# $^{40}Ar(n, \alpha)^{37}S$ Reaction at 14.4 MeV*

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A gridded ionization chamber was used to detect charged particles produced when $^{40}Ar$ was bombarded with 14.4-MeV neutrons. The energies of the $\alpha$ particles so produced yielded levels in $^{37}S$ of $0.59 \pm 0.10$, $1.39 \pm 0.09$, $2.20 \pm 0.05$, and $2.83 \pm 0.09$ MeV. The $Q$ value for the $^{40}Ar(n, \alpha)^{37}S$ reaction was determined to be $-2.41$ MeV. Cross sections calculated for the reaction to the ground state and the four excited states are $2.1 \pm 0.4$, $0.3 \pm 0.1$, $3.1 \pm 0.6$, $3.5 \pm 0.7$, and approximately 0.3 mb. The total cross section for the $^{40}Ar(n, \alpha)^{37}S$ reaction was determined to be $9.4 \pm 1.0$ mb. Comparisons between the results herein reported, other work, and theoretical predictions are made.

## 1. INTRODUCTION

The $^{40}Ar(n, \alpha)^{37}S$ reaction has been previously studied in order to determine the energy levels of the $^{37}S$ nucleus and cross sections to these levels. Bellamy and Flack[1] used a gridded ionization chamber filled to 30 atm with argon and identified five $\alpha$ groups corresponding to the ground state and four excited states in $^{37}S$. More recently Davis *et al.*[2] studied the reaction, also using a gridded ionization chamber, and reported energy levels in $^{37}S$ and calculated cross sections for the $^{40}Ar(n, \alpha)$ reactions to these levels for neutron energies between 1.2 and 9 MeV. The values of the cross sections reported by Bellamy and Flack at 14 MeV differ markedly from those predicted by extrapolation of Davis's results.

Several values of the total cross section for this reaction have been published.[3-7] The experimental methods used did not, in general, allow observation of discrete $\alpha$ groups.

## 2. EXPERIMENTAL METHOD

### A. Ionization Chamber

The chamber (Fig. 1) has a sensitive volume of approximately 2 liters. It consists of an outer case, a series of rings to which potential is applied to collimate the charged particles and electrons, a grid, and a collection anode. In operation, the anode and case are at ground potential while the first ring, A1, is at a negative potential, usually 3500 V. The potentials on the other rings are controlled by a resistor chain which goes to ground potential at the anode guard ring, A6. The grid G is also in the resistor chain and is at a potential equal to half that on A1. Since slight variations may occur over a period of time in the very large resistors that constitute the chain, the potential of the grid could be different from exactly half the potential of A1. In order to correct for such drift, G is maintained at the proper potential by a separate input from the same power supply that controls A1. The power supply, a Power Designs model No. HV-1545, has two outputs, one of which was modified to be at $\frac{1}{2}$ the potential of the other. The anode is ground with respect to A1, but is not earth grounded, so that it collects the charge on the electrons which reach its surface.

The ionization chamber was filled to 2 atm with 90% argon, 10% methane counting gas. Oxygen and carbon dioxide, which are the impurities most detrimental to the pulse-height resolution, were removed by passing the gas through molecular sieves maintained at liquid-nitrogen temperature.

Neutrons of approximately 14.4 MeV were obtained by the $D(t,n)$ reaction in a Technical Measurements Corporation Activatron III neutron generator.

The charge pulse generated in the ion chamber by the neutron-induced reactions was shaped by a Canberra model No. 1406 charge-sensitive preamplifier. The preamplifier output was further amplified by an ORTEC model No. 440 selectable active filter amplifier and an ORTEC model No. 408 biased amplifier. The pulses were then analyzed by a RIDL model No. 30-12B 400-channel analyzer and recorded by an IBM typewriter. The electronics were tested and calibrated with an ORTEC model No. 319 test-pulse generator.

The characteristics of the entire system were studied with an $^{241}Am$ source placed at position a in the chamber. The $\alpha$ spectrum obtained from the $^{241}Am$ is shown in Fig. 2. Under ideal conditions the resolution [full width at half maximum (FWHM)] obtained was better than 1% at 5.48 MeV. Under actual experimental conditions compromises were made which adversely affected the resolution: In the worst case the resolution was 4%.

