standing this, it appears that distorted wave calculations will be necessary to arrive at firm conclusions.

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Symmetry of Neutron-Induced U^{235} Fission at Individual Resonances. II

G. A. COWAN, B. P. BAYHURST, AND R. J. PRESTWOOD*
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico
(Received 8 February 1963)

Neutrons from the Project Gnome nuclear test were resolved in energy by time-of-flight and used to study symmetry of fission in U^{235} in the resonance region. Symmetry was deduced by measurement of the fission product ratio Ag^{111}/Mo^{99} at resonances from 8.8 to 40 eV. The maximum decrease observed in the probability of symmetric fission as compared to the probability in thermal fission of U^{235} was 50%. The maximum increase observed was 22%. Four levels showed an increase in symmetry. Thirteen levels showed a decrease in symmetry. With the exception of one level at 15.4 eV, assignments of levels by symmetry are in agreement, in the region covered, with previous work.

INTRODUCTION

THE Project Gnome explosion of a nuclear device on 10 December 1961 has been used for further development of the neutron time-of-flight technique described in a previous paper.[1] An experiment similar to other so-called "neutron wheel" experiments sponsored by this laboratory was performed in order to ascertain the feasibility of recovery of target material from the vicinity of an underground explosion and, by improvement of over-all neutron energy resolution, to obtain more precise data on the symmetry of fission of U^{235} at individual resonances. Successful recovery of the exposed U^{235} in an undamaged condition was regarded as a necessary assurance for safety in the planned use of Pu^{239} in a follow-on experiment. In the case of Pu^{239}, large scale damage to the target would create an unacceptable level of alpha contamination in the immediate environment.

It was expected that an underground explosion, as compared with an atmospheric explosion, would have the following features bearing on the application of neutron time-of-flight techniques to nuclear research:

1. Since the device is almost totally shielded, scattered neutrons contributing to the background at the target are minimized.
2. Fallout is avoided.
3. Under the most favorable conditions, recovery of the target material is simplified. On the other hand, containment can lead to venting down the neutron pipe with possible destruction of the target. If the destructive effects are minimized by containment, then it becomes possible to maximize the device yield and, consequently, the neutron flux over a given flight path.

This experiment was designed to improve on the resolution of the previous experiment by a factor of three without significant changes in counting statistics. Previous information on symmetry of fission at individual resonances indicated a possible correlation of symmetry with spin. It was assumed that, if ideas[2–4] relating spin to fission symmetry are correct, a sufficient improvement in the resolution of individual levels in the epithermal region would demonstrate that strong resonances are characterized by one or another of two possible fission product yield distributions. If more than two possible distributions exist, the explanation that the effect is due only to spin changes at the resonances might be excluded. The previous wheel experiment demonstrated that symmetry of fission varied from resonance to resonance but did not demonstrate the existence of only two possible distributions.

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EXPERIMENTAL PROCEDURE

A 2-ft diam wheel with 93% U^{235} metal fastened to the outer third of the wheel face was exposed to a beam of neutrons defined by a tapered steel collimating slit, 10.16 cm long and 0.3 cm wide at the rim edge, extending through a concrete shield 4 ft thick. The outer edge of the neutron beam extended to a radius of 28.075 cm and the rim of the metal extended to 28.575 cm. Neutrons reaching the wheel were resolved in energy by time-of-flight over a path length of 290.5 m. The flight path was contained in an evacuated pipe arranged so that the collimating slit viewed a circle of 20-in. diam on a moderating slab located at the source end of the pipe. The slab consisted of 5 cm of lead, 1.6 cm of iron, and 3.8 cm of polyethylene. At exposure time the wheel speed was 48.76 rps. A neutron-black shutter, moved by explosive squibs, closed the slit at approximately 10 msec.

The U^{235} metal portion of the wheel consisted of a top foil with a nominal thickness of 2 mil overlying two foils with nominal thicknesses of 10 mil each. Other experimental details were very similar to those described previously.[1]

Under the conditions of this experiment the collision of a neutron of a given energy with the wheel occurred at a position, measured along the rim of the metal (28.575-cm radius) which is given by the equation

$$S=183.7/E^{1/2},$$

where S is in cm and E is in eV (velocity of a 1-eV neutron is defined as 1.384×10^6 cm/sec).

Resolution of neutrons was limited by the collimating slit width and corresponded to a constant channel width of 34.2 μsec or a little over 10^{-1} μsec/m. This resolution was considered adequate for separation of a large number of resonances in the 10 to 40 eV energy region with enough fissions to permit measurement of "valley" fission product yields with a standard deviation of 5% or better. The pulse width and flight path defined an intrinsic resolution of 10^{-3} μsec/m, considerably sharper than could be exploited at the collimator because of the limitations of fission product counting statistics.

