THE RICE INSTITUTE

MEASUREMENT OF THE ENERGIES OF NEUTRONS FROM THE REACTION $^{27}\text{Al}(d,n)\;^{28}\text{Si}$

by

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INTRODUCTION TO PROBLEM

Much data has been accumulated over the past few years on the energy levels of light nuclei in hope of establishing a basis for the formulation of a theory of nuclear structure, much in the same manner as the study of atomic spectra resulted in the formulation of quantum mechanics and a more or less complete understanding of atomic structure.

The measurement of excited states in nuclei are more difficult to perform and are generally less precise than the corresponding measurement of excited states of the atomic electron cloud. Atomic spectroscopy entails the measurement of electromagnetic radiation in the optical or near optical regions. Excited states of nuclei decay not only to the ground state by electromagnetic radiation in the gamma-ray region, but also by heavy particle emission to form a different nuclide. These nuclear states are often inherently wider than atomic states and the precise energies of the particles or electromagnetic radiation emitted are generally more difficult to measure. This is particularly true of reactions characterized by the emission of neutrons since neutron energies must be measured more indirectly than charged particle energies.

Several review articles have attempted to gather together the vast accumulation of data on light nuclei.\(^1,2,3\) The data if far from complete on some nuclei, but it is essential to have such articles when so much work is going on in a parti-
cular field. The excited states of Si$^{28}$, for instance, have been measured over the entire range excepting the range 9.16 to 11.807 Mev. There are a number of reasons for this exception.

R. A. Peck$^4$ examined the same Al$^{27}$(d,n) Si$^{28}$ reaction which the present author has utilized. Peck, however, detected the neutrons by means of hydrogeneous photographic plates which of course had high stopping power compared to air. His data extended as high as the 9.16 Mev level; here he could not measure any less energetic recoil protons because of the shortness of their track lengths and high angular straggling.

In a like manner the data taken by S. E. Hunt and W. M. Jones$^5$ on the Al$^{27}$(p,$\gamma$) Si$^{28}$ reaction were limited to high states because of the high Q value (11.590 Mev) of that reaction. The 11.807 Mev level corresponded to a proton energy of 226.3 1.5 Kev. Lower energy protons are very difficult to measure.

An analysis of the low energy neutron groups from the Al$^{27}$(d,n) Si$^{28}$ reaction which Peck studied would allow one to examine the entire region of unmeasured Si$^{28}$ excited states. This present thesis concerns an investigation where just such a substitution has been made.

Another means of investigating these levels is provided by the study of the gamma-radiation from the Si$^{28}$ left excited after the emission of the neutron has occurred. A disadvan-
tage of this method is that it is impossible to distinguish between a gamma transition to the ground state and a cascade to an intermediate level. Such an investigation has been carried out here at the Rice Institute by Dr. R. D. Bent and co-workers, and its results will be compared later to those of this article.
APPARATUS AND PROCEDURE

This investigation of neutrons from the reaction $^{27}\text{Al}(d,n)^{28}\text{Si}$ was carried out with a Wilson Cloud Chamber whose inside pressure was defined by pressure from a compressed air line regulated by a Groove pressure regulator and acting through a rubber membrane. The chamber was filled to a total pressure of one atmosphere with: natural gas which consisted of approximately 6% ethane and 94% methane and a vapor which consisted of 95% alcohol and 5% water. The binding of hydrogen in the methane is small compared to the neutron energies occurring in this experiment. The chamber used was 15.5 centimeters inside diameter and was illuminated by a rectangular, parallel light beam which was 3.5 centimeters high and 12.5 centimeters wide. The operation of the chamber was controlled by an electronic circuit which, by means of relays, controlled the operation and timing of the light, the expansion, the clearing field, the deuteron beam, and the camera.

