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Si (n,p) AND Si (n,α) REACTION CROSS SECTIONS AT 14.5 MeV NEUTRON ENERGY

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16. Abstract

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SUMMARY

Measurements of cross sections for (n,p) and (n,α) reactions induced by 14.5 MeV neutrons in various isotopes of silicon are described. The experimentally determined values of activation cross sections σ are $\sigma\left[Si^{28}(n,p)Al^{28}\right] = 213.2 \pm 18.3$ mb, $\sigma\left[Si^{29}(n,p)Al^{29}\right] = 112.5 \pm 16.8$ mb, $\sigma\left[Si^{30}(n,p)Al^{30}\right] = \leqq 5 \pm 5$ mb, and $\sigma\left[Si^{30}(n,\alpha)Mg^{27}\right] = 73.6 \pm 10.3$ mb. By using the measured value of $\sigma\left[Si^{30}(n,\alpha)Mg^{27}\right]$, $\sigma\left[Si^{28}(n,\alpha)Mg^{25}\right]$ and $\sigma\left[Si^{29}(n,\alpha)Mg^{26}\right]$ have been calculated to be 147.2 ± 20.6 mb and 17.7 ± 3.5 mb, respectively. These values are based on $\sigma\left[Al^{27}(n,\alpha)Na^{24}\right] = 114 \pm 6$ mb for the monitor reaction.

INTRODUCTION

Silicon is one of the main constituents of soils of terrestrial origin. It is also a major constituent of lunar soil and, according to the big-bang theory of the universe, quite possibly of other planets. There are several ways of determining the soil composition. In recent years, (n,p) and (n,α) reactions in silicon at neutron energy of 14.5 MeV have been used to obtain information about the relative abundance of different elements in various types of soils, minerals, and meteorites. The technique is very reliable if the Si(n,p) and Si(n,α) cross sections are known with a great degree of precision. Unfortunately, the experimental data on Si(n,p) and Si(n,α) cross sections are in a rather unsatisfactory state. For instance, the reported values of $Si^{28}(n,p)Al^{28}$ cross section range from 157 mb to 340 mb, whereas the $Si^{30}(n,\alpha)Mg^{27}$ cross section values range from 46 mb to 175 mb (1 barn = 10^{-24} cm^2). The differences between various reported values are several times the error limits claimed. Spurred by this disquieting fact, two groups of investigators recently reported measurements on Si(n,p) and Si(n,α) cross sections. One group (ref. 1) used a conventional gamma counting technique, whereas the other group (ref. 2) used a beta counting system employing a thin-window Geiger-Müller (GM) counter. Their results are summarized in table I. It is obvious that the Si(n,x) cross section situation has not been improved by these recent measurements. Therefore, accurate determination of Si(n,p) and Si(n,α) cross sections is necessary in order to use the neutron activation technique for soil analysis. Also, an accurate knowledge of these cross sections will be useful in determining the significance of Si(n,p) and Si(n,α) reactions in neutron radiation damage to silicon devices.

This report describes the results of measurements of Si(n,p) and Si(n,α) reaction cross sections at 14.5 MeV neutron energy by the activation method.

SYMBOLS

A	atomic mass
d	deuteron
E_n	energy of incident neutron
N	total number of neutrons in a nucleus
n	neutron
p	proton
Q_m	energy difference between masses of interacting particles and reaction products
$Q_{n,p}$	Q_m-value for an (n,p) reaction
$T_{1/2}$	half-life of radionuclide
t	triton
Z	atomic number
α	alpha particle
β^+	beta particle (positron emitted from a radionuclide)
β^-	beta particle (electron emitted from a radionuclide)
σ	reaction cross section

THEORY

Recently, several authors have examined trends in the reported values of (n,p) and (n,α) reaction cross sections in the neutron energy range from 14 to 15 MeV in order to determine the best nuclear model for calculating such reaction cross sections. Levkovskii (ref. 3) as a result of analysis of his own data and those reported in the literature proposed the following type of equation for the (n,p) cross section:

$$\sigma(n,p) = \alpha_p \sigma_c(n) \tag{1}$$

where

$$\alpha_p = \sigma(n,p)/\sigma_c(n) = \exp\left[-33(N - Z + 1)/(A + 1)\right]$$

and $\sigma_c(n)$, the geometrical cross section of the nucleus, is $45.2\left(A^{1/3} + 1\right)^2$ mb. The isotopic mass dependence of $\sigma(n,p)$ was determined to be of the form

$$\frac{\sigma(A + \Delta A, Z)}{\sigma(A, Z)} \approx \exp\left(-33 \frac{\Delta A}{A}\right) \tag{2}$$

