THE RICE INSTITUTE

INELASTIC NEUTRON SCATTERING FROM SILICON

by

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[Signature]
I. Introduction

In order to have a better understanding of the atomic nucleus, a variety of nuclear reactions should be studied. One particular type of nuclear reaction is the inelastic neutron scattering from an element, that is, the observation of neutrons scattered from an element which have less energy leaving than when entering the scattering element, the rest of the energy having caused nuclei to be in some excited state.

If the excited states in a nucleus are not too near each other, then one can observe the inelastic neutron cross section over a given incident neutron energy range indirectly by observing the gamma rays produced at energies corresponding to these states; this is both easier and much more accurate than the direct observation of the inelastically scattered neutrons. Silicon is a very satisfactory element for this type of investigation, since the lowest energy level in $^{28}\text{Si}$ is 1.78 MeV$^1$, while the next level is about 4.54 MeV$^1$. Natural silicon$^2$ is 92.2% $^{28}\text{Si}$, 4.7% $^{29}\text{Si}$, and 3.1% $^{30}\text{Si}$. Hence the effect of the $^{29}\text{Si}$ and $^{30}\text{Si}$ is small.

In this experiment, the relative inelastic neutron cross section was observed over an incident neutron energy range of 1.6 to 4.5 MeV by counting the gamma rays from the lowest $^{28}\text{Si}$
level. At certain higher energies, the twenty channels were set so as to observe any peaks produced by gamma rays from levels above 1.78 MeV.
II. Experimental Arrangement and Procedure

A. Production of Neutrons

The neutrons used in this experiment were produced by the reactions

\[ (1) \; _1^1H + _1^3H \rightarrow _1^1n + 0.76 \text{ MeV} \]
\[ (2) \; _1^2H + _1^2H \rightarrow _1^1n + 3.27 \text{ MeV} \]

The first reaction used a proton beam striking a zirconium-tritium target on a tungsten backing; the second was produced by a deuterium beam hitting either a zirconium-deuterium target on a tungsten backing or a deuterium gas target. These beams were produced by the Rice Institute 5.5 MeV Van de Graaff Generator.

B. The Experimental Arrangement

The arrangement for this experiment is shown in Figures 1 and 2. In Figure 1, the proton beam hit the tritium target or the deuterium beam hit the deuterium target. In Figure 2, the deuterium beam passed through a nickel foil into a deuterium gas target. The target shell was made from stainless steel. This target was filled to a pressure of about six inches of mercury.

The iron shield removed 97% of the initial neutron beam, while the lead shield removed 97% of the gamma rays originating in the iron. A 1" diameter by 1" long Harshaw packaged
sodium iodide crystal was affixed to a Dumont 6992 photomultiplier tube. This combination gave a 1.50 to 1 peak to valley ratio and an energy resolution of 8% for the 1.33 MeV gamma ray from Co$^{60}$. The preamplifier output went into a twenty channel pulse height analyzer.

The scatterer consisted of 297 grams of silicon lumps enclosed in a 93 gram thin-walled aluminum retainer. The silicon was 97% pure.
III. Analysis of Data

A. Neutron Energy Determination

The energy of the incident neutrons was determined by measuring with a nuclear magnetic resonance magnetometer the magnetic field which bent the protons or the deuterons. For the magnetometer, the following relation holds:

\[
\text{Frequency} = \frac{\hbar}{H} \quad \text{or} \quad \text{Li}^7 \text{Gyromagnetic Ratio}
\]

where \( H \) is the magnetic field intensity and \( \varphi \) is the orbit radius. The values of \( \hbar \varphi \) correspond to certain proton or deuteron energies.\(^4\)