There are a number of factors inherent in the experimental procedure which distort the pulse-height spectra and, therefore, influence the pulse-height resolution. These factors are: (i) electron attachment, (ii) columnar recombination, (iii) nuclear reactions occurring outside the sensitive volume, (iv) electronic noise, and (v) the wall effect. Factors (i), (ii), and (v) have been previously discussed.[8]

Nuclear reactions occur throughout the entire volume of the chamber; disintegrations which occur between the grid and the collecting plate give a continuous distribution in pulse size and contribute to the tail on the low-energy side of the peaks. It was not possible to reduce this effect. Pulses caused by charged particles entering the sensitive volume after being formed by a reaction outside this region were eliminated by the insertion of a shield, consisting of a nonconducting cylinder which delineated the sensitive volume. Charged particles produced in the region between the front chamber wall and A1 (Fig. 1) were prevented from entering the sensitive volume by a 0.005-cm aluminum foil fastened on the inner surface of A1.

The rf fields associated with the transformers that supply the high voltages to the neutron generator were the primary source of electronic noise. A noise cancellation circuit was constructed which canceled the noise in the signal cable at the amplifier inputs. There was no discernable electronic noise after elimination of rf interferences. Electronic distortion of a test signal was found to be negligible.

The wall effect is a loss of events from the full-energy peak due to charged particles which leave the sensitive volume of the chamber or strike the high-voltage electrodes. Pulses corresponding to such tracks represent a loss in counts for which correction must be made in computing the areas under the peaks. The effect increases markedly with increasing path lengths. The wall effect was studied as a function of particle range in the chamber in order to make appropriate correction. The wall effect, for path lengths short with respect to the size of the sensitive volume, is approximately

$$\rho = \frac{r_0}{2}\left(\frac{1}{R}+\frac{1}{h}\right),$$

where $r_0$ is the path length and $R$ and $h$ are the radius and height of the sensitive volume, respectively. For ranges greater than 1.5 cm, the wall effect was studied by observing the effect of changes in pressure on the spectra from 5.48-MeV $\alpha$ particles of $^{241}Am$ and the $\alpha$ particles from the reactions $^{40}Ar(n,\alpha_0)$ to the ground state of $^{37}S$. In the former case, the wall effect was studied as a function of pressure from 0.25 to 2.0 atm and in

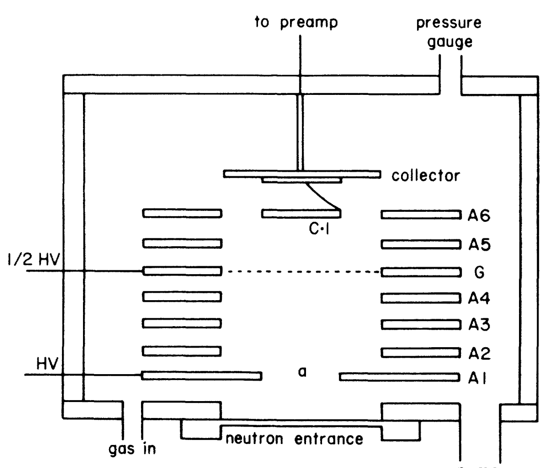


FIG. 1. Schematic diagram of gridded ionization chamber.