The agreement between the predictions of Levkovskii and the experimental results is remarkable, particularly for $9 \leqq Z \leqq 33$. There are a number of elements (including silicon) for which Levkovskii's predictions and the experimental results, however, are in substantial disagreement and for which the experimental data are either badly scattered or meager. Gardner (ref. 4), starting from a semiempirical equation based on the statistical model of the nucleus, has been able to reproduce the isotopic cross sections with good agreement for many observed cases. His initial calculations predicted the following type of relation between (n,p) cross sections in neighboring isotopes:

$$\frac{\sigma(Z, A + 1)}{\sigma(Z, A)} \approx \exp 2\left[\left(aE_m\right)_{A+1}^{1/2} - \left(aE_m\right)_A^{1/2}\right] \tag{3}$$

where a is the nuclear level density parameter widely used in statistical model calculations (the value of a ranges from A/40 to A/10 and Gardner uses A/20) and

$$E_m = E_n + Q_{n,p} - \delta = E_n + \overline{Q}_{av} \tag{4}$$

Equation (4) incorporates one of the weakest points in Gardner's calculations and is probably the main reason why experimentally observed fluctuations in $\sigma(n,p)$ are not reproduced as the target atomic mass increases. In a later attempt, Gardner and coworkers (refs. 5 and 6) used more accurate values of the pairing energy δ and level density a, but the agreement in critical cases was no better. Recently, Chatterjee (ref. 7) has tried, with limited success, to include the shell effects in the (n,p) reactions to reduce the discrepancy at shell closure. Similar calculations have been made for (n,α) cross sections with considerable success (refs. 8 and 9).

In all these attempts to develop formulation for predicting (n,p) and (n,α) cross sections, lack of more accurate data at critical points has hindered the progress towards the refinements which must be included in the present calculations to predict the nuclear reaction cross sections in the neutron energy range from 14 to 15 MeV. Thus, reliable experimental data are needed particularly for the reactions resulting from the less abundant isotopes of the target nuclei.

An alternative approach for calculating $\sigma(n,p)$ and $\sigma(n,\alpha)$ involves use of the Hauser-Feshbach theory (ref. 10) which relates the average compound nuclear cross section for a reaction to the transmission coefficients for all allowed channels. The real test of the validity of the Hauser-Feshbach theory, however, calls for detailed experimental data on partial cross sections for (n,p) and (n,α) reactions in addition to other available channels. Such partial cross section data are far more scarce than the total cross section data. The Hauser-Feshbach theory, therefore, is not considered any further in this report.

A discussion of Si(n,x) reaction at 14.5 MeV is now given. When 14.5 MeV neutrons strike natural silicon targets, a number of nuclear reactions are possible. These reactions and the reported values of their cross sections (refs. 2, 4, 7, 9, 11, and 12) are summarized in table II. From the data in this table, it is obvious that by using standard activation techniques, direct (n,p) cross section measurements can be made in all the isotopes; whereas (n,α) cross section can be measured only for $Si^{30}(n,\alpha)Mg^{27}$ reaction. However, $\sigma\left[Si^{28}(n,\alpha)Mg^{25}\right]$ can be calculated reasonably accurately from $\sigma\left[Si^{30}(n,\alpha)Mg^{27}\right]$ by using the statistical nuclear model which predicts quite well the ratio of (n,α) reaction cross sections in alternate isotopes. From $\sigma\left[Si^{28}(n,\alpha)Mg^{25}\right]$ thus calculated, $\sigma\left[Si^{29}(n,\alpha)Mg^{26}\right]$ can be determined from an experimentally measured ratio of $\sigma\left[Si^{28}(n,\alpha)Mg^{25}\right]$ to $\sigma\left[Si^{29}(n,\alpha)Mg^{26}\right]$ (ref. 13).

The experimental techniques used in making these measurements are described below.

EXPERIMENTAL PROCEDURE

Figure 1 shows the experimental setup used in bombarding zone-refined, high-purity silicon and spectroscopically pure aluminum targets with the neutrons produced by the

150 keV deuterons striking a tritium target. The aluminum target[1] was bombarded simultaneously with the silicon target to determine the instantaneous neutron flux during the silicon target irradiation. The targets were irradiated at fluxes from 10^7 to 10^8 neutrons/cm^2-sec for a time determined by the half-life of the residual radionuclide proposed to be investigated. The silicon and aluminum targets were disks of identical dimensions, 2 cm in diameter and 1/4 cm thick. This target size was dictated by the dimensions of the standard gamma sources used to calibrate the response of the 3-cm^3 (5 cm^2 $\times$ 0.6 cm) Ge(Li) detector (lithium-drifted germanium detector) used to measure the gamma spectra from the residual radionuclides in silicon. The resolution of the detection system (detector plus electronics) was 6 keV FWHM at 1332 keV. The relevant branching ratios (ref. 14) needed for the analysis of individual reactions are summarized in table III. The silicon detector in figure 1 simply served to indicate the constancy of the neutron flux during the irradiation of the target. The targets – silicon and aluminum disks – were bombarded for a period of 1 hr to ensure adequate activity of the aluminum target. At a precisely known time interval after the end of the bombardment, the silicon target was transferred to the counting station in front of the Ge(Li) spectrometer window and the gamma spectra readout was started and continued for a period of 1 hr. After the silicon readout was completed, the aluminum readout was started and continued for a period of 4 hr. Four days later the target bombardment was repeated with the silicon and aluminum targets in reverse order. (This time interval between the two bombardments ensured that all residual activity from the first bombardment had died down.) This repetition was intended to provide information on any difference in neutron flux at the positions of the two targets. No significant difference was detected in the neutron flux values at the two positions. Figures 2 and 3 show typical silicon and aluminum activation spectra, respectively. It should be remembered that $Si^{28}(n,p)Al^{28}$ reaction will contribute a strong single escape peak (that is, 1.78 MeV - 0.51 MeV = 1.27 MeV) at the same position as the major gamma ray from $Si^{29}(n,p)Al^{29}$ reaction. However, the 1.27 MeV single escape peak from the 1.78 MeV gamma ray will be decaying much faster than the total capture peak due to the 1.27 MeV gamma ray from $Si^{29}(n,p)Al^{29}$ reaction. Thus, a sequential spectral measurement (fig. 2) from the irradiated silicon disk, coupled with a precise knowledge of the profile of a 1.78 MeV gamma ray in the spectrometer, should enable an easy separation of the contributions from $Si^{28}(n,p)Al^{28}$ and $Si^{29}(n,p)Al^{29}$ reactions under the 1.27 MeV peak. The 1.78 MeV gamma ray profile in the present spectrometer was obtained by measuring the difference in the spectrum observed from a polyethylene capsule, 2 cm in diameter and 1/4 cm thick, with and without P_2O_5 powder in it