The proton energy was corrected for the target thickness; the deuteron energy was corrected for either the target thickness or the thickness of the nickel foil plus one-half the length of the gas target. The target thickness for the proton beam was 27 KeV at 1.8 MeV and was 17 KeV at 4.5 MeV. The Zr-D target was 100 KeV thick while the Ni foil and \( \text{D}^2 \) gas target together absorbed 118 KeV at 2.22 MeV, 110 KeV at 2.42 MeV, and 75 KeV at 3.68 MeV deuteron energy. It was not essential in this experiment to have the value of the energy more exact than two significant figures when using the deuterium targets. The neutron energy was obtained for both of the reactions from tables\(^5\) at the angle \( \theta = 5°37' \). The loss of
energy due to the scatterer was 7 KeV at the lowest and 9 KeV at the highest proton energies used. Hence the energy loss was 34 KeV at the lowest and 46 KeV at the highest proton energies used.
B. Relative Inelastic Gamma Ray Determination

The relative inelastic neutron cross section was observed from 1.70 to 4.52 MeV incident neutron energy. The only competing reaction for the neutrons is $^{28}\text{Si} (n,p)^{28}\text{Al}$, which has a $Q$ value of -3.87 MeV. Its cross section is 0.2 barns for 14.5 MeV neutrons. Therefore, this reaction was assumed negligible for our relative inelastic cross section determination. It was also assumed that the neutrons scattered into the crystal did not affect the results obtained.

The photo peak is the most pronounced peak in the spectrum of a gamma ray having an energy of 1.78 MeV. Hence the amplifier gain was set so that the photo peak produced by the 1.78 MeV gamma ray was not too near the first or last channel. For each proton resonance signal, the number of counts in each channel was recorded for 1000 counts on the medium integrator scale. The highest four channels were counted as a measure of the inelastic neutron cross section, except for the last five points near $E_n = 4.5$ MeV, where the gain was reduced by a factor of two; in this case the highest two channels near the peak were counted. At certain energies, the silicon target was removed to observe the background effect.

The data was corrected for the difference in the yield of neutrons per proton according to Fowler and Brolley\textsuperscript{6}. 

-7-
IV. Results and Interpretations

The counting rate below the lowest inelastic neutron peak merged into the background at 1.82 MeV neutron energy, that is, the points below 1.82 MeV were not statistically different from each other. Thus the threshold agreed with the expected threshold for a 1.78 MeV level in silicon. The position of this level has been confirmed by many observers\(^1\), \(^7\), \(^8\), \(^9\), \(^10\), \(^11\).

The relative inelastic neutron cross section is plotted from 1.70 to 4.52 MeV incident neutron energy on Figure 3. The resonances observed over this energy range are listed in Tables 1 and 2, and are compared with results from other experiments. There is good agreement between this data and the \(\text{Si}(n,n)\) experiment done at Zurich\(^{12}\), the \(\text{Si}(n,n'\gamma)\) experiment done at Los Alamos\(^{13}\), and the \(\text{Si}(p,p'\gamma)\) experiment done at Oak Ridge\(^{14}\), and the \(\text{Si}(p,p'\gamma)\) experiment done at Duke\(^{15}\). The \(\text{Si}(n,n)\) experiment done at Zurich had seven peaks which did not correspond to any peak observed in this experiment. However, small inelastic peaks may have been present at those energies, but were not observed because they were obscured by a larger inelastic peak nearby. The resonances observed at Los Alamos agree with Figure 3 except for the lowest resonance; Figure 3 agrees better with the 1.93 and 1.97 MeV
resonances observed at Zürich than the 1.90 MeV resonance observed at Los Alamos. $^{29}\text{Si}$ and $^{29}\text{P}$ are mirror nuclei, so that the energy levels should agree, except for the Coulomb effect of about 340 KeV.

Higher levels in silicon occur near 4.54 MeV, 7, 9, 10, 11, 16, 17, 18, near 4.95 MeV, 10, 11, 17, 18, and near 6.24 MeV, 13, 14. There is also evidence of a cascade gamma ray of 2.76 MeV.

The spectrum of gamma rays from the NaI crystal is such that for the 2.76 MeV cascade gamma ray, the photo peak and the one annihilation loss peak would have been about equal in height above the background, whereas for the three higher gamma ray energies, the largest peak would have occurred at 1 MeV electron energy below the gamma ray energy. Hence interest was confined to electron energies of 2.26, 2.76, 3.54, 3.95, and 5.24 MeV.

