Reactions $N^{14}(d,n)O^{15}$(g.s.) and $N^{14}(d,n)O^{15*}$(6.79 and 6.86 Mev)*

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The angular distribution of neutrons from the reaction $N^{14}(d,n)O^{15}$ (g.s.) has been measured at 8 bombarding energies between 1.35 and 2.8 Mev. The same measurements have been made on the neutron groups (unresolved) from the reactions $N^{14}(d,n)O^{15*}$ (6.79 Mev) and $N^{14}(d,n)O^{15*}$ (6.86 Mev) at bombarding energies of 2.55 and 2.7 Mev. Direct-interaction mechanisms are thought to be responsible for most of the observed yields although resonance-like effects are also seen. Neutron yields at forward angles show approximate Butler stripping behavior at all energies in addition to other unexplained processes. The observed yields at large angles can be partially explained by the exchange stripping reaction for the high-Q reaction but can not be explained on this basis for the low-Q reaction.

INTRODUCTION

IT has been known for some time that (d,n) and (d,p) reactions are particularly easy to understand[1] and more recently it has been demonstrated that the primary mechanism for these processes is well explained by the theoretical treatment of Butler and others.[2]

Best agreement between theory and experiment is observed at incident deuteron energies in excess of the Coulomb barrier and at center-of-mass angles for the outgoing light particle which are less than 90°. The yields of the angular distributions at angles in excess of 90° compared with yields at forward angles are universally larger than predicted by theory[3] and, in addition, it has been known for some time that this disagreement is more severe at lower incident deuteron energies.

It has recently been postulated that the Butler type of stripping reaction should be favored, even at low deuteron energies, by reactions where the Q value is low.[4] We therefore have undertaken this investigation with the intention to probe the behavior of these reactions as a function of the three variables, deuteron energy, outgoing particle angle, and reaction Q value with equal emphasis on forward and backward angles.

The reaction $N^{14}(d,n)O^{15}$ has been chosen for this purpose. The high Q-value measurements are those of the neutrons from the O^{15} ground-state channels, the low Q-value measurements employ the neutrons from the channels leading to O^{15} in its 6.79- and 6.86-Mev states. The measurements comprise 8 values of bombarding energy for the high-Q reaction and two values of bombarding energy for the low-Q reaction. At each energy relative yields were measured at about 15 angles from 0° through 160°.

MEASUREMENTS

N^{14} targets were prepared by evaporating 0.6 milligram of adenine[5] onto a clean tantalum blank. Efforts to prepare nitrogen targets by nitriding tantalum metal were unsuccessful. The targets displayed low yield and the observed neutron groups were excessively broad. It was inferred that the tantalum nitride so formed was distributed throughout the target rather than as a layer on the surface. Evaporated melamine, $N_3C_3(NH_2)_3$, produced satisfactory targets but proved to be unstable under bombardment. After a number of runs during which progressive deterioration of the melamine target was observed the adenine target was installed and found to be more satisfactory in this respect. The data previously taken with melamine targets was repeated with adenine targets and found to agree within 10%. The data given herein is that obtained with adenine targets.

The electronics and all other aspects of these measure-

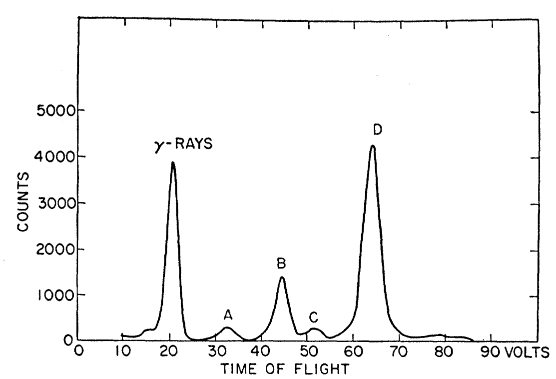

FIG. 1. Time-of-flight spectrum obtained at a bombarding energy of 2.8 Mev. Time increases from left to right, time zero is inferred from the position of the gamma-ray peak.

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[1] J. R. Oppenheimer, Phys. Rev. 47, 845 (1935); J. R. Oppenheimer and M. Phillips, Phys. Rev. 48, 500 (1935).

