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Neutron-Induced Fission Cross Section of Am^{242m}†

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The neutron-induced fission cross section of Am^{242m} has been measured from 0.02 eV to 6 MeV by the time-of-flight method at the Livermore 30-MeV linear electron accelerator. The data are normalized at 0.0253 eV to a value of 6600 b measured in a reactor thermal-neutron flux. The cross section at 0.2 eV is 4700 b; at 1 eV it is 540 b; and at 4 MeV it is 2.1 b. The data are analyzed to obtain values for the neutron strength function $\langle \Gamma_n^0/D \rangle$ of 1.4×10^{-4}, the level spacing $D=1.2$ eV, and the quantity $2\pi\langle \Gamma_f/D \rangle = 2.5$. All three quantities are quoted per spin state. The high cross section at low energies can be attributed to the unusually high value for $2\pi\langle \Gamma_f/D \rangle$, and to the existence of a very large resonance at 0.173 eV. The fission cross section of Am^{241} also was measured in the MeV region and found to be 1.96 ± 0.2 b at 2.5 MeV.

I. INTRODUCTION

THE thermal-fission cross section of the odd-odd nucleus Am^{242m} is higher than that of any other measured nucleus.[1,2] In fact, the thermal-fission cross sections of the odd-odd nuclides seem, in general, to be larger than those for even-odd nuclides. This is illustrated in Fig. 1, where the fission cross section at thermal energy[3] of these targets is plotted versus A. The odd-odd targets are indicated by the dots and the even-odd targets by the squares. The nuclides are rather well separated into two groups by the straight line through the figure, suggesting that the fission cross section is higher, in general, for the odd-odd targets. Heretofore, no fission cross section measurements have been made on any odd-odd nucleus at any energy other than thermal, with the exception of concurrent experiments on Am^{242m} at Los Alamos Scientific Laboratory.[4] Such measurements are required if a clear understanding of the reasons for this high cross section is to be realized. In this paper we report measurements on the fission cross section of Am^{242m} from 0.02 eV to 6 MeV. The Livermore 30-MeV linear electron accelerator was used as the pulsed neutron source for a time-of-flight measurement. From the analysis of these results, we hope to examine at least two possibilities which might enhance the thermal and higher-energy cross section for Am^{242m}. These possibilities are: (1) the existence of more fission channels which may be open to a larger extent than in even-odd nuclei; and (2) an anomalously large neutron strength function for this nucleus. The first factor might characterize all odd-odd nuclides as a class, and therefore might offer an explanation for their high fission cross section. Finally, it was necessary to measure simultaneously the cross section for Am^{241} in the MeV region, where its cross section is of the same order of magnitude as that of Am^{242m}, since an isotopically pure sample of Am^{242m} was not available. These measurements are also reported here.

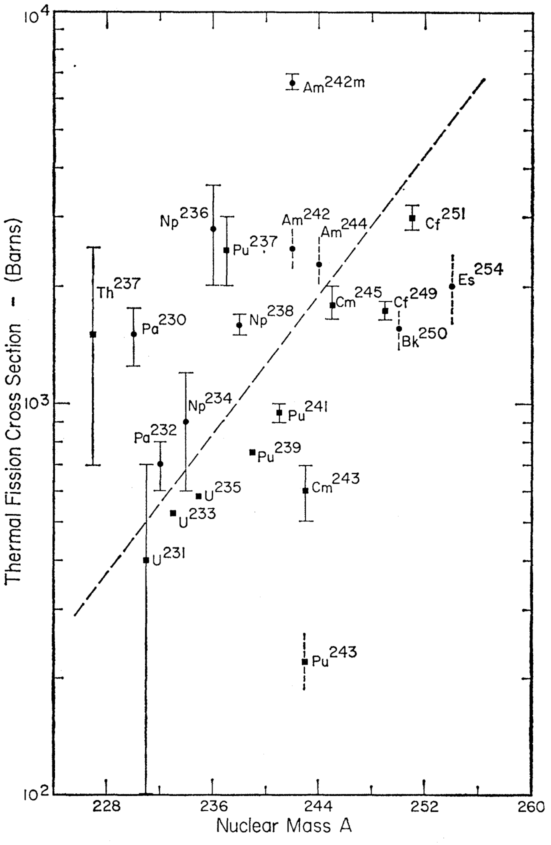

FIG. 1. The thermal-fission cross section versus A is shown with odd-odd nuclei denoted by dots and even-odd nuclei by squares. Error bars are included for most points. Some values are known with such precision that the errors are less than the point size. For some nuclei the errors are uncertain. These are shown by vertical dashed lines through the points. The two species are rather well separated by the dashed line across the figure. The data are from Ref. 3.