[1]This material was chosen since the $Al^{27}(n,\alpha)Na^{24}$ cross section is among the most precisely known data (refs. 4 and 7). Commercially available aluminum targets (purity = 99.99+ %) were used in this investigation.

bombarded with neutrons. The difference spectrum is expected to give the following contributions from the various possible $P^{31}(n,x)$ reactions (none of the energetically possible $O(n,x)$ reactions are expected to interfere with the profile of the 1.78 MeV gamma ray from the $P^{31}(n,\alpha)Al^{28}$ reaction):

$$P^{31}(n,2n)P^{30} \xrightarrow[2.5\ \text{min}]{\beta^+} Si^{30} \quad (+\ 0.51\ \text{MeV gamma ray})$$

$$P^{31}(n,p)Si^{31} \xrightarrow[2.62\ \text{hr}]{\beta^-} P^{31} + 1.48\ \text{MeV gamma ray}$$

$$P^{31}(n,\alpha)Al^{28} \xrightarrow[2.27\ \text{min}]{\beta^-} Si^{28} + 1.78\ \text{MeV gamma ray}$$

Thus, the 1.78 MeV gamma ray from $P^{31}(n,\alpha)Al^{28}$ reaction is sufficiently well separated from other gamma rays to permit an easy and reliable computation of $\frac{\text{Single escape peak intensity}}{\text{Total capture peak intensity}}$. Figure 4 shows the observed difference spectrum.

Because of the extremely short half-life of Al^{30} (3.27 sec) produced in $Si^{30}(n,p)Al^{30}$ reaction, a slightly different procedure was used for this reaction. (See fig. 5 for special experimental arrangement.) In this procedure, the silicon and aluminum samples were bombarded for a period of 5 min. This time interval was chosen to ensure measurable activity in the aluminum disk. Immediately after the end of the bombardment, the gamma spectrum readout from the two targets in situ was started and continued for a period of 1 min. (During this time, all Al^{30} nuclei will have decayed.) This spectrum was stored in the first half of the memory of a pulse height analyzer. At the end of 1 min, the spectrum readout was continued in the second half of the memory for an additional 1 min. A comparison of the two spectra was then made to obtain the $Al^{30} \xrightarrow{\beta^-} Si^{30*}$ contribution. In this comparison, attention was focused on the 3.51 MeV gamma ray rather than on the 1.27 MeV gamma ray which cannot be separated from the $Si^{28,29}(n,p)$ spectra or the 2.23 MeV gamma ray which cannot be separated from the single escape peak due to the 2.75 MeV gamma ray produced in $Al^{27}(n,\alpha)Na^{24}$ reaction. No distinct gamma peak ascribable to $\left(Si^{30}(n,p)Al^{30} \xrightarrow{\beta^-} Si^{30} + \text{Gamma rays}\right)$ reaction was observed.

EXPERIMENTAL RESULTS

From the measured values of the intensities of the total capture peaks, after allowing for isotope effect, saturation effect, decay branchings, and decay corrections, the values of $Si^{28,29,30}(n,p)$ and $Si^{30}(n,\alpha)$ cross sections were calculated by standard activation techniques. A summary of these values is given in table IV. The monitor reaction cross section errors are included in the quoted errors. For (n,p) reactions, it has been assumed that (n,d) or (n,np) reactions in heavier isotopes do not make significant contributions to the population of the radionuclides produced in (n,p) reaction in the lighter isotope (see Discussion).

By using the measured value of $Si^{30}(n,\alpha)$ reaction cross section, $Si^{28}(n,\alpha)$ and $Si^{29}(n,\alpha)$ reaction cross-sections were calculated by the following approach. Recently, Gardner and Yu (ref. 8) have derived a semiempirical equation, based on the statistical model, for the relative (n,α) cross sections at 14.5 MeV neutron energy for isotopes of a given element in the range $6 \leqq Z \leqq 30$. The equation involves parameters which are functions of the incident neutron energy, the nuclear level density in the residual nucleus, and the pairing energy in the daughter nucleus and is as follows:

$$\frac{\sigma(Z,A+1)}{\sigma(Z,A)} = \exp 2\left\{\left[a\left(E_m - \beta_\alpha^*\right)\right]_{A+1}^{1/2} - \left[a\left(E_m - \beta_\alpha^*\right)\right]_A^{1/2}\right\} \tag{5}$$

where

a	nuclear level density parameter, $\frac{1}{10}A$
E_m	total excitation energy available for (n,α) reaction, $E_n + Q_{n,\alpha} - \delta$
δ	pairing energy in the daughter nucleus ($\delta = 0$ for odd nucleus and equal to the neutron and/or the proton pairing energy for the other nuclei)
β_α^*	effective Coulomb barrier height for alpha particles, $\frac{2.058(Z-2)}{(A-3)^{1/3} + 4^{1/3}}\left[1 - \frac{1.13}{(A-3)^{1/3}}\right]$

Since equation (5) predicts only the ratios of cross sections, it is not very sensitive to errors in a.