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[5] Pure adenine $C_5H_3N_4 \cdot NH_2$ was obtained for the purpose from K&K Laboratories Incorporated, 29–46 Northern Blvd., Long Island City, New York.

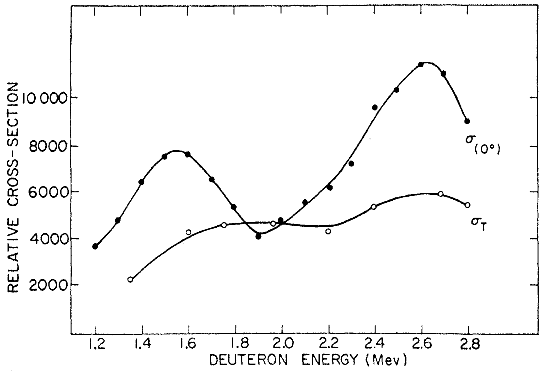

FIG. 2. Total cross section and O^0 yield curves of the reaction $N^{14}(d,n)O^{15}$ (g.s.) as a function of deuteron bombarding energy.

ments are the same as those employed in the measurement[6] of $C^{12}(d,n)N^{13}$.

Figure 1 shows a typical time-of-flight spectrum of the neutron groups obtained. These measurements were made at a bombarding energy of 2.8 Mev and the neutrons were observed at zero degrees. The peak A corresponds to neutrons produced in the formation of O^{15} in its ground state. Peak B is a mixture of $C^{12}(d,n)N^{13}$ and $N^{14}(d,n)O^{15*}$ (5.20 Mev) and $N^{14}(d,n)O^{15*}$ (5.25 Mev). Peak C is primarily $N^{14}(d,n)O^{15*}$ (6.15-Mev neutrons). The last peak D corresponds to the neutrons produced in the formation of O^{15} in its 6.79- and 6.86-Mev states.

RESULTS: $N^{14}(d,n)O^{15}$(g.s.)

Figure 2 shows the O^0 excitation function and the total cross section in arbitrary units. The agreement between the zero-degree data and that of other investigators is within the statistical error quoted by the other authors. Errors in this experiment are more difficult to evaluate. Each point represents more than 1000 detected neutrons. The data were collected and evaluated in a manner similar to that described in reference 6, except that the formula for the neutron detection efficiency of the counter had to be modified to take into account the inelastic scattering of neutrons by carbon in the scintillator (see Appendix).

The corrections for the variation of counter efficiency with neutron energy were small over the range of energies employed in this experiment. The yield from this experiment was, however, lower than in the $C^{12}(d,n)N^{13}$ experiment and because of this the subtraction of background was a somewhat more arbitrary procedure. Inspection of the data indicated that each point should be reliable within 10% of its absolute value and a smooth curve through the points could be somewhat better. Most of this error is attributed to the background subtraction. These considerations also apply to the differential cross-section measurements shown in Figs. 3, 4 and 5. Figures 6 and 7 give the data taken at 1.96 Mev and 2.8-Mev deuteron bombarding energy fitted to a mixture of Butler and heavy-particle-stripping theoretical yields.

RESULTS: $N^{14}(d,n)O^{15*}$(6.79 and 6.86 Mev)

This data (for which the Q value is -1.7 Mev) required the detection (with a known efficiency) of neutrons whose energy ranged from 0.3 Mev to 1.0 Mev. The procedure was similar to that used in reference 6. for $C^{12}(d,n)$ which required the detection of neutrons in a similar energy range. Figure 8 shows the curves obtained at the two bombarding energies (2.55 and 2.7 Mev) together with an $l=0$ Butler fit to the higher energy data. No evidence is seen for $l>0$ stripping. This is consistent with spin-parity assignments of $\frac{1}{2}+$ or $\frac{3}{2}+$ for both levels[7] or for the level with the larger yield. Zero-degree threshold yield measurements by Marion[8] indicate that the yield of the 6.86-Mev level is approximately 30% that of the 6.79-Mev level.

