alpha,2n)}(E_\alpha)}=\frac{\sigma_C(E_n)}{\sigma_C(E_\alpha)}, \tag{7}$$

where the energies E_n and E_α are related by $E_\alpha+S_\alpha=E_n+S_n$. The energies E_n and E_α refer to the center-of-mass system and S_i is the separation energy of the ith-type particle from the compound system in its ground state. Gardner's predicted absolute $(n,2n)$ cross sections for 14–15 MeV neutrons on selenium isotopes (cross-hatched band) were also reproduced in Fig. 1, along with previous and present experimental values. The agreement of the calculated values with the present experimental points is reasonable.

Isomer Ratios and the Spin Cutoff Parameter

The isomer ratios σ_m/σ_g defined as the ratio of the cross sections for the formation of the metastable state to the formation of the ground state, are 4.0±0.8 for Se^{81} and 4.5±1.0 for Se^{73}. The latter agrees with the Se^{73} isomer ratio obtained by Bormann *et al.*[18] as a function of incident neutron energy. Bishop[23] has determined this ratio for Se^{81} produced in the $Se^{80}(n,\gamma)$ reaction; for thermal neutrons, the value is 0.13 and for epi-cadmium neutrons it is 0.19. This increase in the population of the high spin state with increasing energy is to be expected, as the probability of compound nucleus formation in higher angular momentum states increases with increasing energy of the captured neutron.

If one assumes a compound nucleus mechanism in these reactions, the isomer ratio should yield information about the spin cutoff parameter σ present in the spin distribution of level densities:

$$\rho_{(J)}=\rho_{(0)}(2J+1)\exp\left(-\frac{(J+\frac{1}{2})^2}{2\sigma^2}\right). \tag{8}$$

Following the method of Huizenga and Vandenbosch,[24,25] the spin cutoff parameter σ is calculated as follows. There are several quantities that enter into the calculation: a, the level density parameter; $T_l(E)$, the barrier transmission coefficient of a neutron with orbital angular momentum l and energy E; T, the nuclear temperature; and N, the average number of gammas by which the compound nucleus decays after particle emission is no longer possible. A detailed explanation of how to obtain these quantities is given by Bishop,[26] who also has shown that the spin cutoff parameter is insensitive to changes in the level density parameter a. The isomer ratio for Se^{81} was calculated with spin cutoff parameter $\sigma=2$, 3, 4, 5 and $N=1$, 2. The best value of the spin cutoff parameter that agrees with the present experimental isomer ratio is found to be 2.9±0.4.

It is possible to associate a moment of inertia I with the nuclear spin distribution.[27] The spin cutoff parameter is related to I by the equation

$$\sigma^2 h/2\pi T=I. \tag{9}$$

It is customary to compare the value of I with the

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rigid-body moment of inertia I_R, given by

$$I_R=\tfrac{2}{5}MAR^2, \quad (10)$$

where M is the nucleon mass, A is the mass number, and R is the nuclear radius. For $r_0=1.2\times10^{-13}$ cm, the ratio $I/I_R\approx1.0$. The level density parameter used in obtaining the nuclear temperature[28] is taken from the work of Erba *et al.*[29] A similar calculation was done by Bormann *et al.*[18] for Se^{73} and his isomer ratio agrees with the present work.

Se(n,p) Reactions

The only reliable datum available previously on (n,p) cross sections of selenium is by Bormann *et al.*,[30] who measured $Se^{74}(n,p)As^{74}$ (18 day) excitation function between 12 and 20 MeV. In the present study, the (n,p) cross sections of the three even-even isotopes, $Se^{74,76,78}$, are measured at 14.4 MeV. The reaction products, 18-day As^{74}, 26-h As^{76}, and 90-min As^{78}, were measured by determining the yield of 596-, 559-, and 615-keV gammas, respectively, de-exciting the first excited states in the corresponding daughter nuclei. The results are listed in Table II. The present value of 107 ± 11 mb for the $Se^{74}(n,p)As^{74}$ (18 day) reaction agrees very well with the excitation curve obtained by Bormann *et al.*[30]

The decrease of the (n,p) cross sections of selenium with increasing mass number, observed by Levkovskii[31] for other elements in this region, occurs in the present case. The calculations based on Gardner[3,32] and on Gove and Nakasima,[33] using the statistical model of the compound nucleus for the selenium (n,p) reactions exhibit the trend, but the absolute values do not agree with experiment. The discrepancy might be attributed to the role of other reaction mechanisms in addition to that of the compound nucleus.