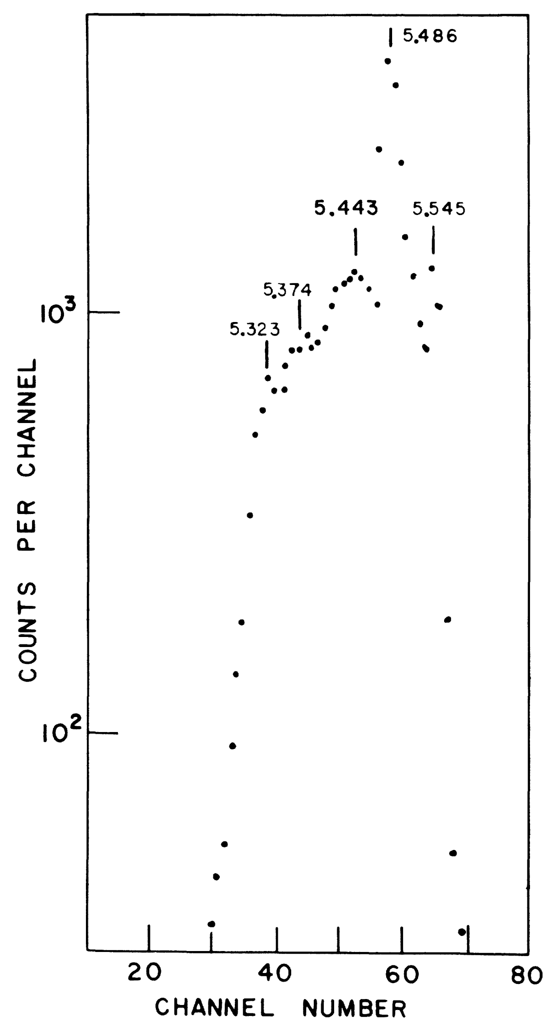


FIG. 2. Spectrum of $^{241}Am$.

the latter case from 1.0 to 5.0 atm. For the $^{40}Ar(n, \alpha_0)$ experiment the results were normalized with respect to neutron flux and total number of $^{40}Ar$ nuclei. The results are shown in Fig. 3. In order to calculate the true value of the intensity of a particular peak, the observed peak intensity is divided by the appropriate correction factor $(1 - \rho)$.

### B. Flux Determination and Energy Calibration

In order to determine cross sections it is necessary to determine the neutron flux incident upon the entire volume of the gaseous target (i.e., the sensitive volume of the chamber). Other investigators have used a calibrated $BF_3$ counter placed behind the gridded ionization chamber. The count rate of the $BF_3$ counter must be corrected for the difference in geometry of the counter and the chamber with respect to the neutron source. This procedure is complicated by the fact that the walls of the chamber attenuate and scatter the neutrons to some extent.

A calibration of the energy scale of the spectra is necessary for energy-level determinations. It would be advantageous to calibrate the spectrum of each experimental trial based on a minimum of two reference peaks of known energy and at least one secondary reference to check for linearity of the spectrum. If such references are not available assumptions will have to be made or the experimenter must perform a tedious and complicated electronic calibration of the pulse heights.

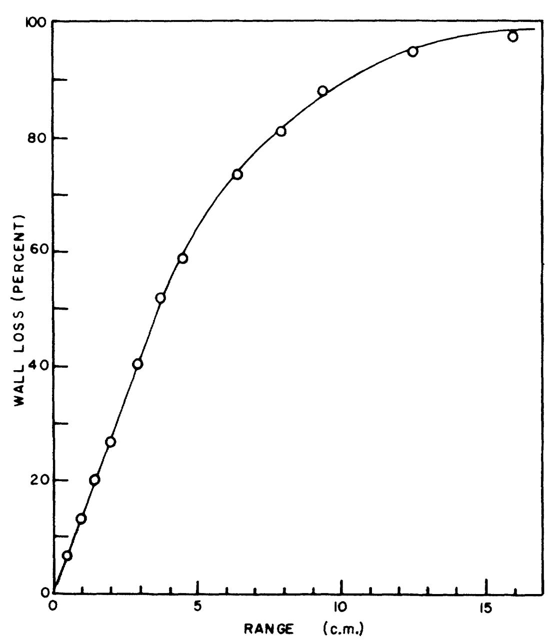


FIG. 3. Wall loss as function of particle range.

If the gas under neutron bombardment is a mixture, the parameter $W$, the energy to form one ion pair, must be determined experimentally.

The incorporation of internal flux monitors and energy standards into the target gas eliminates the difficulties described above and also greatly simplifies analysis of the data derived from such experiments. We have used the $^{12}C(n, \alpha_0)^9Be$ reaction as an internal flux monitor and energy standard in studies of $(n, \alpha)$ and $(n, p)$ reactions on various gases at neutron energies in the range 14.0 to 14.5 MeV.