The ground state of $^{28}\text{Si}$ has a J value of $0^+$; the 1.78 MeV level has a J value of $2^+$. Suppose the 4.54 level had a J value of $4^+$. Now the probability of a neutron exciting a certain state in the silicon nucleus is

\begin{equation}
P = \sum_{1,1'} \sum_{n,n'} G(E_n, E_n', l, l')(2l+1)T(l)T(l')
\end{equation}
where $l$ is the angular momentum of the incoming neutron, $l'$ is the angular momentum of the outgoing neutron, $T(l)$ is the transmission coefficient for an incoming neutron entering the nucleus with energy $E_n$ and angular momentum $l$, $T(l')$ is the transmission coefficient for an outgoing neutron leaving the nucleus with energy $E_n'$ and angular momentum $l'$. $C$ is a normalizing constant, and $N(E_n, E_n', l, l')$ is a factor depending upon the properties of the nucleus. It was assumed that $N$ stayed relatively constant. If this is true, the ratio of $P$ for the second excited state to $P$ for the first excited state would have been the same as the number of nuclei excited to the second state divided by the number of nuclei excited to the first state. The counter efficiency over the electron energy range from 1.78 to 5.24 MeV did not change these ratios significantly. Since each inelastically scattered neutron produced one gamma ray (two, of 2.76 and then 1.78 MeV, in the case of the cascade gamma ray), the ratio of the gamma ray count from the two states should have been essentially the same as the ratio of the excitation probabilities for the two states.

Since the spin of the neutron is $\frac{1}{2}$, the difference in $l$ and $l'$ necessary to excite the first level should be one, two, or three; for the second level, if $J = 4^+$, the differ-
ence should be three, four, or five. Parity considerations allow only values of \( l \) and \( l' \) which are both even or both odd. The important combinations of \( l \) and \( l' \) are listed in Table 3. Equation (4) was used to compute \( P \) for the first and second excited levels at energies of 5.43, 5.68, 6.40, and 6.75 MeV for the incident neutrons. The ratios of the probabilities of exciting the two states for these neutron energies were 12\%, 17\%, 25\%, and 32\%. If the \( J \) value of the second level were 1, 2, or 3, these percentages would have been larger. Hence one should expect to have seen some indication of higher levels in silicon when above their thresholds. The neutron energies of 5.43, 5.68, and 6.40 MeV were above the thresholds of the 4.54 and the 4.95 MeV levels of silicon; the 6.75 MeV neutron energy was above these levels and also above the 6.24 MeV level threshold.

In order to determine the actual amount of excitation of the various levels by the incident neutrons, a comparison between the peak at 1.78 MeV and the curves at 2.26, 2.76, 3.54, and 3.95 MeV electron energy was made at various incident neutron energies. Figures 4 through 7 are electron energy curves at these neutron energies; figure 8 illustrates the appearance of the 1.78 MeV gamma ray peak at 4.1 MeV. The 1.78 MeV gamma ray peak was omitted at the higher
energies because it retained the same general appearance.

With the exception of two small peaks observed at 6.40 MeV incident neutron energy, the electron energy curves were essentially straight near 2.76, 3.54, 3.95, and 5.24 MeV. The statistical error indicates the maximum size a peak could have at that position without being visible on the curve. Thus the ratio of the statistical error of the count (the square root of the total count) at the higher electron energies to the numerical peak minus valley value for the 1.78 MeV gamma ray peak, corrected to the same number of integrators, was calculated. Unfortunately, the 1.78 MeV peak was not observed at 5.43 MeV neutron energy; the value used for this energy was the same, except for the correction to the same number of integrators, as the value used for the 5.68 MeV incident neutron energy. These ratios obtained by this comparison indicate the amount of actual excitation of these higher levels for the given incident neutron energies with respect to the first level. If the 4.54 MeV gamma ray and the 2.76 MeV cascade gamma ray were of equal intensity, the observed peaks would be half the height that one peak or the other would have been if the other were not present. Then the expected height of the 3.54 and the 2.76 MeV electron energy peaks would have been,
according to equation (4), 6%, 8%, 13%, and 16% of the 1.78 MeV peak minus valley value for the neutron energy values of 5.43, 5.68, 6.40, and 6.75 MeV.