Substituting appropriate values of the various parameters in equation (5) gives the following relative values of $Si(n,\alpha)$ reaction cross sections:

$$\frac{\sigma\left[Si^{28}(n,\alpha)Mg^{25}\right]}{\sigma\left[Si^{29}(n,\alpha)Mg^{26}\right]} = \frac{1.00}{1.27} \tag{6}$$

$$\frac{\sigma\left[Si^{29}(n,\alpha)Mg^{26}\right]}{\sigma\left[Si^{30}(n,\alpha)Mg^{27}\right]} = \frac{1.270}{0.485} \tag{7}$$

Since errors in the chosen values of the pairing energy δ affect greatly the predicted cross section values for the adjacent isotopes, but not as much the predicted values for alternate isotopes (where δ values are the same), it was decided to obtain the $\sigma\left[Si^{28}(n,\alpha)Mg^{25}\right]$ value from the measured $\sigma\left[Si^{30}(n,\alpha)Mg^{27}\right]$ value by using the predicted ratio for these reaction cross sections, that is,

$$\frac{\sigma\left[Si^{28}(n,\alpha)Mg^{25}\right]}{\sigma\left[Si^{30}(n,\alpha)Mg^{27}\right]} = \frac{1.000}{0.485}$$

In this manner, $\sigma\left[Si^{28}(n,\alpha)Mg^{25}\right]$ has been calculated to be 147.2 ± 20.6 mb based on the measured value of 73.6 ± 10.3 mb for $\sigma\left[Si^{30}(n,\alpha)Mg^{27}\right]$. The $Si^{29}(n,\alpha)Mg^{26}$ reaction cross section was then calculated on the basis of an experimentally measured value (ref. 13) of

$$\frac{\sigma\left[Si^{28}(n,\alpha)Mg^{25}\right]}{\sigma\left[Si^{29}(n,\alpha)Mg^{26}\right]} = 8.5 \pm 1.2$$

DISCUSSION

In discussing the isotopic cross section results, the possibility of interference from competing reactions in neighboring isotopes should be considered. The relative contributions of the various reactions involved are strongly dependent on their respective Q_m-values. However, as seen from data in table II, the Q_m-values of the competing reactions are very small and, hence, their contributions to the primary channels may be ignored. In line with this argument and coupled with the relative abundance of various isotopes of silicon, the observed Al^{28} and Al^{29} decays have been attributed entirely to $Si^{28}(n,p)Al^{28}$ and $Si^{29}(n,p)Al^{29}$ reactions, respectively.

An examination of the data in table IV shows that the calculated values based on the statistical nuclear model predict $Si^{28}(n,p)$ and $Si^{29}(n,p)$ reaction cross sections quite well but the measured value of $Si^{30}(n,p)Al^{30}$ reaction cross section is in disagreement with all predicted values. Part of this disagreement could be due to uncertainty in the state of Al^{30} involved. A $T_{1/2} = 72.5 \pm 1.5$ sec activity with unknown gamma decay has been ascribed to Al^{30m} (ref. 15). If $Si^{30}(n,p)Al^{30}$ reaction populates this state appreciably and if this state decays by direct beta emission to Si^{30}, the experimental value of $\sigma\left[Si^{30}(n,p)Al^{30}\right]$ could be in considerable error. This discrepancy can be resolved by measuring the $(\beta - \gamma)$ coincidence spectra in the $Si^{30}(n,p)Al^{30} \xrightarrow{\beta^-} Si^{30*}$ reaction in enriched Si^{30} target.[2]

The predicted and measured values of $Si^{28}(n,\alpha)$ and $Si^{30}(n,\alpha)$ reaction cross sections are in reasonably good agreement. However, the calculated value of $\sigma\left[Si^{29}(n,\alpha)\right]$ does not agree with the value computed in the present work. An investigation of the alpha spectrum in $Si^{29}(n,\alpha)Mg^{26}$ reaction in an enriched Si^{29} target is needed to resolve this difference.

As indicated in the Introduction, the values of cross sections reported in references 1 and 2 are in serious disagreement except for $Si^{28}(n,p)Al^{28}$ reaction (see table I). Part of this difference could be ascribed to the measurement techniques used by the two groups. Pasquarelli used a thin window GM counter to measure the beta activity in the product nuclei. Self-absorption in the target as well as scattering in the GM window can lead to considerable errors in the measured cross sections, particularly for the less abundant isotopes. Present measurements support the results in reference 1.

CONCLUSIONS

Cross sections for (n,p) and (n,α) reactions at 14.5 MeV neutron energy have been measured in various isotopes of silicon. The experimentally measured value of $Si^{30}(n,\alpha)Mg^{27}$ reaction cross section has been used to calculate $Si^{28,29}(n,\alpha)$ reaction cross sections. Since the calculated ratio of (n,α) reaction cross sections in alternate isotopes is more reliable than that in adjacent isotopes, an experimentally determined ratio of reaction cross sections of $Si^{28}(n,\alpha)Mg^{25}$ and $Si^{29}(n,\alpha)Mg^{26}$ was used to calculate $Si^{29}(n,\alpha)Mg^{26}$ reaction cross section. Present measurements support the results of Ranakumar, Kondaiah, and Fink (Nuclear Physics, Dec. 30, 1968).

