Neutrons from the He^3 Bombardment of O^{16} and Mg^{24}†

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A thin target of magnesium oxide enriched in Mg^{24} was bombarded by 5.52-Mev He^3 particles. The outgoing neutrons were measured by the method of proton recoils in photographic emulsions. The ground-state Q value of the $O^{16}(He^3,n)Ne^{18}$ reaction is determined in this experiment to be -3.19 ± 0.04 Mev. The Q value of the $Mg^{24}(He^3,n)Si^{26}$ ground-state reaction is 0.08 ± 0.08 Mev. The mass of Si^{26} is then 25.99232 ± 0.00007 amu (C^{12} standard). In addition, excited states of Si^{26} at 1.78 ± 0.06 and 2.79 ± 0.08 Mev have been observed. Angular distributions of these four neutron groups and of the $C^{12}(He^3,n)O^{14}$ ground-state group are also reported: in all but one case, the distributions are peaked in the forward direction.

I. INTRODUCTION

THIS investigation was undertaken primarily to study Si^{26} for which no direct evidence had heretofore been presented.[1] The only previous experiment dealing with Si^{26} was one involving the bombardment of Al^{27} by 23-Mev protons.[2] A 1.7-second half-life activity was attributed to Si^{26} formed in the reaction $Al^{27}(p,2n)Si^{26}$. A very straightforward way of studying Si^{26} is afforded by the $Mg^{24}(He^3,n)Si^{26}$ reaction for which an approximate Q value of about 0 was computed from knowledge of the energy of the first $T=1$ state of Al^{26}, 0.228 Mev[1]—assuming charge independence of nuclear forces. The highest He^3 energy available to us was used in order to study not only the ground state of Si^{26} but also its first few excited states, to compare these with the corresponding states in the mirror nucleus Mg^{26}, and in the $T_z=0$ nucleus, Al^{26}.

It turned out that the target contained oxygen and we were therefore also able to study the reaction $O^{16}(He^3,n)Ne^{18}$. Until recently very little information had been available[3] on Ne^{18}. Lately, however, two investigations of this reaction by the neutron threshold method have led to $Q_0=-3.206\pm0.013$ Mev (Dunning and Butler[4]) and $Q_0=-3.200\pm0.010$ Mev (Towle and Macefield[5]). The work by Dunning and Butler also indicated the possible existence of an excited state of Ne^{18} at 0.114 ± 0.015 Mev. This energy is anomalously low compared[3] to the energy of the first excited state of the mirror nucleus O^{18}, 1.982 Mev, or to the energy of the corresponding $T=1$ state in F^{18}.

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[1] P. M. Endt and C. M. Braams, Revs. Modern Phys. **29**, 683 (1957).
[2] H. Tyrén and P.-A. Tove, Phys. Rev. **96**, 773 (1954).
[3] F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. **11**, 1 (1959).
[4] K. L. Dunning and J. W. Butler, Bull Am. Phys. Soc. **4**, 444 (1959), and private communication.
[5] J. H. Towle and B. E. F. Macefield (private communication) quoted by D. A. Bromley and E. Almqvist, Atomic Energy of Canada Limited Report, Chalk River, September, 1959 (unpublished), and private communication to J. W. Butler.

II. EXPERIMENTAL PROCEDURES AND RESULTS

A. Exposure of the Plates

A 100% enriched Mg^{24} target, electromagnetically deposited[6] on 0.005-inch tantalum, was bombarded by 5.524 ± 0.010 Mev He^3 particles from the NRL Van de Graaff generator. The thickness of the target corresponded to an energy loss of approximately 25 kev for 5.5-Mev He^3 particles, and the average energy of the particles in the target was therefore 5.51 Mev. The emitted neutrons were detected by observing proton recoil tracks in Ilford *C*-2 nuclear emulsions, 400 microns thick, mounted at 10 angles (0° to 135°) to the incident He^3 beam. The plates were processed and scanned in a standard manner.[7] The total exposure was 10 200 microcoulombs (uncertainty approximately 0.5%). A shorter background run was also carried out with plates exposed to neutrons from He^3 bombardment of the target backing, and from the room background.