Se(n,α) Reactions

$Se^{80}(n,\alpha)Ge^{77(m+g)}$. The (210+215 keV) gammas were used to monitor the activity of this reaction. Owing to the short half-life (54 sec) of the metastable state, which decays only 24% to 11-h Ge^{77g}, the rest going directly to the first and second excited states of As^{77}, the total (n,α) cross section could not be determined uniquely. Consequently, the lower and upper limits given for this cross section correspond, respectively, to the limiting assumptions that all of the $Se^{80}(n,\alpha)$ reaction goes to 11 h Ge^{77g} or to the 54 sec Ge^{77m} state. The number of 210+215-keV gammas per decay in Ge^{77m} and Ge^{77g} are 0.14 and 0.60, respectively, based on the decay scheme data of Wood[34] and Van der Kooi and Van den Bold.[35]

$Se^{78}(n,\alpha)Ge^{75(m+g)}$. The 49-sec metastable state $(\frac{7}{2}+)$ in Ge^{75} decays completely to the ground state of Ge^{75} and hence the cross section measured using the intensity of the 265-keV gamma in the decay of Ge^{75g} (82 min) is the total (n,α) cross section. As the 265-keV peak observed in the Ge(Li) detector contained contributions from Se^{75}, As^{78}, and Ge^{77g}, which are also produced in the irradiation of natural selenium, corrections were made for their presence in obtaining the yield of Ge^{75}.

The (n,α) cross sections, according to Chatterjee,[36] are roughly proportional to the level density of the residual nucleus. The shell effect on the level densities should be reflected in the trend of (n,α) cross sections. A plot of (n,α) cross sections versus residual nuclear charge should have a dip in the Ga-Ge-As region corresponding to the $2p_{3/2,1/2}$ proton subshell closure. The previously available cross section for $Se^{80}(n,\alpha)Ge^{77}$ is 38 ± 16 mb,[6] which is higher than the values for the neighboring (n,α) cross sections for the neighboring Ga and As nuclei, thus casting doubt on the existence of this subshell effect. The present values for the two Se (n,α) cross sections leading to product nuclei Ge^{75} and Ge^{77} lie below the value of 12.5 mb[30] for the $As^{75}(n,\alpha)Ge^{72}$ reaction and 10 mb[5] for the $Br^{79}(n,\alpha)As^{76}$ reaction at 14–15 MeV. A substantial dip in the (n,α) cross section systematics is thus confirmed. Further confirmation of this shell effect is demonstrated in the work of Wood *et al.*,[37] on the (n,α) cross sections in germanium isotopes.

$Fe^{54}(n,p)$ and (n,α) Cross Sections

Fast-neutron cross sections of iron are of interest in astrophysical theories of nucleosynthesis, since there is a large peak in the relative abundance of iron. The $Fe^{54}(n,p)Mn^{54}$ reaction also is of interest in reactor physics because of its application as an integrator of fast-neutron flux.

Irradiation of natural iron and FeS powders were made. Cr^{51} (27.8 days) from the $Fe^{54}(n,\alpha)$ reaction was measured by following the 320.3-keV gammas. The Mn^{54} activity from the $Fe^{54}(n,p)$ reaction was measured by following the 835-keV gamma several days after the 2.6 h Mn^{56} activity from $Fe^{56}(n,p)$ reaction had decayed. The results are listed in Table II.