### C. Determination of the $^{12}C(n, \alpha_0)^9Be$ Cross Section

Although values for the cross sections of the $^{12}C(n, \alpha_0)^9Be$ reaction in the energy range 14.0 to 14.5 MeV are known, an independent verification of these data was performed with our apparatus. In this case, the chamber was filled with methane.

The neutron flux was measured by determining the absolute counting rate of $^{18}F$ produced in Teflon disks via the reaction $^{19}F(n, 2n)^{18}F$. A 3-in. $\times$4-in. NaI(Tl) detector was used to detect the $\gamma$ radiation. The absolute counting rate was determined by comparison with a $^{22}Na$ source which had been calibrated by the $\gamma$-$\gamma$ coincidence method. The efficacy of Teflon disks for neutron flux monitors has been demonstrated by Priest, Burns, and Priest,[9] and Shiokawa *et al.*[10] A correlation was made between the neutron flux at the neutron en-

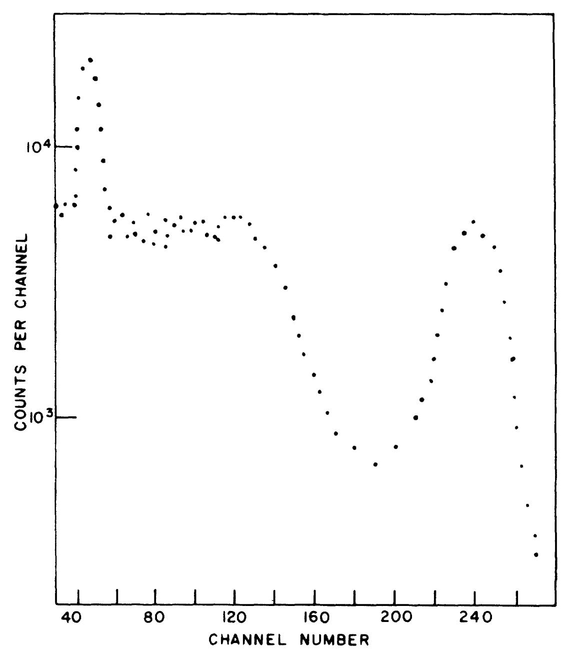


FIG. 4. $\alpha$-particle spectrum from bombardment of methane with 14-MeV neutrons.

TABLE I. Cross sections of $^{12}C(n, \alpha)$.

| Comparison of results | $E$ (MeV) | $\sigma$ (mb) |
|---|---|---|
| Brendle *et al.* (Ref. 11) | 13.9 | 79 ±20 |
| Graves and Davis (Ref. 12) | 14.1 | 80 ±20 |
| Al-Kital and Peck (Ref. 13) | 14.1 | 62 ±15 |
| Kopsch and Cierjacks (Ref. 14) | 14.1 | 72.7±6.8 [a] |
| Kitazawa and Yamamuro (Ref. 15) | 14.1 | 76 ±11 |
| Chatterjee and Sen (Ref. 16) | 14.5 | 69 ±13 |
| Brendle *et al.* (Ref. 11) | 15.6 | 77 ±20 |
| This work | 14.3 | 75 ±40 |

[a] The $\alpha_0$ transition is not well resolved; at large angles, $\alpha_0$ particles are lost.

trance and inside the chamber by making an irradiation with five disks at the neutron entrance and five disks at position a in the chamber (Fig. 1). It was found that the flux at the exterior position was 4.5±1 times greater than that at position a. Also, at position a the flux was distributed uniformly over the area covered by the Teflon disks, while in the exterior position there was as much as a 300% difference in flux over the various positions in the area tested. This was due to the proximity of the exterior foils to the target which led to great variations in the solid angle subtended by each foil.