The absolute magnitudes of the Si(n,p) and $Si(n,\alpha)$ cross sections indicate that these reactions will play a significant role in determining the extent of radiation damage by neutrons in silicon devices.

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[2] It would be very interesting to study again the β^- decay of Al^{30} to determine the β^- branching ratios unambiguously. A redetermination of Al^{30} - Si^{30} mass difference is also needed for more accurate theoretical calculation of $\sigma\left[Si^{30}(n,p)Al^{30}\right]$ value. (See eq. (3).) It is also desirable to look for possible effects of Ericson fluctuations in $Si^{30}(n,p)Al^{30}$ reaction around a neutron energy 14 MeV.

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TABLE I.- MOST RECENT DATA ON TOTAL Si(n,p) AND Si(n,α) REACTION CROSS SECTIONS AT 14.5 MeV

Reaction	Cross section, mb, from –	
	Reference 1 (1968)	Reference 2 (1967)
$Si^{28}(n,p)Al^{28} \xrightarrow{\beta^-} Si^{28}$ + Gamma rays	252 ± 15	222 ± 12
$Si^{29}(n,p)Al^{29} \xrightarrow{\beta^-} Si^{29}$ + Gamma rays	130 ± 16	22.7 ± 1.0
$Si^{30}(n,\alpha)Mg^{27} \xrightarrow{\beta^-} Al^{27}$ + Gamma rays	68 ± 8	175 ± 18

TABLE II.- SUMMARY OF Si(n,p), Si(n,d), Si(n,t), AND Si(n,α)

REACTION ENERGETICS AND CROSS SECTIONS

Nuclear reaction	Decay mode of reaction product	Q_m-value of reaction	Reported values of cross sections and comments
$Si^{28}(n,p)Al^{28}$	$Al^{28} \xrightarrow[2.27\ \mathrm{min}]{\beta^-} Si^{28}$	-3.852 MeV	157 - 340 mb (refs. 2, 4, 7).
$Si^{28}(n,d)Al^{27}$	Stable	-9.358 MeV	Reaction observed but no cross section data available.
$Si^{28}(n,\alpha)Mg^{25}$	Stable	-2.652 MeV	No data available.
$Si^{29}(n,p)Al^{29}$	$Al^{29} \xrightarrow[6.52\ \mathrm{min}]{\beta^-} Si^{29}$	-2.894 MeV	22 - 110 mb (refs. 2, 4, 7).
$Si^{29}(n,d)Al^{28}$	$Al^{28} \xrightarrow[2.27\ \mathrm{min}]{\beta^-} Si^{28}$	-10.103 MeV	Not observed.
$Si^{29}(n,t)Al^{27}$	Stable	-11.567 MeV	Not observed.
$Si^{29}(n,\alpha)Mg^{26}$	Stable	-0.033 MeV	No data available.
$Si^{30}(n,p)Al^{30}$	$Al^{30} \xrightarrow[3.27\ \mathrm{sec}]{\beta^-} Si^{30}$	-6.510 MeV	No data available.
$Si^{30}(n,d)Al^{29}$	$Al^{29} \xrightarrow[6.52\ \mathrm{min}]{\beta^-} Si^{29}$	-11.288 MeV	Not observed.
$Si^{30}(n,\alpha)Mg^{27}$	$Mg^{27} \xrightarrow[9.46\ \mathrm{min}]{\beta^-} Al^{27}$	-4.210 MeV	46 - 175 mb (refs. 2, 9, 11, 12).

Si(n,2p) or Si(n,He^3) types of reactions have not been included since they are much less likely to occur than Si(n,p) or Si(n,α) reactions.

TABLE III.- DECAY SCHEMES OF RADIONUCLIDES FORMED IN $Si(n,p)$ AND $Si(n,\alpha)$ REACTIONS

Reaction	Nuclear reaction	Energies of electromagnetic radiations emitted following β^- decay, MeV (a)	Relative intensity of various modes of decay or fractional decay, % (a)
1	$Si^{28}(n,p)Al^{28} \xrightarrow{\beta^-} Si^{28*}$	1.78	100
2	$Si^{29}(n,p)Al^{29} \xrightarrow{\beta^-} Si^{29*}$	1.27	93
		2.03	<2
		2.43	≈7
3	$Si^{30}(n,p)Al^{30} \xrightarrow{\beta^-} Si^{30*}$	1.27	42
		2.23	58
		3.51	42
4	$Si^{30}(n,\alpha)Mg^{27} \xrightarrow{\beta^-} Al^{27*}$	0.84	70
		1.01	30

[a]Data taken from reference 14.