Photographs were taken stereoscopically, by means of a mirror, giving one direct and one reflected image on one frame of film. The photographs were taken with a camera setting of $f = 3.6$. A 2000 watt lamp was used for lighting during an expansion. An expansion ratio of 1.14 was found to be best for distinct proton tracks when using the above mentioned chamber gas and vapor. Several enlarged photographs are shown at the end of this thesis.
The timing of operation was as follows: first the 2000 watt lamp was turned on, several seconds later the expansion occurred and the clearing field was shorted out, 0.1 seconds later the beam of deuterons was deflected onto the aluminum target by means of an electrostatic deflector, 0.1 seconds later the camera was opened, 0.2 seconds later the camera and the beam were turned off and the clearing field restored, 5 seconds later the expansion solenoid was reactivated and the pressure raised again for 50 seconds at which time the cycle began again.

Several targets of \( \text{Al}^{27} \) were prepared, by means of evaporation while in a vacuum system, of pure \( \text{Al}^{27} \) onto a tantalum blank 2.58 cm in diameter. There are no reactions of deuterons with tantalum at this energy which give neutrons. The two targets used were 100 Kev and 33 Kev thick respectively to a 3.00 Mev deuteron beam. The first set of data which is not reported in this thesis, was taken with the 100 Kev target and did not show any resolved resonances. This necessitated preparation of the 33 Kev target for better resolution. The cross section for the \((d,n)\) reaction was large enough at this particular energy so that the chamber would detect a sufficient number of neutrons and at the same time provide better resolution.

The Rice Institute 6.0 Mev Van de Graaff was used to obtain the needed deuteron beam and energy. The pulsed beam
current varied between 0.4 and 0.8 micro-amps, the only requirement being that the flux of neutrons at the chamber be sufficient to give 4 to 10 tracks per expansion. The beam was analyzed by means of a magnet whose field strength was determined very accurately by means of a Pound lithium resonance magnetometer.

The chamber was placed with its center 12.2 centimeters from the target. The glass was \( \frac{1}{2} \) of an inch in thickness between target and chamber gas.
ANALYSIS OF DATA

As has been said, the photographs were reprojected through the same system through which they were taken. Only those recoil proton tracks which were approximately in the same direction as the incident neutron (i.e., those protons which received nearly all of the neutron's energy) were counted. This method is the same previously used by Dr. T. W. Bonner in a number of investigations. In particular, see\textsuperscript{6,7}. The neutron energy may be computed by

\[ E_n \cos^2 \Theta = E_p \frac{(M_p + 1)^2}{4 M_p} \]

where

- \( E_n \) = initial energy of the neutron
- \( E_p \) = energy given to the proton
- \( \Theta \) = angle between their paths
- \( M_p \) = mass of proton

One can see that this reduces to

\[ E_n \cos^2 \Theta = E_p \]

Thus if \( \cos^2 \Theta \) is kept near a value of 1, then \( E_p \approx E_n \). If one includes tracks with \( \Theta \) up to 15° then this will introduce only a 7% error since \( \cos^2 \Theta = 0.93 \).

If one considers an imaginary recoil proton track beginning 2 cm from the center of the chamber on the side of the chamber nearest the target, then one can compute how far from
the center of the target this proton track would project to for a particular angle of recoil proton with incident neutron.

During reprojection a board was placed in the position of the Al₂₇ target relative to the optical system. On this board were marked concentric circles which represented positions to which will project recoil protons of angles 15, 14, 13, 10, and 5 degrees from incident neutron direction if they originate at the stated point. Of course those recoils which originated in the volume closer to the target (hereafter called volume #1) would actually have less energy than indicated by the circle to which they pointed. The reverse is true for those tracks originating in the volume behind the point mentioned (hereafter called volume #2).

Thus track length, volume of origination of recoil, and target area to which the track projected were all recorded for each track. The track lengths were recorded to the nearest 0.5 mm to induce accuracy of measurement and then grouped into 1.0 mm groups for purposes of presentation of data.

To be counted, a proton track had both to originate and end in the illuminated portion of the chamber volume. In the experiment run with the 100 Kev target those tracks which originated but did not end in the illuminated volume were also recorded. Forty percent of all tracks recorded fell into this last mentioned category. Since this ratio would not be changed
by using a thinner target and since this was all the useful information concerning these tracks, they were not recorded in the data taken with the 33 Kev Al$^{27}$ target.