B. Data

A total of approximately 1500 tracks was measured on the 0°, 15°, 30°, 45°, 90°, and 135° plates. It would of course have been desirable to have more extensive data, but the extremely low track density in the plates placed the above limit on the measurements. Approximately 1.3×10^5 fields of view of the microscope were examined to obtain the results presented here. Figures 1–4 show the data at 0°, 15°, 45°, and 135°. Besides neutron groups from the $Mg^{24}(He^3,n)Si^{26}$ reaction which may be identified from the E_x (excitation energy) scale, groups due to two other reactions were identified: $O^{16}(He^3,n)Ne^{18}$ and $C^{12}(He^3,n)O^{14}$. These are labelled on the figures by the symbols O^{16} and C^{12}. The first of these groups was presumably due to the target being mag-

[6] The target was supplied by the Atomic Energy Research Establishment, Harwell, England. We are extremely grateful to Mr. R. W. McIlroy for his attention to the preparation of the target.
[7] A. Rubin, F. Ajzenberg-Selove, and H. Mark, Phys. Rev. **104**, 727 (1956).

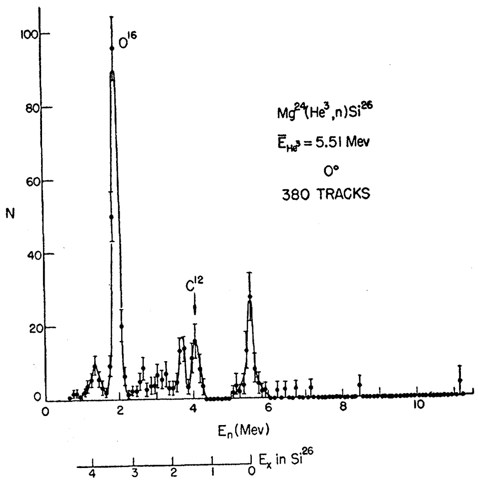

FIG. 1. Data at 0° (in the laboratory system) and at $\bar{E}(He^3)=5.51$ Mev. N is the corrected number of neutrons per 100-kev interval. E_n is the neutron energy. E_x is the excitation energy in Si^{26}. The groups marked O^{16} and C^{12} are due to the reactions $O^{16}(He^3,n)Ne^{18}(0)$ and $C^{12}(He^3,n)O^{14}(0)$.

nesium oxide, and the second is probably the combined effect of several factors. Some tracks from the C^{12} reaction also appeared on the background plates.

The background neutrons accounted for approximately 2 to 15% of the tracks, depending on the angle. At all angles the energies of almost all the background tracks were in the range 1.0 to 1.5 Mev. While one might expect to observe neutron groups corresponding to levels with $E_x \sim 3.8$ to 4.2 Mev in Si^{26} (because of the existence of such mirror levels in Mg^{26}), it should be pointed out that no evidence for such levels has been found in this experiment. The groups with $E_n \sim 1.3$ Mev (0°), 1.5 Mev (15°), 1.0 Mev and 1.3 Mev (45°) also occur with comparable intensities on the background plates. It is not excluded, of course, that weak groups due to Si^{26*} (3.8 to 4.2 Mev) could be present, but they have not been observed. In addition the group at

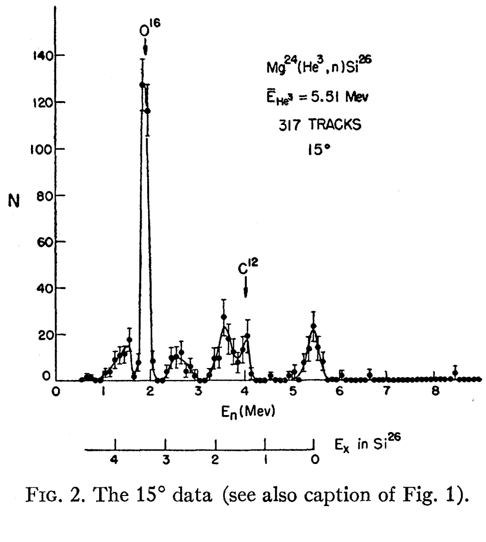

FIG. 2. The 15° data (see also caption of Fig. 1).