TABLE IV. SUMMARY OF Si(n,p) AND Si(n,α) REACTION CROSS SECTION

VALUES AT 14.5 MeV NEUTRON ENERGY

Nuclear reaction	Calculated cross section, mb, from –				Experimental cross section, mb, from –			
	Ref. 4	Ref. 6	Ref. 3	Ref. 11	Present investigation (a)	Present investigation (b)	Ref. 1 (b)	Ref. 2 (c)
$Si^{28}(n,p)Al^{28}$	240	187.1	240	70	252.4 ± 25.2	213.2 ± 18.3	252 ± 15	222 ± 12
$Si^{29}(n,p)Al^{29}$	120	113.4	70	133	133.2 ± 21.3	112.5 ± 16.8	130 ± 16	22.7 ± 1.0
$Si^{30}(n,p)Al^{30}$ $Si^{30}(n,p)Al^{30m}$	60	90.0	22		≦(5 ± 5)	≦(5 ± 5)	≦7	
$Si^{28}(n,\alpha)Mg^{25}$	140 ± 75% (ref. 9)	103.7 (ref. 8)			179.8 ± 26.9	147.2 ± 20.6		
$Si^{29}(n,\alpha)Mg^{26}$		131.4 (ref. 8)			22.1 ± 6.5	17.7 ± 3.5		
$Si^{30}(n,\alpha)Mg^{27}$	70 ± 75% (ref. 9)	50.3 (ref. 8)		13	87.2 ± 13.1	73.6 ± 10.3	68 ± 8	175 ± 18

[a]Based on $\sigma\left[Al^{27}(n,\alpha)Na^{24}\right] = 135 \pm 10$ mb.

[b]Based on $\sigma\left[Al^{27}(n,\alpha)Na^{24}\right] = 114 \pm 6$ mb.

[c]Based on $\sigma\left[Cu^{63}(n,2n)Cu^{62}\right] = 511 \pm 15$ mb.

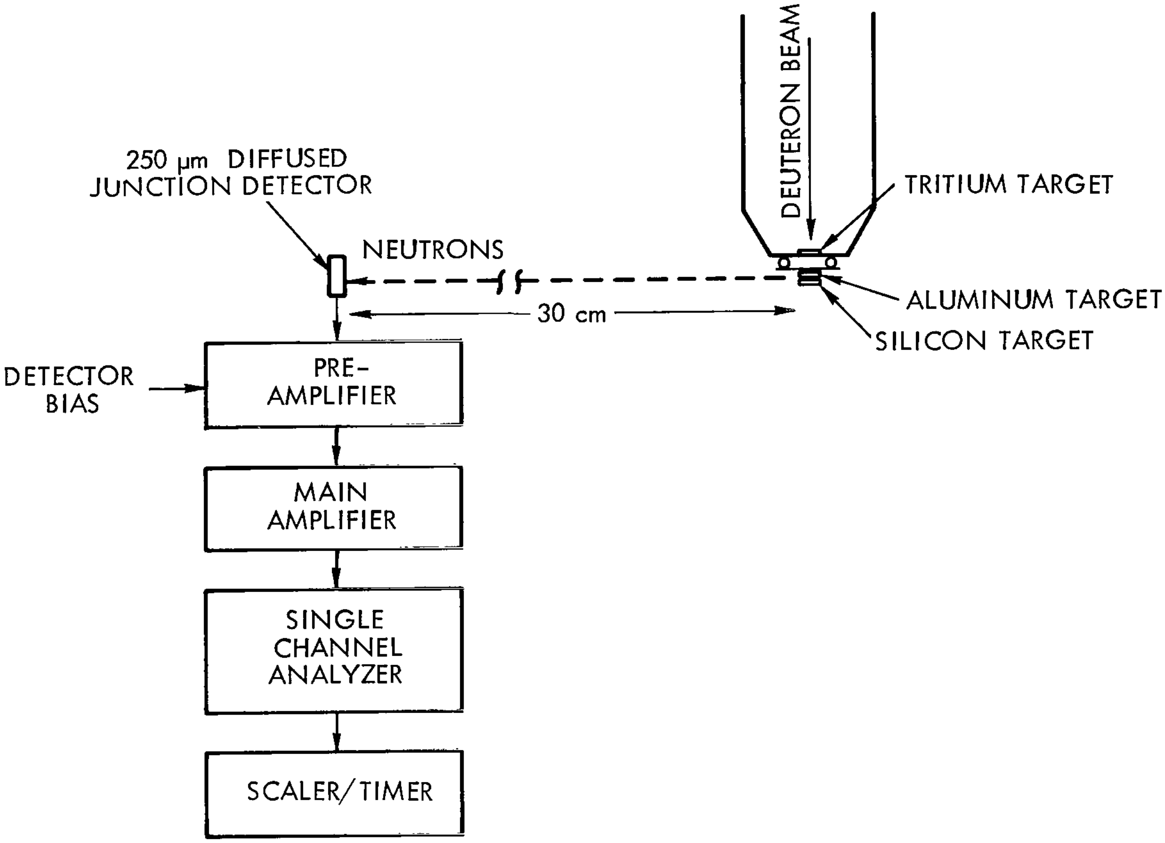
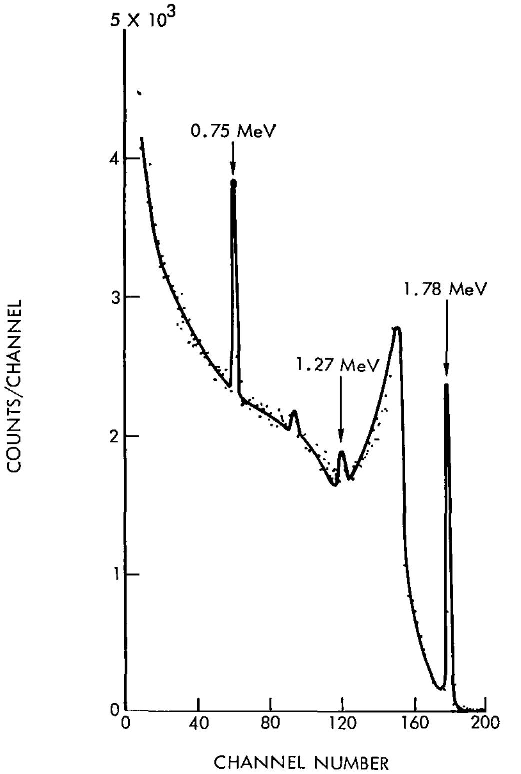
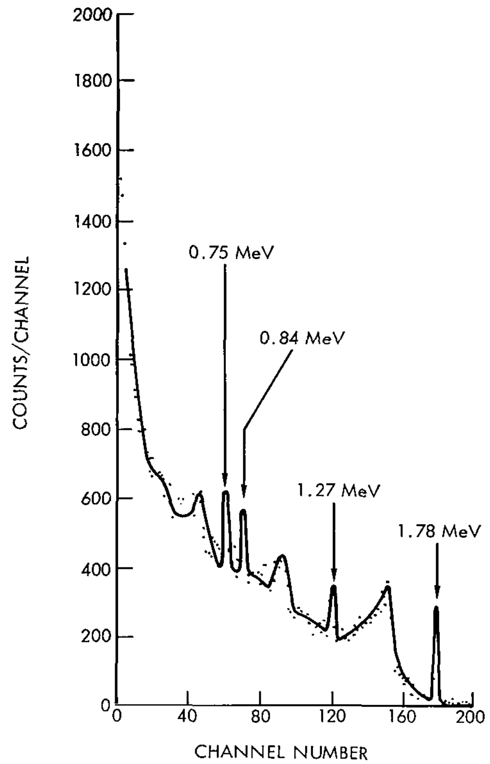