In the run with the 33 Kev target 435 tracks were measured. Of these 435 there were 43 which were not plotted because some comment as to their reliability had been recorded along with their lengths. The remaining 392 tracks are plotted as a histogram with a broken line on graph I. The histogram which is drawn with a solid line on the same graph represents 278 tracks which remain after subtraction of 114 tracks which originated in volume #1 and projected to a point outside the 13° target circle.

The lower histogram shows much improvement over the total histogram since those proton recoils which each represented a smaller proportion of the true neutron energy have been removed. For that reason the 278 tracks are used in all other analysis of the data. This process of eliminating those protons which received less of the neutron energy could be extended down to the last inner circle except for the limited amount of data; a further elimination leaves too few tracks for reliability.

The ranges of the proton recoils were transformed to energies by means of a range energy curve calculated by the method of Livingston and Bethe\textsuperscript{5} using the stopping power for oxygen measured by Mano\textsuperscript{9} and utilizing the known composition
of the chamber gas and vapor under the conditions during the sensitivity of the chamber.

A smoothed-out curve is shown in graph III, using the data from the 278 better tracks and drawn so that sharp discontinuities at low neutron intensities are smoothed-out. The ranges have been converted to proton energy by means of the calculated range energy curve given on graph II.

An idealized shape for one resonance is shown on graph III. Its shape is due to target thickness and the inclusion in the data of protons representing down to 93% of the neutron energy. The low energy tail is also lengthened due to the detection of neutrons scattered from the walls of the chamber.

In all of these histograms, track lengths longer than 6.5 cm are not shown since they are too few and far between to be of any value in group determination. It was impossible to determine the true direction and length of tracks shorter than 0.5 cm and those less than 1.0 cm in length are unreliable.

Once the maximum energies of the proton groups are determined from graph I, these energies are then taken as the energies of the neutron groups. The Q values of the Al$^{27}(d,n)$ Si$^{28}$ reaction are then computed by:

$$Q = E_n (1 + \frac{M_n}{M_{Si}^2}) - E_d (1 - \frac{M_d}{M_{Si}^2}) - \frac{2}{M_{Si}^2}(E_d E_n M_d M_n)^{1/2} \omega_{2\theta}^2$$
where \( \cos \theta = 1 \) and

\[
E_n \text{ and } E_d = \text{energies of the neutron and deuteron respectively}
\]

\[
M_n, M_d, \text{ and } M_{Si} = \text{the masses of a neutron, a deuteron, and Silicon respectively}
\]

This relation is derived by a simple consideration of conservation of particle energy plus reaction energy and momentum in an inelastic collision.

The energies of the corresponding excited states in \( Si^{28} \) are then calculated by adding \(-Q\) and \( 9.364 \text{ Mev} \). \( 9.364 \text{ Mev} \) is the \( Q \) value for the neutrons to the ground state determined by the mass difference of the reactants and products. Thus for the \( 1.025 \text{ Mev} \) proton group we find a \( Q \) of \(-2.213\) which indicates an excited level of \( 11.58 \text{ Mev} \).

The question of relative intensities of the neutron groups is quite complicated. Corrections can be applied for the decrease in the neutron-proton scattering cross section for larger neutron energies. The probability of losing tracks because they leave the light at the far end of the chamber has been eliminated for track lengths shorter than 9.0 cm by considering only those tracks which originate in volume \#1. The probability for leaving the illuminated region in volume \#1 has been further reduced by including only tracks which project inside the \( 13^0 \) target circle. As before one cannot eliminate much further. A histogram representing these tracks has been plotted on graph \#4. A 10% energy spread entails a larger spread in proton track lengths for higher energy neutrons;
this means that resonances corresponding to higher energy neutrons will be broader and shorter than a resonance of identical intensity at low energies. Thus a simple comparison of peak heights will not suffice to determine the neutron intensities. A 10% energy spread for each group is shown and the number of tracks in that region gives an indication of the relative intensities when corrected for the n-p cross section. These corrected intensities are the relative intensities which are given in this paper.