$E_n \sim 1.3$ Mev at 135° (which would, if due to Si^{26*}, correspond to an anomalous level at ~3.3 Mev) is reproduced in intensity on the background plate.

The possibility of impurities other than O^{16} and C^{12} in the target was considered. The ground state Q values of the (He^3,n) reaction on O^{18}, F^{19}, Mg^{25}, and Mg^{26} are all extremely exoergic, with values ranging from 6 to over 13 Mev. The contribution of neutrons from these reactions is negligible. One other reaction was considered: $N^{14}(He^3,n)F^{16}$ with $Q_0=-1.18$ Mev. In the forward direction, neutrons from this reaction could not be distinguished from the ground-state neutrons from the $C^{12}(He^3,n)O^{14}$ reaction ($Q_0=-1.15$ Mev). At 90° and 135°, the neutrons from the N^{14} reaction have energies 140 kev and 190 kev greater than the C^{12} neutrons. It is on the basis of the 90° results that we assign the groups to the C^{12} reaction. In addition it is not possible to assign the groups corresponding to the

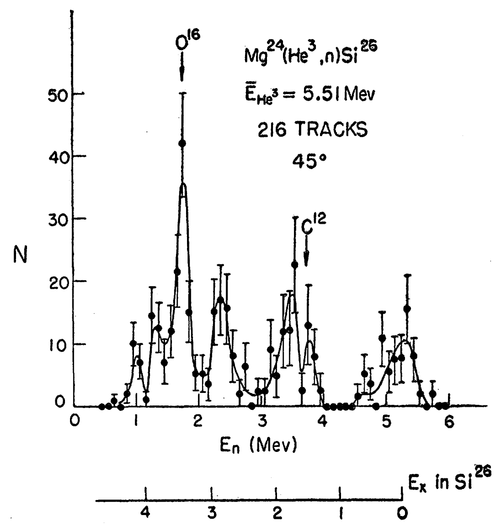

FIG. 3. The 45° data (see also caption of Fig. 1).

1.78-Mev state of Si^{26} (which will be discussed in Sec. E) to the several excited states of F^{16} which, by analogy with its mirror nucleus N^{16}, should occur within $E_x \sim 0.5$ Mev: The "1.78-Mev" groups vary properly in energy with angle to belong to the $Mg^{24}(He^3,n)Si^{26}$ reaction.

The data therefore indicate the formation of three states in Si^{26}, and the ground states of O^{14} and Ne^{18}.

C. Ne^{18} Results

The ground-state Q value of the $O^{16}(He^3,n)Ne^{18}$ reaction is found from these data to be -3.19 ± 0.04 Mev (rms deviation ±0.01 Mev). This result is in excellent agreement with the Q values reported earlier.[4,5] No evidence is found for the existence of an excited state of Ne^{18} at 114 kev.[4] In fact, the Q_0 value obtained in this experiment, and the narrow widths of the corresponding neutron groups argue strongly against the existence of such a state. While it could not have been resolved, such a state would have contributed to the widths of the groups and would have resulted in an appreciable energy shift, unless anomalously low intensities of neutrons at all angles were involved.

Based on the new Mattauch-Wapstra masses,[8] the atomic mass defect of Ne^{18}, $M-A$, is then 5.31 ± 0.04 Mev (based on the C^{12} standard) and 10.64 ± 0.04 Mev (based on the O^{16} standard). The corresponding masses are 18.00570 ± 0.00004 amu (C^{12} standard) and 18.01143 ± 0.00004 amu (O^{16} standard).