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

[1] E. K. Hulet, R. W. Hoff, H. R. Bowman, and M. C. Michel, Phys. Rev. **107**, 1294 (1957).

[2] K. Wolfsberg, G. P. Ford, and H. L. Smith, J. Nucl. Energy, Pt. A & B **20**, 588 (1966).

[3] The values for Pu^{243} and Bk^{250} are unpublished data supplied to us by P. R. Fields of the Argonne Heavy Element Group. The other data are taken from E. K. Hyde, *The Nuclear Properties of the Heavy Elements III* (Prentice-Hall, Inc., Englewood Cliffs, N. J., 1964).

[4] P. A. Seeger, A. Hemmendinger, and B. C. Diven, Nucl. Phys. **A96**, 605 (1967).

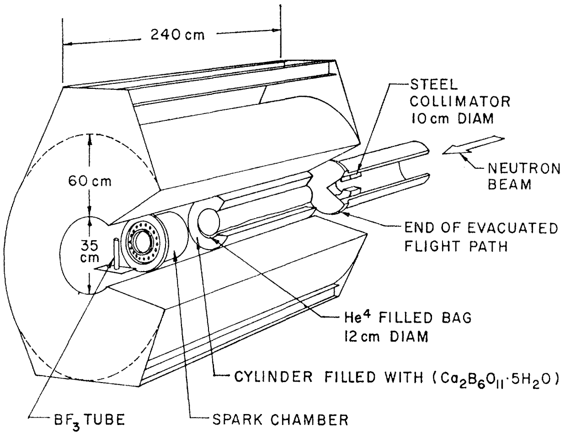

FIG. 2. Shielding and beam collimation in the neighborhood of the detector.

II. THE DETECTOR

A corona spark detector appears to be the most favorable for this experiment, for the following reasons[5]: (1) The detector very effectively discriminates against the α activity of the sample, thus allowing the detection of fission fragments with essentially no background signal from α-particle pileup; (2) the insensitivity of the detector to γ radiation allows measurements to be made into the MeV region. The intense γ flash which appears at the time of neutron production is a severe problem in many time-of-flight fission cross section measurements using an electron linear accelerator as a pulsed neutron source. Fission events are therefore not recorded until the detector has recovered from the effects of the γ flash and, in many experiments, this determines the upper energy limit beyond which measurements cannot be made; (3) the detector is sufficiently fast in time response to allow measurements into the higher kilovolt region with adequate resolution; and (4) since the relative fission cross section can be measured from thermal energy into the MeV range with the same experimental arrangement, the full spectrum of measurements can be normalized to a fission cross section at thermal energy, where it has been determined with high precision.

Each detector unit was constructed of two 0.0075-cm-thick foils of copper, which were corrugated into 32 adjacent 0.32-cm-diam channels. The corrugated foils were then glued back-to-back into a supporting, nonconducting frame. Stainless-steel wires of 0.0123-cm diameter were stretched along the axis of each cylindrical corrugation. As many as four of these detector units can be stacked one upon the other with fission foils between, so that both sides of three fission foils can be observed and one side of two others at the top and bottom of the stack. The stack is enclosed in a chamber which provides means for gas circulation. The parameters of the detector, such as the voltage between the wire and the groove, the pressure, and the composition of the gas, can be varied to obtain the best discrimination against α particles while maintaining a satisfactory efficiency for fission fragments. Several gases have been studied, some more thoroughly than others. No mixture was found to be superior to natural air, which was used in these experiments. A pressure of 46 cm of mercury and an applied voltage of 2600 V provided satisfactory operating conditions for the detector during these measurements.

III. FISSION CROSS SECTION MEASUREMENTS

Measurements on Am^{242m} are complicated by the growth of the Cm^{242} contaminant by β decay from the Am^{242} ground state. The pertinent transitions are

$$\mathrm{Am}^{242m}\xrightarrow[152\text{ yr}]{\text{I.T.}}\mathrm{Am}^{242}\xrightarrow[16\text{ h}]{\beta^-}\mathrm{Cm}^{242}\xrightarrow[163\text{ days}]{\alpha}\mathrm{Pu}^{238}\xrightarrow[86.4\text{ yr}]{\alpha}.$$

Since the Cm^{242} has a relatively short partial spontaneous-fission half-life of 7×10^6 yr[6] the spontaneous-fission background becomes prohibitively large long before equilibrium is established. It is important, therefore, that the Cm^{242} be well separated from the Am^{242m} before the start of the experiment and that the measurements be completed in a short time.