Figure 1.- Schematic diagram of the experimental setup for bombarding targets to measure Si(n,p) and Si(n,α) reaction cross sections. (Gamma emission readout part of the setup is not shown in this figure; monitor channel only is shown.)



(a) Spectrum observed when readout was started 17 sec after end of neutron bombardment and continued for 8 min. Counting rate correction has not been applied to this spectrum.



(b) Spectrum observed when readout was started 8 min after neutron beam was turned off and continued for 1 hr.

Figure 2.- Typical gamma ray spectra from Si(n,x) reaction.

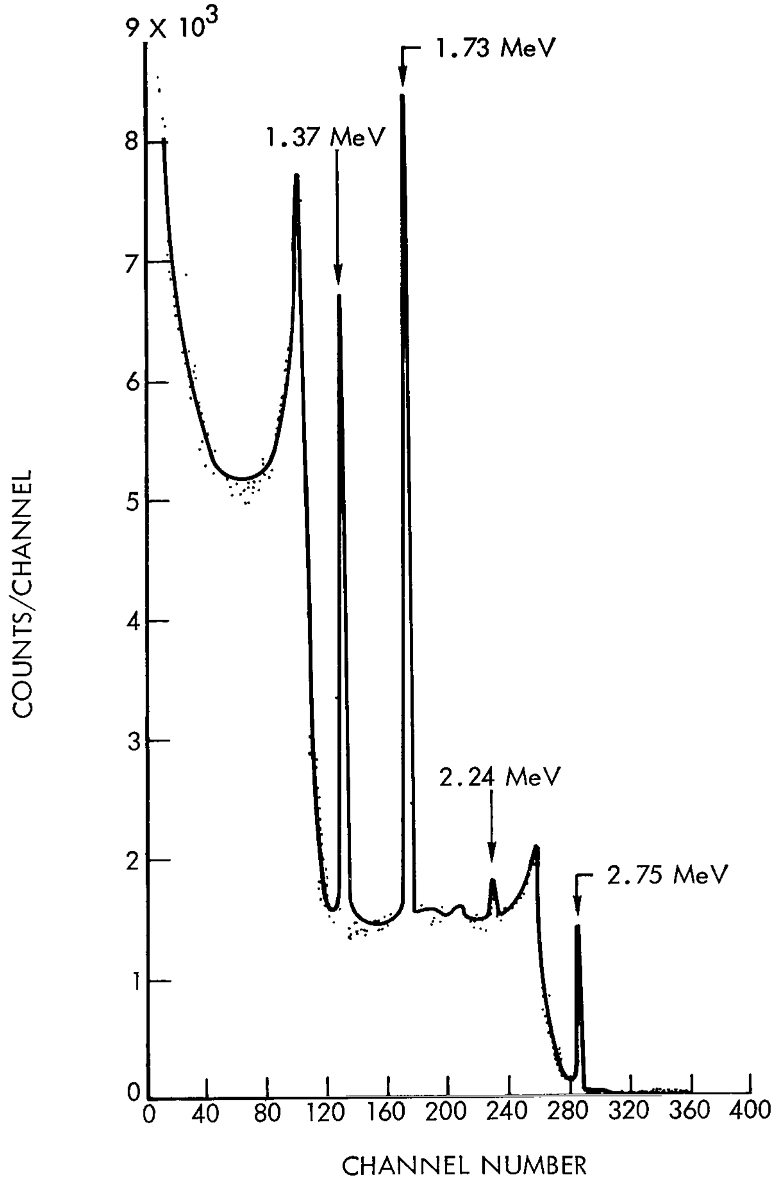


Figure 3.- Typical gamma ray spectrum from $\left(Al^{27}(n,\alpha)Na^{24} \xrightarrow[15.04\ hr]{\beta^-} Mg^{24} + \text{Gamma rays}\right)$ reaction. Spectroscopic purity of aluminum target ≈ 99.99%.