The angular distribution in the center-of-mass system of the $O^{16}(He^3,n)Ne^{18}(0)$ reaction at $\bar{E}_{He^3}=5.51$ Mev is shown on Fig. 5. The 90° (lab) data point is not weighed in the drawing of the distribution because it included background neutrons which are estimated to account for half the intensity of the neutron group at that angle.

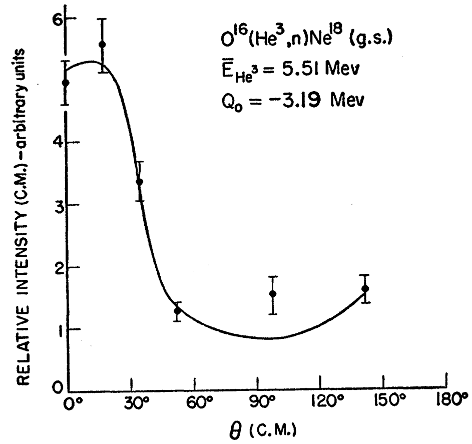

FIG. 5. The angular distribution of the groung-state neutrons from the $O^{16}(He^3,n)Ne^{18}$ reaction in the center-of-mass system. The intensity units are arbitrary but are the same in Figs. 5–8.

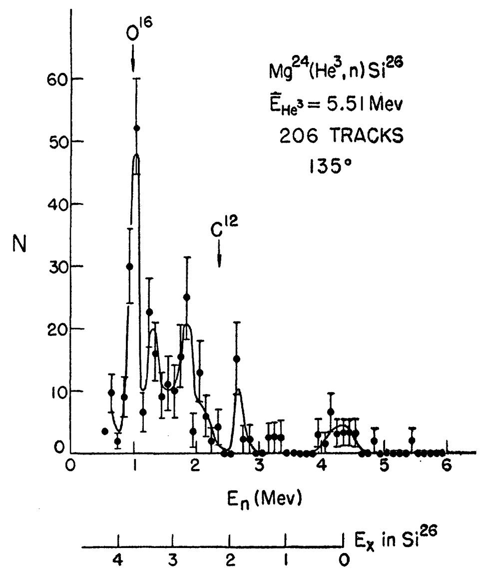

FIG. 4. The 135° data (see also caption of Fig. 1).

A chemical analysis of the target shows[9] that the amount of oxygen present in the target was (47 ± 2) $\mu g/cm^2$. Using this determination, the differential cross section at 0° for the $O^{16}(He^3,n)Ne^{18}(0)$ reaction is calculated to be 1.6 ± 0.3 mb/sr. The cross-section value takes into account attenuation of the neutrons in the emulsion.

D. O^{14} Result

The $C^{12}(He^3,n)O^{14}(0)$ neutron groups appeared where calculated from the known Q value of the reaction. The angular distribution of these neutrons is shown in Fig. 6. The 90° (lab) data point is missing because at that angle the neutrons from $O^{14}(0)$ and $Si^{26}(1.78)$ could not be resolved. Angular distributions of neutrons from the C^{12} reaction have previously been determined at $E(He^3)=1.89$, 2.16, 2.40, and 2.51 Mev.[10]

E. Si^{26} Results

The ground-state Q value of the $Mg^{24}(He^3,n)Si^{26}$ reaction is determined to be 0.08 ± 0.08 Mev. This leads to $(M-A)=-7.15\pm0.08$ Mev (based on the C^{12} standard[8]) and 0.55 ± 0.08 Mev (O^{16} standard). The mass of Si^{26} is 25.99232 ± 0.00007 amu (C^{12} standard) or 26.00051 ± 0.00007 amu (O^{16} standard). This determines the mass difference $Si^{26}-Al^{26}$ to be 5.05 ± 0.08 Mev. The Q values of the neutron groups to the first two excited states of Si^{26} are measured to be -1.70 and -2.71 Mev: $E_x=1.78\pm0.06$ and 2.79 ± 0.08 Mev.