There is still the possibility of longer tracks leaving the illuminated volume through the top or bottom. Since the target is close to the chamber and the illuminated volume is only 3.5 cm high, this probability would depend on the azimuthal angle as well as the angle of scattering between neutron and proton. Since the azimuthal angle was not recorded, this correction would be quite hard to apply and was not applied. Therefore the intensities for the longer tracks lengths are much smaller than they actually should be.
The proton groups and the corresponding excited states indicated by this study are shown in table I. Of these the 11.56 excited state is by far the most reliable. The others are of varying reliability excepting the two lowest excited states of 11.1 and 10.9 which are really only indications of levels in those general regions. While the relative intensities for the four highest levels should be reliable, the relative intensities for the two lowest should not be for the reasons stated in the previous section.

It is unfortunate that the resolution is not better, but it is not too surprising when one considers the effect of target thickness and the inclusion of proton recoils with down to 93% of the neutron energy. Indeed for the proton group of 1.03 Mev energy a 7% variance gives a 72 Kev variance of energy. The square root of the sums of the squares of the 72 Kev variance and the 33 Kev variance would be 80 Kev. Since the \((p-\gamma)\) data indicates levels of approximately 50 Kev apart for slightly higher levels, there is the possibility of levels of low intensity between the prominent groups indicated. Thus taking every contributing factor into consideration the resolution is fairly good under these conditions.

The 11.87 Mev level measured in this investigation matches one level measured by the \((p-\gamma)\) experiment. The energy range was adjusted so that there would be an overlap with the \((p-\gamma)\) experiment. This was done in order to be able to
check with the (p-γ) results in case there was an allowed transition by neutrons from the Al^{27}(d,n) Si^{28} reaction to an excited state of Si^{28} corresponding to levels indicated by the Al^{27}(p-γ) Si^{28} data. That there is no group corresponding to the 11.807 Mev level from the (p-γ) data is not bothersome since there is no requirement that the intensities to excited levels be the same for the two different reactions. However, there is some indication of an unresolved level in this region, but it was not deemed significant.

Here at the Rice Institute Dr. R. D. Bent, using a pair spectrometer, has detected γ's corresponding to a 10.83 Mev excited state in Si^{28} (private communication) by examination of the γ-rays from the excited *Si^{28} left after the Al^{27}(d,n) *Si^{28} reaction. This would roughly correspond to the state of 10.9 Mev measured in this investigation. This gives some assurance that the γ-s measured by Bent do correspond to a 10.83 Mev excited state and are not cascade -s to some intermediate excited state. It is unfortunate that our data does not overlap to a larger extent, but it is expected that this will be corrected by running this identical experiment over again with a gas of higher stopping power so that the longer tracks will not leave the chamber. Ethane is such a gas and will present no difficulty other than a slightly higher expansion ratio. This will definitely be done in the near future.
The neutron group intensities indicate a maximum intensity at 1.03 Mev for the compound Si^{29} nucleus when Al^{27} is bombarded with deuterons of 3.268 Mev. The intensity distribution with neutron energy is given by the relation first derived by Weisskopf.\textsuperscript{11}

\[ N dE = e^{-\frac{E}{T}} E dE \]

where \( N \) = number of neutrons per unit energy
\( E \) = neutron energy
\( T \) = nuclear temperature

This relation depends on the assumptions: a) the nuclear levels are close together and subject to statistical treatment, and b) the excitation energy is high.

In our case (b) is satisfied, but it is open to question whether (a) is satisfied.

Peck's investigation of Al^{27}(d,n) Si^{28} examined the high energy tail of the energy distribution and thus he could not determine the maximum intensity directly. Using Weisskopf's relation he was able to compute a nuclear temperature of \( T = 1.5 \) Mev which is the right order of magnitude for his data taken with a deuteron beam energy of 3.7 Mev.