The spectrum obtained when methane is bombarded with neutrons having a mean energy of 14.3 MeV is shown in Fig. 4. The pulse distribution in channels 40 to 65 correspond to the 5.48-MeV $\alpha$ particles from the $^{241}Am$ standard. The pulses in channels 210 to 275 represent the $\alpha$ particles emitted in the $^{12}C(n, \alpha)$ reaction to the ground state of $^{9}Be$. $\alpha$ particles to excited states in $^{9}Be$ are not resolved, although the end of the continuum at channel 150 may correspond to $\alpha$ transitions to the very broad state in $^{9}Be$ at 4.70 MeV. Resolution in this experiment was poor, about 16%.

The number of reactions, obtained by integration under the peak and correction for wall losses

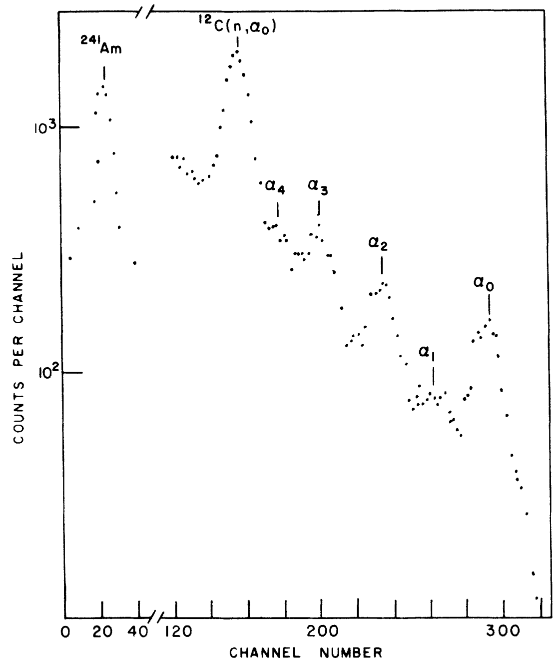


FIG. 5. Spectrum from bombardment of argon-methane mixture with 14-MeV neutrons.

(70%), and the neutron flux calculated from the activity of the Teflon monitors gave a cross section of 75±40 mb to the ground state of $^{9}Be$.

The value determined for the $^{12}C(n, \alpha_0)$ cross section exhibited the largest experimental error of all the cross sections determined in this work. It is, however, interesting to compare our results with other work to illustrate the validity of this technique and also to justify use of the $^{12}C(n, \alpha_0)$ reaction as an internal standard. Table I lists the values[11-16] of this cross section reported in the literature for neutron energies between 13.9 and 15.6 MeV.

Our result, despite its large uncertainty, agrees remarkedly well with other work. It is seen that, within experimental error, the cross section for the $^{12}C(n, \alpha_0)$ reaction is more or less constant over the range of neutron energies reported.

TABLE II. Energy levels in $^{37}S$ (MeV).

| This work [a] | Bellamy and Flack [a] | Davis *et al.* [a] | Azjenberg-Selove [b] |
|---|---|---|---|
| 0.59±0.10 | ... | 0.65±0.06 | 0.647±0.015 |
| 1.39±0.09 | 1.3±0.05 | 1.39±0.07 | 1.399±0.020 |
| 2.20±0.05 | 2.2±0.1 | 2.19±0.09 | 2.020±0.020 |
| 2.83±0.09 | 2.7±0.1 | 2.8 ±0.2 | 2.775±0.015 |
| ... | ... | ... | 2.978±0.015 |
| ... | ... | ... | 3.262±0.015 |
| ... | ... | ... | 3.337±0.015 |
| (3.50±0.20) | 3.5±0.2 | ... | 3.43 ±0.030 |

[a] Levels obtained from $^{40}Ar(n, \alpha)^{37}S$.

[b] Levels obtained from $^{37}Cl(t, {}^{3}He)^{37}S$.

Since the area under the peak can be related to the $^{12}C(n, \alpha_0)$ cross section with a reasonable degree of accuracy, it appears valid to use the reaction as an internal flux monitor. The internal standard affords a considerable reduction in experimental uncertainty due to the flux, since the $^{12}C(n, \alpha_0)$ cross section is well known and the counts under the peak in the reaction spectrum are due only to neutrons incident in the sensitive volume.