DISCUSSION

Although the low-Q data taken are scanty it is clear that they fit the simple Butler theory better than the high-Q data. This study is not sufficient to establish this point as a generality although this conclusion is also born out by the work on $C^{12}(d,n)N^{13}$.

It is seen that (Fig. 2) the total cross section of the high-Q reaction has a smaller variation with energy than the zero-degree yield. This effect reveals the existence of interferences and therefore the presence of multiple processes. In addition to this, because of the very smooth behavior of σ_T, and the high angular momenta apparent in the differential cross-section curves, it is tempting to choose a direct-interaction mechanism for a first description of this reaction.

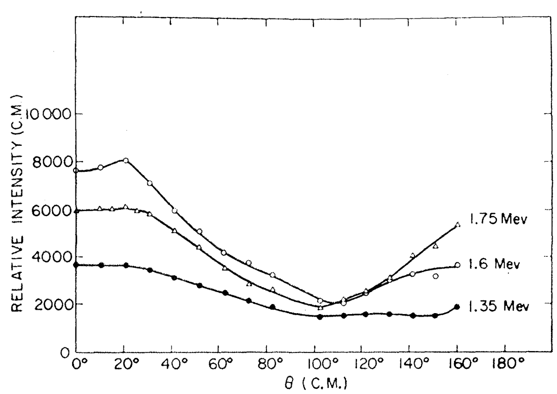

FIG. 3. Experimental differential cross section of the reaction $N^{14}(d,n)O^{15}$ (g.s.) in arbitrary units as a function of center-of-mass angle at bombarding energies indicated.

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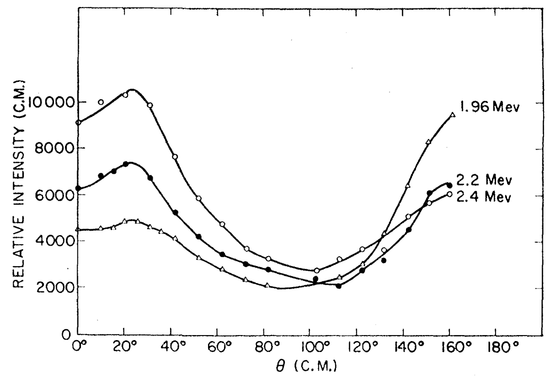

FIG. 4. Experimental differential cross section of the reaction $N^{14}(d,n)O^{15}$ (g.s.) in arbitrary units as a function of center-of-mass angle at bombarding energies indicated.

Accordingly we have attempted Butler fits to the data at two values of bombarding energy in the same manner as was employed in reference 6 although in this case heavy-particle stripping as described by Owen and Madansky[9] is included to cover the yield in the backward direction. The formula used to fit the angular distribution at 1.96 and 2.8 Mev is

$$d\sigma/d\Omega=\text{const}\,|G_D(K_1)j_1(k_1R_1)+(\Lambda_2/\Lambda_1)G_H(K_2)j_0(k_2R_2)|^2,$$

where the quantities involved have been defined in reference 9. As in reference 9 and reference 3, the calculation of $G_H(K_2)$ involves the neutron in N^{14} to be in a P state. Calculations of $G_H(K_2)$ for various values of radius and potential well depth have been made, and the results vary very little from each other. $G_H(K_2)$ is a slowly varying function of angle. Λ_2/Λ_1 is the ratio of the heavy-particle stripping amplitude to the deuteron stripping amplitude. One might expect this ratio to be small at low energies, and to increase as the deuteron energy increases reaching a constant value above the Coulomb barrier.[9] In the present case $\Lambda_2/\Lambda_1=4.0$ at $E_d=1.96$ Mev, and 2.1 at 2.8 Mev, not as might be predicted. Λ_2/Λ_1 and R_1 and R_2 are treated as phenomenological parameters which can vary as a function of energy.[9]