Chatterjee[38] summarized all available $Fe^{54}(n,p)$

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values at 14–15 MeV. Salisbury and Chalmers[39] reported values for neutrons between 2 and 17 MeV, and they included a theoretical curve obtained by Büttner, Lindner, and Meldner[40] from a statistical-model calculation. Liskien and Paulsen[41] discussed the relative merits of all existing measurements. Most of these were made by the emulsion technique and thus are actually values for the sum of the $(n,p)+(n,pn)$ reactions, which would be larger. The values obtained by direct detection of emitted protons with a scintillator are also expected to yield the sum. Thus, only two previous activation measurements exist for the (n,p) cross section of Fe^{54}, by Pollehn and Neuert (254 mb at 14.1 MeV)[42] and by Cross *et al.*[43] (310 mb at 14.5 MeV), which are in fair agreement with the present value.

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TABLE III. Summary of available 14–15-MeV cross-section values for $Fe^{54}(n,\alpha)Mn^{54}$.

Neutron energy (MeV)	σ (mb)	Reference
14.1	131 ±25	Ref. 42
14.7	270 ±135	Ref. 11
14.5	109 ±10	Ref. 43
14.05	91.6±37.1	Ref. 39
14.4	90 ±10	Present work

The values of (n,α) cross sections of Fe^{54} available are summarized in Table III. The present value stands lower than many previous measurements, but somewhat higher than the calculated value by Büttner *et al.*[40]

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Gamma Decay of $Se^{73m,g}$ and $Se^{81m,g}$ Isomeric Pairs*

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The gamma decay of the isomeric pairs (42-min Se^{73m}, 7-h Se^{73g}), and (57-min Se^{81m}, 18.6-min Se^{81g}) was investigated with Ge(Li) and NaI(Tl) detectors by means of singles, coincidence, and sum-peak coincidence spectrometry. The half-lives of Se^{73g} and Se^{81m} were determined to be 7.0±0.1 h and 56.6±0.6 min, respectively. The gamma energies from 7-h Se^{73g} were determined to be 66.9±0.5 and 360.4±0.5 keV. A new gamma of 75.7±0.5 keV was found in 42-min Se^{73m} decay and is placed as the ground-state transition from a 76-keV level ($\frac{1}{2}$-, $\frac{3}{2}$-) in As^{73}. The absence of a 42-min component in the intensity of the 67-keV gamma indicates that the 67-keV ($\frac{5}{2}$-) first excited state of As^{73} is not fed from 42-min Se^{73m} either directly or through the 76-keV state. The energies and relative intensities of seven gammas in $Se^{81m,g}$ equilibrium decay have been measured: 102.7±0.5 (100) (isomeric transition), 275.8±0.5 (10.2), 289.9±0.5 (8.7), 539.0±0.5 (0.8), 553.0±0.5 (1.5), 566.1±0.5 (2.9), and 829.0±0.5 (4.9) keV. A new level at 539.0 keV is proposed tentatively in Br^{81} with a possible spin parity of $\frac{5}{2}$- or $\frac{7}{2}$-. Decay schemes are proposed for $Se^{73m,g}$ and $Se^{81m,g}$ which are consistent with all available data.

INTRODUCTION

EXCITED levels in odd-A nuclei contain, in addition to single-particle states, both quasi-particle and phonon states, resulting from pairing interactions and vibrational modes, respectively. Nathan and Nilsson[1] have pointed out that if nuclear oscillations are small-amplitude harmonic oscillations, the level scheme will consist of pure quasi-particle states and a band of vibrational states. The energy of the degenerate multiplet, resulting from the combination of a particle state and a vibrational state, is nearly equal to that of the corresponding first phonon state in neighboring even-even nuclei. In most cases, however, the coupling between particle motion and the oscillating field is strong, and the low-lying levels in odd-A nuclei are strongly mixed.

The situation concerning odd-A bromine isotopes has been summarized by Bonacalza[2], who points out that the first excited states lie lower than the corresponding first phonon state in neighboring even-even nuclei. In

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