Energy calibration of each spectrum was accomplished via the 5.48-MeV $\alpha$ particle from the $^{241}$Am standard located at position a in the chamber (Fig. 1) and the $^{12}C(n, \alpha_0)$ peak for which the $Q$ value is well known. The linearity of the spectrum was confirmed by calculating the $Q$ value of the highest-energy peak in the spectrum which was attributed to $^{40}Ar(n, \alpha_0)$ and comparing with the theoretical $Q$ value for the reaction.

## 3. DATA AND RESULTS

A representative spectrum is shown in Fig. 5. The peak in channels 140 to 172, with a mean energy of 8.75 MeV, corresponds to the $^{12}C(n, \alpha)$ reaction from the 10% methane present. The resolution for this peak is better than 4%, a marked improvement over the resolution when methane was the sole gas in the chamber. On the basis of the energy reference points provided by the 5.48-MeV $\alpha$ from $^{241}$Am, at channel 23, and the $^{12}C(n, \alpha)$ reaction, the peak at channel 294 is calculated to have a mean energy of 12.04 MeV. This corresponds to a reaction having a $Q$ value of −2.41 MeV, which can only be due to the reaction $^{40}Ar(n, \alpha)$ to the ground state of $^{37}$S. This corresponds exactly to the $Q$ value calculated from the nuclidic masses. The remaining peaks can all be assigned to the $^{40}Ar(n, \alpha)$ reaction to four excited states in $^{37}$S. The evidence to support this assignment comes from experiments in which (1) the relative concentrations of methane to argon were changed in order to determine whether the peaks were due to $^{12}$C or $^{40}$Ar; and (2) the pressure of the P-10 gas was varied to observe resolution and wall-loss changes, since protons and $\alpha$ particles are affected to different extents. The energies of the peaks precluded deuteron or triton emission. Although the peaks appearing in channels 203, 236, and 294 are intense and easy to assign, the assignment of energies to the less-intense pulse distributions in channels 178 and 265 were made only after careful analysis of the individual trials for this experiment. Evidence for these weak transitions was persistent in every experiment and could be attributed to no other causes. Resolution of the individual prominent peaks was in all cases better than 4%.

TABLE III. 14.4-MeV cross sections of $^{40}$Ar relative to $^{12}C(n, \alpha_0)$ 76 ± 11 mb.

| Reaction | $\sigma$(mb) | Level in $^{37}$S (MeV) |
|---|---|---|
| $^{40}Ar(n, \alpha_0)$ | 2.1 ± 0.4 | Ground |
| $^{40}Ar(n, \alpha_1)$ | 0.3 ± 0.1 | 0.59 ± 0.10 |
| $^{40}Ar(n, \alpha_2)$ | 3.1 ± 0.6 | 1.39 ± 0.09 |
| $^{40}Ar(n, \alpha_3)$ | 3.5 ± 0.7 | 2.20 ± 0.05 |
| $^{40}Ar(n, \alpha_4)$ | $\lesssim$0.3 | 2.83 ± 0.09 |
| $^{40}Ar(n, \alpha_5)$ | $\lesssim$0.1 | 3.5 ± 0.2 |

The energies for the first four excited states determined from our data are shown in Table II. Indications of a peak corresponding to a level in $^{37}$S at 3.50 ± 0.20 MeV were also observed in several experimental trials. No peaks could be discerned in the spectra which corresponded to reactions of $^{36}$Ar or $^{38}$Ar. Similarly, reactions yielding protons, deuterons, or tritons were not observed.