The angular distribution of the neutrons to the ground

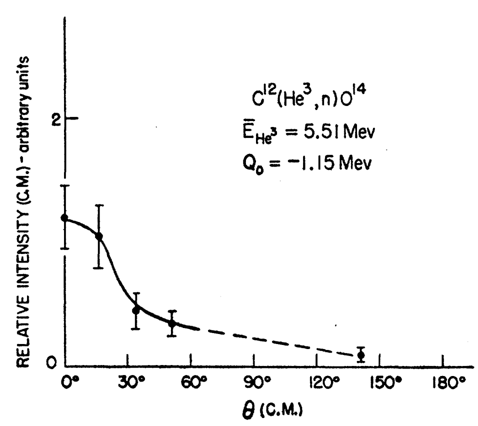

FIG. 6. The angular distribution of the ground-state neutrons from the $C^{12}(He^3,n)O^{14}$ reaction (see also caption of Fig. 5).

[8] F. Everling, L. A. König, J. H. E. Mattauch, and A. H. Wapstra, Nuclear Phys. **15**, 342 (1960).

[9] We are very grateful to D. R. Gates, G. A. Picklo, and D. I. Walter of the NRL Metallurgy Division for performing the quantitative analysis of the target.

[10] D. A. Bromley, E. Almqvist, H. E. Gove, A. E. Litherland, E. B. Paul, and A. J. Ferguson, Phys. Rev. **105**, 957 (1957).

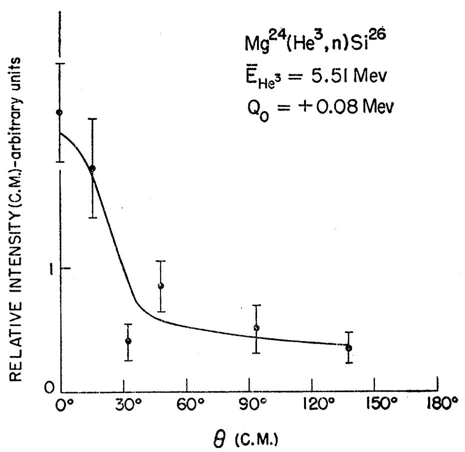

FIG. 7. The angular distribution of the ground-state neutrons from the $Mg^{24}(He^3,n)Si^{26}$ reaction (see also caption of Fig. 5).

and first[11] excited states of Si^{26} are peaked in the forward direction (see Figs. 7 and 8). The distribution of the neutrons to the second excited state is isotropic within the rather poor statistics. The very close similarity of the shapes of the angular distributions for $O^{16}(He^3,n)Ne^{18}$, $C^{12}(He^3,n)O^{14}$, and $Mg^{24}(He^3,n)Si^{26}(0)$ should be pointed out. All three reactions involve 0^+ target nuclei and 0^+ residual states, since all these are even-even nuclei. The angular distribution to the *first* 2^+ state in Si^{26} (1.78 Mev) is also similar, but the distribution to the second 2^+ state (2.79 Mev) is not.[12]

The target analysis[9] shows that the weight of Mg^{24} was (20±2) μg/cm². The differential cross section at 0° for the $Mg^{24}(He^3,n)Si^{26}(0)$ reaction is then 2.0±0.5 mb/sr.

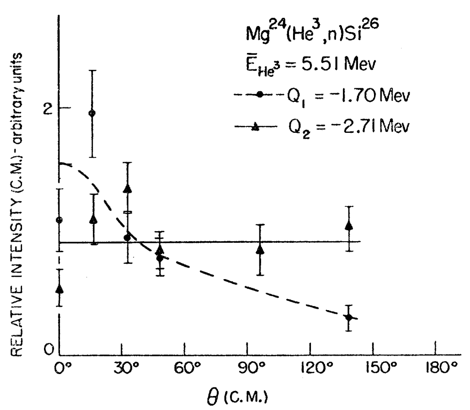

FIG. 8. The angular distributions of the neutrons to the 1.78-Mev and 2.79-Mev excited states of Si^{26} (see also caption of Fig. 5).

[11] The 30° (lab) data point in Fig. 8 for the Q_1 group should probably be somewhat lower because of some contribution of background neutrons. The 90° point is missing for the reason discussed in Sec. D.