The present experiment was run with a deuteron energy of 3.288 Mev. However, because of the high Q value, the total excitation will be approximately 12 Mev in both cases and 400 Kev should not make much difference within experimental accuracy.
In our case the maximum proton recoil intensity at 1.03 Mev indicates a nuclear temperature of approximately 1 Mev. However, since the intensities of the longer track lengths are imperfectly known, the true maximum neutron intensity may occur for higher neutron energies which seems to be in line with Peck's value of 1.5 Mev. Thus even if the concept of nuclear temperature has a significance in this reaction, all that can be said is that this data indicates a nuclear temperature which is probably somewhat larger than 1 Mev.
CONCLUSIONS AND RÉSUMÉ

The highest and lowest levels of $^8\text{Si}^{28}$ reported in this paper correspond to levels previously determined by other investigators. The method used shows promise in application to this reaction and will be applied to lower excited levels in the near future. The relative intensities are only roughly significant.

The energy determinations are inherently more accurate than the intensities. In particular, the four lowest neutron group energies are reliable while the two highest are rough values.
NUMBER OF RECOILS VS. RANGE

NUMBER OF RECOILS

PROTON RANGE IN CHAMBER GAS (CM.)

ARROWS INDICATE NEUTRON GROUPS
Range vs. Energy

Range in Chamber Gas (cm.)

Proton Energy (MEV)
INTENSITY DETERMINATION.

10% OF

NEUTRON ENERGY

NUMBER OF RECOILS

PROTON RANGE (CM.)
Table I

DATA FROM THIS INVESTIGATION OF Al$^{27}$(d,n) Si$^{28}$

<table>
<thead>
<tr>
<th>$E_n$ (Mev)</th>
<th>$Q$ (Mev)</th>
<th>Excited State (Mev)</th>
<th>Reliability</th>
<th>Relative Intensity (see text)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.700</td>
<td>-2.506</td>
<td>11.67</td>
<td>***</td>
<td>4.8</td>
</tr>
<tr>
<td>0.875</td>
<td>-2.349</td>
<td>11.71</td>
<td>***</td>
<td>5.8</td>
</tr>
<tr>
<td>1.025</td>
<td>-2.213</td>
<td>11.58</td>
<td>****</td>
<td>13.0</td>
</tr>
<tr>
<td>1.145</td>
<td>-2.067</td>
<td>11.43</td>
<td>**</td>
<td>6.0</td>
</tr>
<tr>
<td>1.575</td>
<td>-1.708</td>
<td>11.1</td>
<td>*</td>
<td>2.0</td>
</tr>
<tr>
<td>1.750</td>
<td>-1.545</td>
<td>10.9</td>
<td>*</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Subscript numbers for computation only

Energy determination

**** - most reliable
* - least reliable

DATA FROM Al$^{27}$(p,γ) Si$^{28}$

<table>
<thead>
<tr>
<th>$E_p$ (Kev)</th>
<th>Excited State (Mev)</th>
<th>Relative Intensities</th>
</tr>
</thead>
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<tr>
<td>226.3</td>
<td>11.807</td>
<td>0.005</td>
</tr>
<tr>
<td>294.1</td>
<td>11.873</td>
<td>0.015</td>
</tr>
<tr>
<td>325.6</td>
<td>11.904</td>
<td>0.080</td>
</tr>
<tr>
<td>407.7</td>
<td>11.980</td>
<td>0.30</td>
</tr>
<tr>
<td>438.5</td>
<td>12.012</td>
<td>0.05</td>
</tr>
<tr>
<td>504.0</td>
<td>12.076</td>
<td>2.0</td>
</tr>
</tbody>
</table>
100 Resonances in this Region

Al$^{27}$ + d - n

9.364

9.61

8.18

7.55

7.10

6.65

6.11

4.91

4.47

1.78

Si$^{28}$


Miscellaneous:

A good reference on cloud chamber techniques is Wilson, J. G., Principles of Cloud Chamber Technique (Cambridge, 1951).
ACKNOWLEDGMENTS

The author wishes to express his appreciation to Dr. T.W. Bonner for his suggestion of the problem and his continued interest during the investigation. I also wish to thank Dr. R. D. Bent for the communication of unpublished data. Thanks goes also to Mr. Van der Henst and the men of the Physics shop for their assistance.
EXEMPLARY PHOTOGAPHS

-neutrons enter from below

-direct image on left
a measurable track

showing a Carbon (?) disintegration
various tracks

a) late
b) measurable
c) originating outside illuminated volume

high neutron flux