The cross sections for the $^{40}Ar(n, \alpha)$ reactions were calculated relative to the $^{12}C(n, \alpha_0)$ cross section. Wall losses for the various peaks ranged from 61% for the $\alpha$ particles from the $^{12}C(n, \alpha_0)$

TABLE IV. Total cross sections for $^{40}Ar(n, \alpha)$.

| Authors | $E_n$ (MeV) | $\sigma$(mb) |
|---|---|---|
| Ranakumar, Kartunnen, and Fink (Ref. 3) | 14.4 | 10.5 ± 1.0 |
| Husain and Kuroda (Ref. 4) | 14.4 | 10 ± 1.5 |
| Mathur and Morgan (Ref. 5) | 14.1 | 13 ± 1.5 |
| | 14.1 | 2 [a] |
| | 14.5 | 3 [a] |
| Gray, Zander, and Ebrey (Ref. 6) | 14.5 | 24 ± 2 |
| Yu and Gardner (Ref. 7) | 14.1 | 31 ± 5 [b] |
| Gardner and Yu (Ref. 18) | 14.1 | 30.2 [c] |
| This work | 14.4 | 9.4 ± 1.0 |

[a] Theoretical prediction based on compound-nucleus theory and statistical model for decay of compound nucleus.
[b] Experimental value; error does not include uncertainty in reaction used as standard.
[c] Theoretical prediction semiempirical, based on statistical model.

reactions to 81% for the $\alpha$ particles from the $^{40}Ar(n, \alpha_0)$ reaction. The cross sections obtained are shown in Table III.

The total cross section for the $^{40}Ar(n, \alpha)^{37}S$ reaction can be estimated from the above to be; $\sigma \approx 9.4 \pm 1.0$ mb. Since no other peaks could be observed in the spectra it is unlikely that reactions to higher levels in $^{37}S$ contribute more than a negligible amount to the total cross section.

## 4. DISCUSSION

Energy levels in $^{37}S$ from the $^{40}Ar(n, \alpha)$ reaction have been reported by Bellamy and Flack[1] and Davis *et al.*[2] and are listed here in Table II. Both groups used apparatus similar to that used in our experiments but without benefit of recent advances in solid-state electronics. Bellamy and Flack used neutrons of energies between 14.1 and 14.8 MeV; Davis *et al.* studied the reactions in the range from 5.8 to 9.0 MeV.

Bellamy and Flack did not report the level in $^{37}S$ at 0.59 MeV. The low cross section for the $(n, \alpha)$ reaction at 14 MeV and the very high background exhibited in their spectra, may have obscured the peak. Davis *et al.* had no difficulty observing this peak, since at 9 MeV its cross section is about three times greater than its value at 14 MeV. On the other hand, Davis *et al.* did not report the 3.5-MeV level. Most likely this was due to a high concentration of $N_2$ impurity in the argon which led to a prominent recoil peak at the lower end of their spectrum: This recoil peak apparently obscured the 3.5-MeV level. Our data are apparently in excellent agreement with that of both groups of experimenters.

Recent experiments by Azjenberg-Selove and Igo[17] determined levels in $^{37}S$ via the $^{37}Cl(t, {}^3He)^{37}S$ reaction. Their results (see Table II) are in general agreement with the levels reported herein. Three levels which they report do not appear in any of the studies of the $^{40}Ar(n, \alpha)$ reactions. Their spectra show these three levels to be of very low intensity. The possibilities are that these levels are populated only very slightly, or not at all, in the $^{40}Ar(n, \alpha)$ reactions or the broad distribution we observed, but do not report, at $3.5 \pm 0.2$ MeV may include contributions from these three peaks.

The only previous data available for the 14-MeV neutron cross sections of $^{40}Ar(n, \alpha)$ reactions to various levels in $^{37}S$, are from the work of Bellamy and Flack. They report a cross section for the reaction to the ground state of $30 \pm 15$ $\mu$b which is almost 2 orders of magnitude less than the value of $2.1 \pm 0.4$ mb reported here. The great discrepancy may be due in part to the fact that they calculated neutron flux indirectly from the integrated deuteron flux incident on the tritium target. Also they did not discuss wall effects in their paper, and may not have made appropriate corrections.

Although they do not calculate other cross sections, Bellamy and Flack do give relative intensities of their peaks as 1.0 : 1.45 : 2.2 : 1.15 : 1 for the transitions to the ground and second through fourth excited states. This trend is in general agreement with our cross-section values of $2.1 \pm 0.4$, $3.1 \pm 0.6$, and $3.5 \pm 0.7$ mb which correspond to the first three peaks they observed (they do not report the 0.59-MeV level).