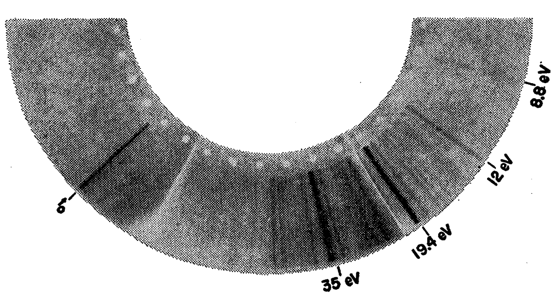

FIG. 1. Autoradiograph of uranium metal produced by contact exposure of x-ray film to fission products in the target foils. An energy scale is provided by identification of lines at t_0 (gamma ray and fast neutron induced fission), 35, 19.4, 12, and 8.8 eV.

The wheel was recovered six days after the event (somewhat later than planned because of venting of explosion products through the main drift) and the location of the resonance band was established by contact autoradiography on x-ray film.

The pictures obtained from exposure of x-ray film to radioactive fission fragments in the metal plates are shown in Fig. 1. Resonance structure in the sectors shows as dark bands, varying from high neutron energy to low neutron energy in a counter clockwise direction. With the aid of these pictures, which were superimposed on the metal, the regions of maximum contrast were sheared off the top 10-mil plate with precision shears in cuts corresponding in width to the collimating slit

TABLE I. Sample schedule and experimental results.

Sample No.	Fissions/g U*[a] ($\times10^{-8}$)	Energy band (eV) E_1	Energy band (eV) E_2	Activity ratio $A_{Ag^{111}}/A_{Mo^{99}}$ ($\times10^3$)
1	47.0	...	377 $\times10^3$	...
2	34.0	377 $\times10^3$	94 $\times10^3$	...
3	15.2	94 $\times10^3$	42 $\times10^3$	1.06 ± 3%
4	11.5	42 $\times10^3$	23.5 $\times10^3$	1.15 ± 4%
5	10.5	32.5 $\times10^3$	15.1 $\times10^3$	0.996± 6%
6	21.8	39.6	38.3	1.12 ± 6%
8	25.9	36.2	35.4	1.13 ± 3%
9	49.5	35.4	34.7	1.07 ± 2%
12	53.5	19.5	19.3	0.588± 3%
13	39.1	19.3	19.0	0.667±10%
14	17.4	19.0	18.7	0.544± 7%
15	12.2	18.7	18.4	0.525±15%
16	19.6	18.4	18.1	0.641± 7%
17	18.6	18.1	17.9	0.822± 6%
19	16.4	16.9	16.7	0.548±11%
20	13.2	16.7	16.5	0.692± 7%
21	6.9	16.5	16.4	0.983±12%
22	11.0	16.4	16.0	0.708± 8%
23	6.5	16.0	15.7	0.833± 9%
24	11.6	15.7	15.4	0.753± 9%
26	1.71	9.34	9.18	1.46 ±26%
27	2.28	9.18	9.03	1.09 ±16%
28	3.13	9.03	8.88	0.69 ±42%
29	3.06	8.88	8.74	0.47 ±72%
31	22.7	21.4	21.09	0.771±13%
32	21.4	21.1	20.6	0.926± 7%
35	42.2	34.7	34.0	0.981± 8%
36	20.6	34.0	32.9	0.903± 5%
37	21.0	32.9	32.1	0.933± 4%
38	19.3	32.1	31.5	0.783±13%
40	9.5	30.4	29.3	0.761±10%
42	24.2	28.2	27.8	0.925± 5%
44	24.7	26.9	26.4	0.959± 6%
46	33.0	25.7	25.3	1.18 ± 4%
47	25.2	25.3	24.0	1.03 ± 2%
48	32.6	24.0	23.6	0.591± 3%
49	29.2	23.6	23.2	0.816± 5%
50	22.3	23.2	22.8	0.715± 8%
B1-1[b]	1.88	...	...	...
B1-2[b]	0.62	...	...	...
B1-3[b]	0.47	...	...	...
B1-4[b]	0.48	...	...	...
B1-5[b]	1.17	...	...	...

[a] U* stands for 93.2% U^{235}.
[b] B1-1 and B1-5 came from the nonexposed bottom and top areas, respectively, of uranium metal immediately adjacent to the areas exposed to neutrons of 20–300 eV in energy. B1-2 came from similar nonexposed areas of metal in the region of the wheel corresponding to neutron energies of 7–20 eV; B1-3 from unexposed metal in a region corresponding to 4–7 eV; and B1-4 from unexposed metal in a region corresponding to 2–4 eV. Neutrons below 5 eV were cut off by the shutter.