Figure 4 is the electron energy curve at 5.43 MeV incident neutron energy. When one compared the ratio of the statistical error to the peak minus valley value of the 1.78 MeV gamma ray, one found that the ratio was 20% of the expected height at the 2.76 MeV cascade energy. The ratio was less than 11% of the expected height at 3.54 MeV electron energy. At 3.95 MeV electron energy, the statistical error was less than 0.6% of the peak minus valley value for the 1.78 MeV gamma ray.

Figure 5 is the electron energy curve at 5.68 MeV incident neutron energy. When one compared the ratio of the statistical error to the peak minus valley value of the 1.78 MeV gamma ray, one found that the ratio was 14% of the expected height at the 2.76 MeV cascade energy. The ratio was less than 7% of the expected height of 3.54 MeV electron energy. At 3.95 MeV electron energy, the statistical error was less than 0.4% of the peak minus valley value for the 1.78 MeV gamma ray. It is true that there was a small peak at 2.24 MeV electron energy which was 20% as high as the 1.78 MeV peak. But this could definitely be ascribed to aluminum,
as Day pointed out, since both the target retainer and much of the associated equipment were made from aluminum. Besides, as shown in Figure 8, this peak also shows up clearly at a neutron energy of 4.1 MeV, which is below the second level in silicon.

Figure 6 is the electron energy curve at 6.40 MeV incident neutron energy. The same ratio at 2.76 MeV electron energy was less than 26% as large as expected. The statistical errors at 3.54 and 3.95 MeV were less than 3% and 2% of the peak minus valley value for the 1.78 MeV gamma ray. The small peaks observed at 3.54 and 3.95 MeV electron energy were 5% and 4% as large as the 1.78 MeV gamma ray peak minus valley value. Hence these observed peaks are real. But the expected value as calculated by equation (4) was at least 13% as large as the 1.78 MeV gamma ray peak. Thus the 4.54 MeV level was not populated so much as might have been expected.

Figure 7 is the electron energy curve at 6.75 MeV incident neutron energy, the highest incident neutron energy used. The ratios of the statistical errors at 3.95 and 5.24 MeV electron energy to the 1.78 MeV peak minus valley value were 7% and 2%, respectively. The part of the electron energy spectrum between 3.5 and 2.2 MeV was not observed at this
neutron energy.

It is seen that there is no evidence for higher states of silicon being excited by neutrons of 5.43 and 5.68 MeV. There is evidence that the 4.54 and 4.95 MeV states are excited at 6.40 MeV neutron energy, but the number of silicon nuclei excited to these levels is much smaller than the number excited to the 1.78 MeV level. At 6.75 MeV neutron energy, the statistics are poorer, so that peaks might not have been observed. The electron energy peak at 5.24 MeV which would be produced by a 6.24 MeV gamma ray might also be expected to be greater than 2% of the height of the 1.78 MeV gamma ray peak, but the J value of this level could easily be greater than 4, so that the effect from this level would be very small.

It seems that either there must be some selection rule to hinder excitation of the higher levels by neutrons, or the J values of the 4.54 and 4.95 MeV states are higher than four, or the nuclear effect N varies by a considerable amount.
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<th>ZURICH</th>
<th>LOS ALAMOS</th>
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## TABLE 2

**Energy Levels in Si$^{29}$**

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<td>(\Delta J = 2)</td>
<td>(\Delta J = 4)</td>
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<tr>
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<td>----------------</td>
</tr>
<tr>
<td><strong>First Excited State</strong></td>
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<tr>
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EXPERIMENTAL ARRANGEMENT FOR INELASTIC SCATTERING

FIGURE 2
Figure 4: 5.43 MeV Neutron Energy
FIGURE 5
5.68 MEV NEUTRON ENERGY

ELECTRON ENERGY, MEV

2.4

2.76 MEV

3.54 MEV

3.95 MEV

15,000

COUNTS

0
FIGURE 8  4.1 MEV NEUTRON ENERGY
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Acknowledgments

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