It is perhaps appropriate to mention, in connection with the Owen-Madansky formula, that only little attention has been given to the interference term. This term might affect the cross section in the region 60° to 100°. A better fit was obtained using a plus sign than a minus sign for the second term in the absolute-square bracket. The partial agreement of the Owen-Madansky theory for the $N^{14}(d,n)O^{15}$ reaction should perhaps be considered as fortuitous in light of the neutron binding energy of 10.6 Mev in N^{14} (however, see reference 9). It is felt that one cannot completely rule out a surface reflection mechanism for this reaction.[10] Nevertheless, because the Butler process is well established in (d,n) reactions we hypothesize that the yield at forward angles is basically explained by this process. The large Butler stripping radius ($r=7.5\times10^{-13}$ cm) should be viewed with suspicion although it is noteworthy that a small maximum is present in the differential cross section at an angle near the second maximum predicted by the Butler theory. (See Fig. 7.) This effect, however, is just of the same order of magnitude as the possible systematic errors in measurement in this region. Weil and Jones[3] have also obtained a large effective stripping radius (6.5×10^{-13} cm) for this reaction at $E_d=1.96$ Mev. Evans *et al.*[11] have obtained fits at $E_d=7.7$ Mev using $r=4.7\times10^{-13}$ cm. Therefore, it would be desirable to extend these angular distribution measurements to higher energies (3–6 Mev), at which energies the second peak may appear more prominently. In previous work[6] it has been shown phenomenologically that the effect of interfering processes is to modify the Butler stripping radius. In $C^{12}(d,n)$ the variation of radius was relatively pronounced over energy changes less than 1 Mev. In $N^{14}(d,n)$ the radius changes by almost a factor of two between 2.7 Mev and 7.7 Mev but seems to be almost constant below 2.7 Mev. Following this reasoning the questions to be answered are: (1) Is the observed forward peaking really stripping in the Butler sense? (2) How do interactions neglected in the Butler theory modify the Butler pattern?

Lastly the anomalous yield at backward angles will again be considered. Results obtained at this laboratory are as follows: $N^{14}(d,n)O^{15}$ ($Q=5.1$ Mev) gives backward peaks which are partially consistent with heavy particle stripping. $C^{12}(d,n)N^{13}$ ($Q=-280$ kev) gives backward peaks which appear more consistent with a surface reflection mechanism.[6] $N^{14}(d,n)O^{15}$ ($Q=-1.7$ Mev) appears to fit neither of these mechanisms. (See Fig. 8.)

It might be pointed out here that in a study of the $C^{12}(d,p)C^{13}$ reaction to a state in C^{13} at 3.09 Mev

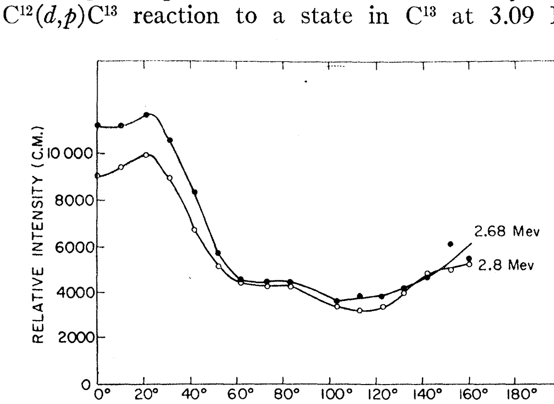

FIG. 5. Experimental differential cross section of the reaction $N^{14}(d,n)O^{15}$ (g.s.) in arbitrary units as a function of center-of-mass angle at bombarding energies indicated.

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[10] S. T. Butler (private communication).
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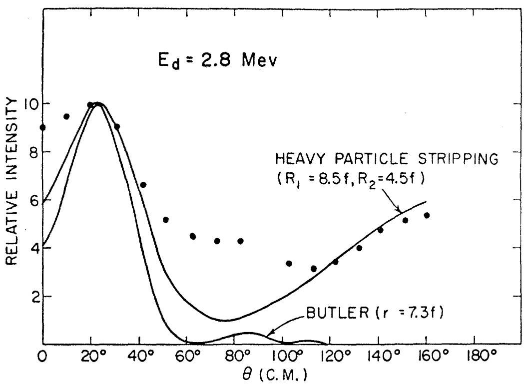

FIG. 6. Theoretical fits to experimental angular distributions at 2.8 Mev for the reaction $N^{14}(d,n)O^{15}$ (g.s.). Lower curve is the Butler fit. Upper curve is the fit using the exchange stripping theory of Owen and Madansky. The parameters that are adjusted are the interaction radii R_1 and R_2 and the ratio of deuteron and the nuclear stripping amplitudes Λ_2/Λ_1. The value of these parameters used are 8.5f, 4.5f, and 2.1, respectively.