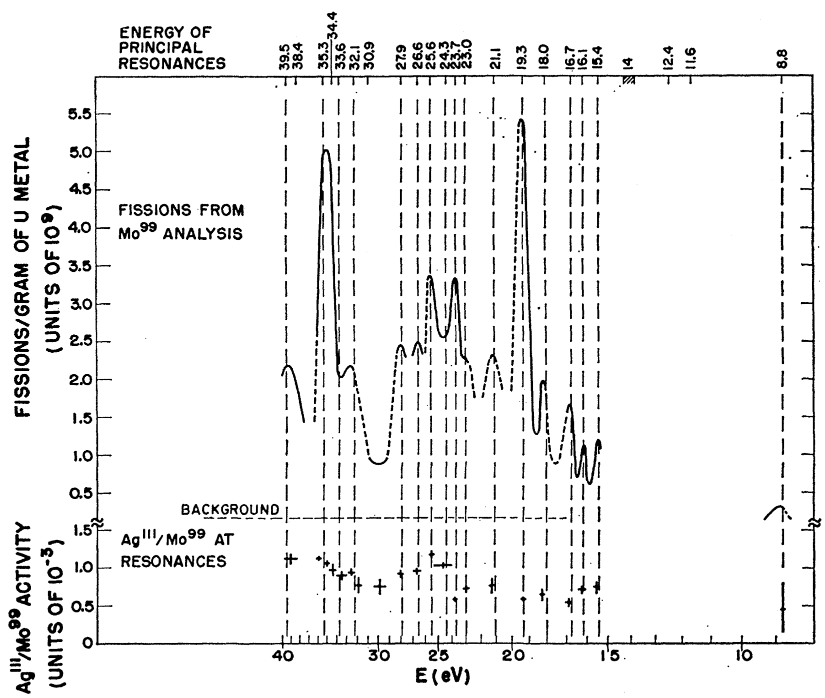

FIG. 2. Experimental results on fission density and Ag^{111}/Mo^{99} activity ratios. Although data points represent energy bands of finite width, the upper curve is smoothed according to the indications of the autoradiographs (Fig. 1). The horizontal lines in the crosses marking the Ag^{111}/Mo^{99} points represent the width of metal cuts. The vertical lines represent the estimated error in the ratio. The dashed background line represents fissions induced in the metal by sources other than collimated neutrons.

width. The metal was dissolved and analyzed for Mo^{99}, a "peak" fission product, and Ag^{111}, a "valley" fission product.

Four samples of uranium metal were cut from the wheel rim immediately adjacent to various exposed portions in order to determine fissions due to noncollimated neutrons. These "blanks" were analyzed too late for good Ag^{111} or Mo^{99} measurement, and 50-day Sr^{89} was used as an index of the number of fissions.

EXPERIMENTAL RESULTS

The experimental results are summarized in Table I. The observed fissions per gram of uranium metal is given in column 2, the neutron energy band to which each sample was exposed is given in column 3, and the ratio of Ag^{111} to Mo^{99} activity is given in column 4. The ratio of these two activities in thermal fission of U^{235}, as measured in the same way by the same analysis, is 0.970×10^{-3}.

The data for fissions per gram of metal from 8.8 to 40 eV, as measured by radiochemical analysis, are plotted as a smoothed curve according to the indications of the autoradiographs in Fig. 2. Values of Ag^{111}/Mo^{99} activity ratios at each resonance isolated in this energy region are plotted in the lower portion of the figure.

The background signals measured in *B*1-1 and *B*1-5 apply over most of the energy region covered in Fig. 2. The average is indicated by a dashed line. The Ag^{111}/Mo^{99} activity ratio characteristic of this noncollimated background is not known. From inspection of data obtained where the signal-to-background ratio is lowest, the Ag^{111}/Mo^{99} activity ratio appears to lie near

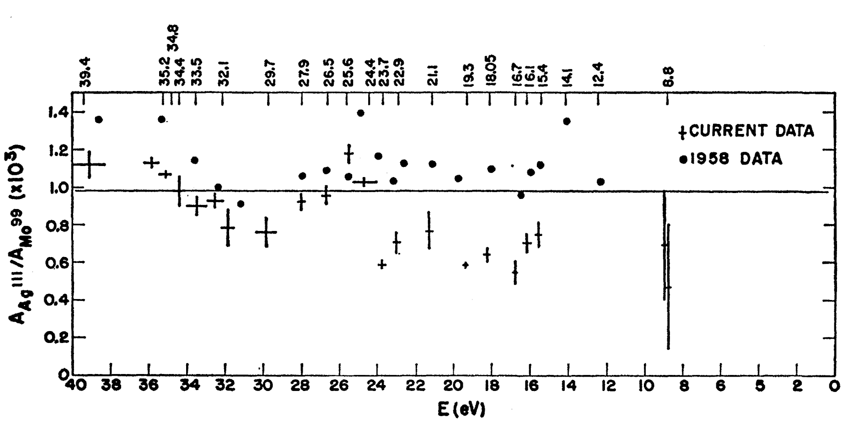

FIG. 3. Comparison of Ag^{111}/Mo^{99} activity ratios at resonances, 1958 data, and current data. Location of known resonances is indicated at top of figure. Length of vertical lines in current data crosses indicates estimated error. Solid line indicates thermal value of Ag^{111}/Mo^{99} activity ratio.

the thermal value. However, the background is no more than 14% of the signal at resonances over energies from 15 to 40 eV and, for most of this region, is less than 8% of the signal at resonances.