Table IV lists previously reported values[3-7, 18] of the $^{40}Ar(n, \alpha)$ total cross sections and two semiempirical predictions. Our value for this cross section is also included in the table.

Our experimental value for the total $^{40}Ar(n, \alpha)$ cross section is in good agreement with the most recent of the values listed in the table. These cross sections, reported by Ranakumar, Kartunnen, and Fink[3] and Husain and Kuroda,[4] were both determined by counting the induced radioactivity. Our result is in reasonable agreement with that of Mathur and Morgan, who used a scintillation counter to observe the prompt $\alpha$ particles emitted, and also used standard activation techniques on liquid-argon samples. The experimental values of Gray *et al.*, and Yu and Gardner are not consistent with the previously discussed results.

Our results do not confirm either of the theoretical predictions listed in Table IV. Indeed, all indications are that the reaction proceeds via a direct reaction which would minimize the significance of the predictions of Mathur and Morgan based on compound-nucleus theory. Although the experimental value reported by Gardner and Yu seem to confirm their own prediction based on a statistical model, both values, predicted and experimental, are not consistent with the other experimentally derived values.

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# Reactions of $^{20}$Ne with 14.3-MeV Neutrons*

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Energy levels in $^{17}$O and $^{20}$F have been observed in the $^{20}$Ne$(n,\alpha)$ and $^{20}$Ne$(n,p)$ reactions using a gridded ionization chamber. In the reaction $^{20}$Ne$(n,\alpha)^{17}$O, cross sections to the ground state and four excited states in $^{17}$O at 0.83, 3.18, 3.90, and 4.63 MeV were determined to be $6.6\pm2.5$, $1.0\pm0.4$, $1.5\pm0.4$, $2.0\pm0.4$, and $1.3\pm0.3$ mb, respectively. The total cross section for the $^{20}$Ne$(n,\alpha)$ reaction is $12.4\pm4$ mb. The $^{20}$Ne$(n,2\alpha)^{13}$C reaction was observed and the $Q$ value and cross section to the ground state of $^{13}$C were found to be $-7.00\pm0.02$ MeV and $41.8\pm8.1$ mb, respectively.

## INTRODUCTION

Naturally occurring neon consists of three stable isotopes, $^{20}$Ne, $^{21}$Ne, and $^{22}$Ne. Reactions with 14.3-MeV neutrons leading to the emission of protons, deuterons, tritons, and $\alpha$ particles are energetically possible with all three isotopes.

The reaction $^{20}$Ne$(n,\alpha)^{17}$O at 14 MeV, has previously been studied by McDicken and Jack,[1] and by Cevolani, DiCapariacco, and Petralia.[2] Both groups concluded that the reaction proceeded via a direct mechanism, although there is some doubt as to whether stripping or heavy-particle stripping is the primary mechanism. McDicken and Jack report cross sections but only to the ground state and first excited state in $^{17}$O. It was the purpose of this investigation to study neutron-induced reactions of $^{20}$Ne in greater detail than previously.

## EXPERIMENTAL PROCEDURE

The charged particles emitted from the neutron-induced reactions of neon were detected in a gridded ionization chamber. The ion chamber was filled with a mixture of 95% neon and 5% methane. The gases were purified by passing them through molecular sieves cooled to liquid-nitrogen temperature. The 14.3-MeV neutrons were produced via the $^3$H$(d,n)^4$He reaction in a TMC Activatron III neutron generator. The ion chamber, associated electronics, and experimental procedure have been described in detail in a previous paper.[3]

The neutron flux was measured utilizing the $^{12}$C$(n,\alpha_0)$ reaction as an internal flux monitor. The value of the cross section used for this reaction was $76\pm11$ mb.[4] This technique was also discussed in the previous paper.[3]

## RESULTS

A typical spectrum is reproduced in sections in Figs. 1 and 2. The results from one experimental trial to the next exhibited good reproducibility. The energies of the individual peaks were deter-