($Q=-0.367$ Mev), using low-energy deuterons, Sellschop[12] finds exceptionally good agreement between the experimental angular distributions and the simple Butler formalism even at backward angles. This agreement even holds for angular distributions taken across resonances in the yield. This type of agreement is not the case for either the previously studied $C^{12}(d,n)N^{13}$ reaction or the present study of the low Q-value $N^{14}(d,n)O^{15}$ states. The backward peaks in these two reactions are too large to fit the elementary Butler description. It thus appears that some kind of interference effects play a more important role in the case of the low-Q (d,n) reactions studied here, than in Sellschop's study of some low-Q (d,p) reactions. (See also Warburton and Chase.[13])

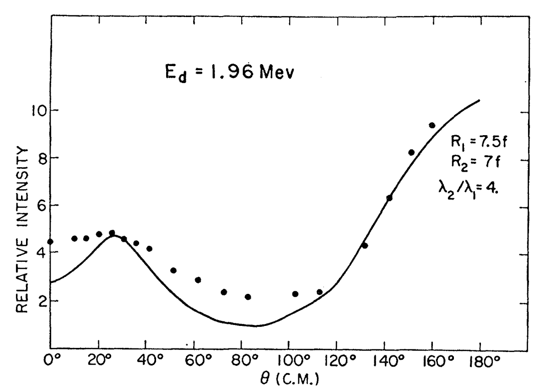

FIG. 7. Theoretical fit to the angular distribution of the reaction $N^{14}(d,n)O^{15}$ (g.s.) at 1.96 Mev using the exchange stripping theory of Owen and Madansky.

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CONCLUSION

The above considerations have been discussed within a phenomenological framework. These results are too incomplete to enable us to make any definitive phenomenological correlations. An attempt has been made to clarify the picture and it is our belief that the Butler theory provides a remarkably good starting point although, as indicated, further work for verification purposes is desirable. The complexity of the yields at large angles is emphasized by these measurements and further work is clearly needed here in order to understand whether these effects are due to properties of the final state or to some as yet unexplained property of nuclear reactions. In any event the weight of evidence from these measurements indicates that the observed yields at large angles are the result of some type of direct-interaction effect.

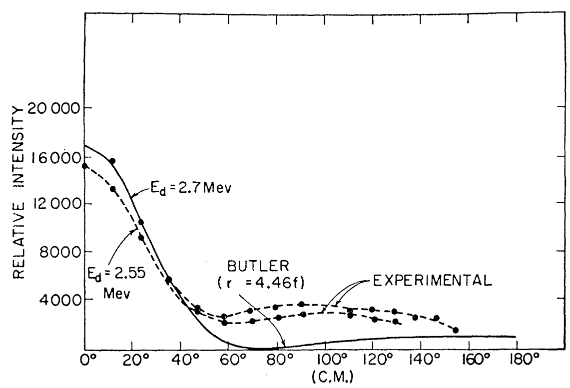

FIG. 8. The points and the dashed curve represent the experimental differential cross section of the reaction $N^{14}(d,n)O^{15}$ (6.79- and 6.86-Mev levels) as a function of center-of-mass angle at 2.7 Mev and 2.55 Mev. Solid curve represents the $l=0$ Butler fit to the 2.7-Mev data.

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APPENDIX: EFFICIENCY OF THE PLASTIC DETECTOR (TAKING INTO ACCOUNT THE INELASTIC SCATTERING OF NEUTRONS)