For easier comparison of the current Ag^{111}/Mo^{99} data with that obtained in the 1958 experiment, results obtained at resonances in the energy region 8.8 to 39 eV are plotted in Fig. 3 for both experiments.

DISCUSSION

In this experiment, values for the Ag^{111}/Mo^{99} activity ratio fell below the thermal value by as much as 50% at the following resonances (uncertain assignments indicated by parentheses): (8.8), 15.4, 16.1, 16.7, (18.0), 19.3, 21.1, 22.9, 23.6, (26.5), (27.8), (32.1), and (33.2) eV. Observed values were as much as 22% greater than thermal for the following resonances: 25.5, (34.4), 35.3, and 39.4 eV. An explicit contradiction of the earlier assignments of levels by symmetry occurs at 15.4 eV.

In both the 1958 data and the present data, there is some indication of a periodicity in the symmetry with changing energy. This effect, if it is real, may be an indication that the strongest resonances produce small bands which have a common spin or some other property influencing symmetry in fission.

Although the quantitative results for the Ag^{111}/Mo^{99} activity ratios are systematically lower than those reported in the earlier paper, due chiefly to improvements in the signal-to-background ratio, substantial confirmation of most of the qualitative results of the 1958 experiment is reassuring as to the reality of the effect. The simplest explanation of these results is that fission occurs in one or another of only two possible distributions. A more definitive answer will probably be obtained from similar measurements on Pu^{239}.

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Excitation Functions for Tb^{149g} from Reactions between Complex Nuclei*

JOHN M. ALEXANDER AND GABRIEL N. SIMONOFF†
Lawrence Radiation Laboratory, University of California, Berkeley, California

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Excitation functions have been measured for twelve reactions that produce 4.1-h Tb^{149g} from Tb compound nuclei. Projectiles were B^{10}, B^{11}, C^{12}, N^{14}, N^{15}, O^{16}, O^{18}, and F^{19}. Peak cross sections range from approximately 0.5% to approximately 7% of the calculated total reaction cross section. The excitation functions are well systematized by the simple assumption that only those compound nuclei of angular momentum less than $7.5\pm1.5\hbar$ are effective in these reactions.

I. INTRODUCTION

THE production of different isomeric states by nuclear reactions gives information about the effect of angular momentum on the decay of the initial compound nuclei. Huizenga and Vandenbosch have given a detailed discussion of the various factors that influence relative isomeric yields.[1] The basic assumption in these considerations is the preference for small changes in angular momentum associated with photon or neutron emission. Huizenga and Vandenbosch have used relative isomeric yields to obtain information about the spin dependence of the nuclear level density.[1]

A particularly favorable case of nuclear isomerism is that of Tb^{149}. The product 4.1-h Tb^{149g} can be identified by its α radiation, and isomeric transition from 4.0-min Tb^{149m} is very improbable.[2] We use yields of the low-spin state 4.1-h Tb^{149g} to obtain information about the angular momenta of the initial compound nuclei in $(HI,xn)Tb^{149g}$ reactions (HI denotes a heavy ion, e.g., C^{12}, N^{14}, etc.).

We have measured excitation functions for twelve different $(HI,xn)Tb^{149g}$ reactions. The peaks of these excitation functions have values between approximately 0.5% and approximately 7% of the calculated total reaction cross section.[3] Recoil range studies previously presented give strong evidence that these reac-

* This work was done under the auspices of the U. S. Atomic Energy Commission.

† Present address: Nouvelle Faculté des Sciences de Bordeaux, Talence (Gironde), France.

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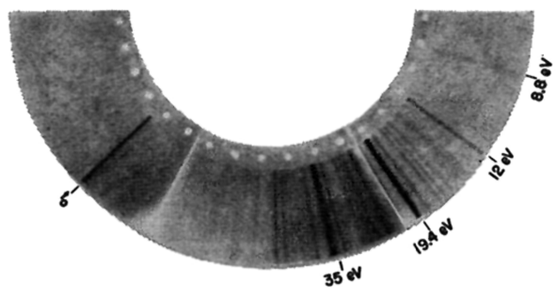

FIG. 1. Autoradiograph of uranium metal produced by contact exposure of x-ray film to fission products in the target foils. An energy scale is provided by identification of lines at t_0 (gamma ray and fast neutron induced fission), 35, 19.4, 12, and 8.8 eV.