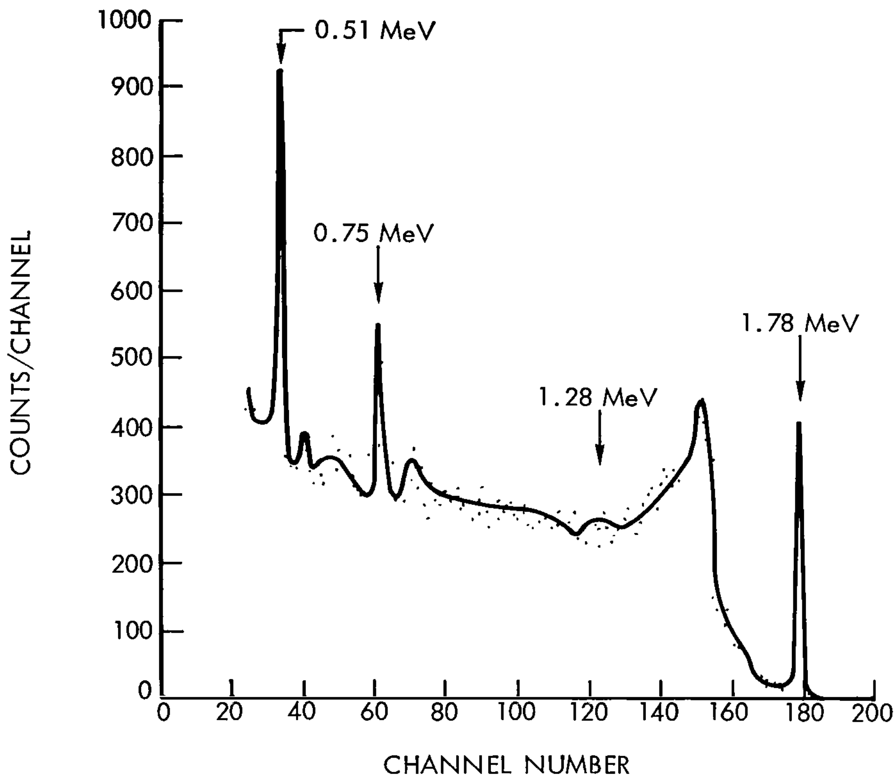


Figure 4.- Gamma ray spectrum from $\left(P^{31}(n,\alpha)Al^{28} \xrightarrow[2.27\text{ min}]{\beta^-} Si^{28} + \text{Gamma rays}\right)$ reaction. This spectrum gives the profile of a 1.78 MeV gamma ray in the spectrometer.

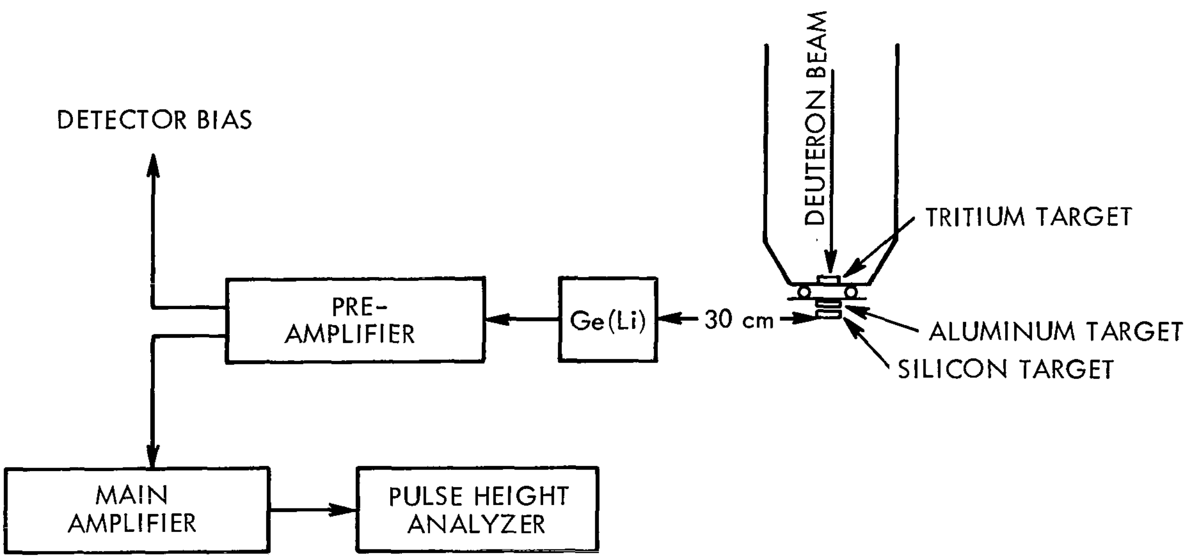


Figure 5.- Special experimental arrangement for measuring $\left(Si^{30}(n,p)Al^{30} \xrightarrow[3.27\text{ sec}]{\beta^-} Si^{30} + \text{Gamma rays}\right)$ spectrum.

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