[12] The J^π assignments for the Si^{26} states are deduced on the basis of charge symmetry from the known information[1] on Mg^{26}.

F. General Results

The most important result of this work is the determination of the mass of Si^{26} and the location of two of its excited states. The relevance of this work to the $A=26$ isobaric triad is shown in Fig. 9. The energies of the ground states of Mg^{26} and Si^{26} have been arbitrarily adjusted to the energy of the first $T=1$ state in Al^{26}. If instead of this arbitrary adjustment, the isobaric mass differences are calculated on a simple model, the following results are found. Let us take $(Al^{26}-Mg^{26})$ =4.015 Mev[8] and $(Si^{26}-Al^{26})=5.05$ Mev. The isobaric shifts (Coulomb energy difference minus the $n-H^1$ mass difference) for these two pairs of isobars are, respectively, 4.05 and 4.46 Mev (based on the model of a

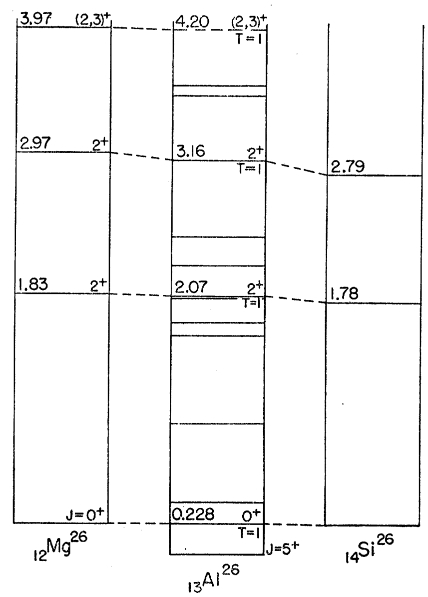

FIG. 9. The $A=26$ isobaric triad. The levels whose energies are indicated are believed to be $T=1$ states: the Mg^{26} and Al^{26} results are summarized in P. M. Endt and C. M. Braams, Revs. Modern Phys. **29**, 683 (1957); the Si^{26} results are those presented in this paper. The energies of the ground states of Mg^{26} and Si^{26} have been arbitrarily adjusted to the energy of the first $T=1$ state in Al^{26} (see the text for further details).

uniformly charged nucleus). These shifts must be subtracted from the above mass differences yielding the following isobaric energy differences for the ground states: $(Mg^{26}-Al^{26})=+0.03$ Mev and $(Si^{26}-Al^{26})$ $=+0.59$ Mev. These two numbers may be compared with the energy of the first $T=1$ state in Al^{26}, 0.228 Mev. Since the Coulomb correlation made above is crude, it is not unreasonable to adjust the energies of the first $T=1$ states artificially. The energies of the second $T=1$ states in the triad are then in good agreement: 1.83 Mev (Mg^{26}), 2.07−0.23=1.84 Mev (Al^{26}), 1.78 Mev (Si^{26}), as are those of the third set of analogous $T=1$ states: 2.97 Mev (Mg^{26}), 3.16−0.23=2.93 Mev (Al^{26}), 2.79 Mev (Si^{26}). These energy differences are based on the artificial adjustments of the first $T=1$ states. All the states shown in Fig. 9 are bound: in Mg^{26}, the lowest binding energy is that of an α particle ($E_b=10.62$ Mev); in Al^{26}, that of a proton ($E_b=6.30$ Mev); in Si^{26}, the lowest binding energy is that of a proton also ($E_b=5.51$ Mev).

Si^{26} is undoubtedly a positron emitter, presumably primarily to the $T=1$, $J=0^+$ state of Al^{26} at 0.228 Mev. The ground state of Si^{26} is 0^+ (even-even nucleus) and the $0^+\rightarrow 5^+$, $\Delta T=1$, transition to the ground state of Al^{26} would be highly forbidden. The maximum energy of the positrons involved in the $0^+\rightarrow 0^+(\Delta T=0)$ decay would be 3.80 Mev. Assuming a log ft value of ~ 3, typical[13] of such transitions, the lifetime of the ground state of Si^{26} should be of the order of magnitude of 1 sec. Thus, Tyrén and Tove[2] probably did indeed observe the decay of Si^{26}.