The formula give in the Appendix of reference 6 for the neutron detection efficiency of a plastic scintillator does not take into account the possibility of inelastic scattering of neutrons by the carbon in the detector. The threshold for such scattering is $T=4.8$ Mev. The energies of the neutrons emitted in the $N^{14}(d,n)O^{15}$ (g.s.) are higher than T and the formula of reference 6 had to be modified. If the energy of a neutron is lower than 9.6 Mev it can only be inelastically scattered once in the

detector and the total probability that a neutron entering the phosphor will make at least one collision with hydrogen is

$$\epsilon=\frac{p_1f_1}{1-p_2f_2}+\frac{p_1f_3p_2^*f_1^*}{(1-p_2f_2)(1-p_2^*f_2^*)},$$

where the following notation is used: L = length of plastic phosphor; n_H and n_C = respective densities of hydrogen and carbon atoms in detector; σ_H and σ_C = respective neutron elastic scattering cross section in hydrogen carbon; σ_{Ci} = neutron inelastic cross section in carbon; $\sigma_t=(n_H/n_C)\sigma_H+\sigma_C+\sigma_{Ci}$, $f_1=(n_H/n_C)\sigma_H/\sigma_t$, $f_2=\sigma_C/\sigma_t$, $f_3=\sigma_{Ci}/\sigma_t$; $p_1=1-\exp(-n_C\sigma_tL)$; p_2 is defined and approximated as in reference 6; p_2^*, f_1^*, and f_2^* = respective values of p_2, f_1, and f_2 at an energy $(E-T)$; E is the energy of incoming neutrons, and T is the threshold for inelastic scattering of neutrons by the carbon. This formula is derived in essentially the same way as the formula in the Appendix of reference 6.

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Nuclear Zeeman Effect in Sn^{119}†

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Ferromagnetic alloys of manganese and tin have been used to obtain large internal magnetic fields at the tin nuclei. The resultant Zeeman splittings of the two low levels of Sn^{119} have been measured by observing the hyperfine spectra in the resonant absorption of the 24-kev radiation of Sn^{119}. In Mn_4Sn an internal field of roughly 40 koe was found. In this field the splitting of the ground state was observed but that of the excited state was unresolved. In Mn_2Sn an internal field of about 190 koe was produced. In this field additional structure was obtained which was attributed to the splitting of the excited state. The measured splitting gives a value of (0.78 ± 0.08) nm for the magnetic moment of the excited state.

THE Mössbauer absorption and scattering by the 24-kev level of Sn^{119} has been studied in some detail by several investigators.[1,2] With nonferromagnetic sources and absorbers, no magnetic splitting of the nuclear levels has been reported. In this communication we describe a series of measurements on ferromagnetic alloys of tin in which we have observed the nuclear Zeeman effect in the resonant absorption in Sn^{119}.

The source of radiation was metallic tin containing Sn^{119m}. This radioactive tin had been prepared three years earlier by a six-month irradiation of natural tin metal in the Argonne research reactor. After irradiation the active tin was heated to 1000°C to drive off the contaminant Sb^{125} which has a 2-yr half-life and produces a 27-kev x ray. Sources having a strength of roughly 100 μC were prepared by rolling the active metal into foils approximately 1 mil thick and using circular pieces of this foil $\frac{1}{2}$ in. in diameter. A source was held rigidly by clamping it against a solid backing with a thin beryllium disk. In most of the work the radiation from the source was filtered by a 2-mil palladium foil in order to reduce greatly the 25-kev x ray from tin. The radiation was detected by means of a sodium iodide crystal, 40 mil thick and 2 in. in diameter. Velocity spectra were obtained by moving the source back and forth by means of the lead screw of a lathe, as in our previous work on the Fe^{57} nucleus.[3] In all the observations both source and absorber were kept at about 80°K by mounting them in vacuum on the bottoms of metal cans containing liquid nitrogen. The 24-kev radiation passed through 2-mil Mylar windows in the walls of the vacuum chambers. The absorber was mounted rigidly by clamping it between two thin pieces of beryllium.

At the top of Fig. 1 is shown the absorption spectrum obtained with a pure tin absorber (a 2-mil metal foil of natural tin). With this absorber only a single resonant line, symmetric about zero velocity, is observed. The width of this line is approximately three times the width which can be attributed to the natural width of the nuclear level. The cause of this broadening has not been investigated in detail.

The first alloy studied was Mn_4Sn (or possibly $Mn_{11}Sn_3$) which was reported[4,5] to be ferromagnetic

† This work was performed under the auspices of the U. S. Atomic Energy Commission.

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