[13] J. B. Gerhart, Phys. Rev. **109**, 897 (1958).

There is very little experimental information on the angular distributions of neutrons emitted in (He^3,n) reactions with the exception of the work presented in this paper, the investigation of $C^{12}(He^3,n)O^{14}$ by Bromley *et al.*[9] and that of $B^{10}(He^3,n)N^{12}$ by Ajzenberg-Selove *et al.*[14] There is considerably more information on (He^3,p) distributions which also involve two-nucleon transfer. A satisfactory means of theoretically analyzing (He^3,n) distributions is not available at this time.[5]

ACKNOWLEDGMENT

We are much indebted to Professor Aaron Lemonick and to Dr. R. O. Bondelid for their help in the exposure of the plates.

[14] F. Ajzenberg-Selove, M. L. Bullock, and E. Almqvist, Phys. Rev. **108**, 1284 (1957).

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Spontaneous Fission Yields of Cf^{252}†

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A radiochemical investigation has been made of the fission yield curve for the spontaneous fission of Cf^{252}. One source of 1×10^6, another of 2×10^7, and a third of 7×10^7 fissions per minute were used to obtain the data. Thirty-six radioactive nuclides between mass numbers 77 and 166 were separated, identified, and their fission yields calculated. Upper limits were set for nine other nuclides. The fission yield curve has maxima of 6.05% at masses 107 and 141, with a "full width at $\frac{1}{10}$ maximum" of each peak of approximately 27 mass units. There is a very narrow "trough" with a minimum value of $\leq 8\times10^{-3}\%$ at mass number 124. In addition, while the curve as a whole is symmetrical about mass 124, each peak is not symmetrical about its own maximum, being significantly spread toward the most asymmetric fission modes. A small fine-structure peak was observed at mass 113. No evidence was seen of activities that could be ascribed to ternary fission events, upper limits of $10^{-4}\%$ fission yield being set for individual nuclides between mass numbers 28 and 72.

INTRODUCTION

SEVERAL investigators[1,2] have reported radiochemical fission yields for the products of the spontaneous fission of Cf^{252}. Due to the scarcity of Cf^{252} at the time those experiments were performed, however, the investigations were limited to the most easily measured peak elements. When a source of approximately 1×10^6 fissions per minute became available several years ago,[3] it was decided that a more thorough investigation of the Cf^{252} spontaneous-fission yield curve would be profitable. After several experiments with this source it became apparent that nuclides with fission yields below 0.1% could not be determined with the desired accuracy. Subsequent availability of sources of approximately 2×10^7 and 7×10^7 fissions per minute made measurement of the entire fission yield curve feasible.

PROCEDURE

In order to eliminate the problem of handling fairly large amounts of alpha and neutron activity in solution and, more importantly, to prevent loss of the extremely valuable Cf^{252} in chemical manipulations, a recoil technique was used to collect the fission fragments. A schematic diagram of the experimental arrangement is shown in Fig. 1. An essentially weightless source was prepared by electroplating purified Cf^{252} in a small area on a 0.001-inch thick platinum disk which was subsequently flamed at red heat. Fission fragments were collected on 0.001-inch aluminum foils which were suspended $\frac{1}{8}$ inch above the Cf^{252} source by means of a brass ring. Range studies indicated that with this

† This work was performed under the auspices of the U. S. Atomic Energy Commission.
[1] L. E. Glendenin and E. P. Steinberg, J. Inorg. Nuclear Chem. **1**, 45 (1955).
[2] J. G. Cuninghame, J. Inorg. Nuclear Chem. **6**, 181 (1948).
[3] The author wishes to express his sincere appreciation to Dr. Stanley Thompson and the Heavy Elements Group in Berkeley or preparing the Cf^{252} used in these experiments.