By oxidation of the americium to the V state and two successive precipitations of $\mathrm{KAmO_2CO_3}$, the curium content of the enriched $\mathrm{Am}^{241-242m}$ was reduced to a $\mathrm{Cm}^{242}/\mathrm{Am}$ atom ratio of 1×10^{-7}. Background measurements, described in detail in later paragraphs, indicated no serious interference from Cm^{242} spontaneous-fission events. About 50 mg of a mixture containing 19.8% Am^{242m}, 79.5% Am^{241}, and 0.7% Am^{243} was electroplated on both sides of a 0.076-mm-thick, 10-cm-diam nickel foil to a thickness of 350 μg/cm². Three other foils were electroplated with better than 97% isotopically pure Pu^{239}, Am^{241}, and U^{238}. The Pu^{239} was used as a flux monitor at the highest and lowest energies measured. A $\mathrm{BF_3}$ proportional counter enriched in B^{10} was used as the flux minitor elsewhere. The Am^{241} allowed corrections for the large Am^{241} contaminant in the Am mixture. The U^{238} helped measure the background and resolution in the higher-energy region. The arrangement of the detectors in the shielding and the beam collimation in the neighborhood of the detectors is shown in Fig. 2. The detector was placed in a large cylindrical shield which was filled with boric acid solution. This shield reduced the extraneous neutron background which leaked through the relatively thin shielding around the neutron source. The diameter of the neutron beam was collimated to 10 cm by the steel collimator at the end of the evacuated portion

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[5] C. D. Bowman and R. W. Hill, Nucl. Instr. Methods 24, 213 (1963).

[6] G. C. Hanna, B. G. Harvey, N. Moss, and P. R. Tunnicliffe, Phys. Rev. 81, 466 (1951).

Table I. Experimental conditions for the three measurements.

Measurement	Interval (eV)	Filters	Pulses Per sec	Pulse width (μsec)	Channel width (μsec)	Flight path (m)
Low-energy	0.019–3.7	None	50	2.0	1.0	6.50
Intermediate	$2.3–2.5\times10^3$	Cd, Mn	360	0.10	0.125	6.50
Intermediate background	$2.3–2.5\times10^3$	Cd, Mn, Ta	360	0.10	0.125	6.50
High-energy	$1\times10^3–6\times10^6$	Cd	360	0.10	0.03125	15.47

of the flight tube. The neutrons passed down the axis of the cylindrical insert containing $Ca_2B_6O_{11}\cdot5H_2O$, which was placed inside the shield. A plastic bag filled with He to reduce neutron scattering was placed in this portion of the flight path. Both the spark chamber and the BF_3 tube were surrounded by Cd to prevent neutrons which were scattered into the boric acid solution from returning to the detector and causing background fission events. The whole assembly could be moved easily from one flight path position to the other.

Signals from the spark chamber were attenuated, passed through a discriminator, and then to the multichannel time analyzer or to a gated scaler. Five scalers, one for each isotope and the BF_3 tube, were operated in parallel with the time analyzer. These scalers were gated on during the recording portion of the analyzer cycle and will be referred to as the "prompt" scalers. Another five scalers in parallel with the first five were gated on for an equal-time interval which just preceded the machine pulse when no neutrons from the machine were present. In this way we determined, in effect, the machine-off, time-independent background from α-particle pileup, etc. The latter scalers are referred to as the "delayed" scalers.

Three measurements were required: a low-energy measurement below 5 eV, an intermediate-energy measurement between 2.3 eV and 2.5 keV, and a high-energy measurement from 1 keV to 6 MeV. The conditions for these measurements and a background measurement are summarized in Table I. For the low-energy measurements, data were recorded only for the Am mixture and the Pu^{239} foils. At the machine pulse rate of 50 pulses/sec, the delayed scaler indicated that no background correction was required, owing to overlap of neutrons from one pulse to the next, or from time-independent sources such as spontaneous fission. The unnormalized cross section of the mixture was obtained by using the fission cross section of Pu^{239} as a flux monitor. The data were normalized to the Am^{242m} cross section at 0.0253 eV, using a value which has been derived from measurements of the Am^{242m} fission cross section in a Maxwellian thermal-neutron spectrum. The cross section for thermal neutrons σ_{th} is related to the cross section at 0.0253 eV, $\sigma_{0.0253}$ by the relation $\sigma_{\text{th}}=f\times\sigma_{0.0253}$, where f takes into account[7] the non-$1/V$ energy dependence of the cross section. From the shape of the cross section curve in the vicinity of 0.0253 eV as determined from our unnormalized measurements and with the assumption of a Maxwellian distribution of neutrons about 20°C in the reactor measurements, f was found to be 1.104 for Am^{242m}.

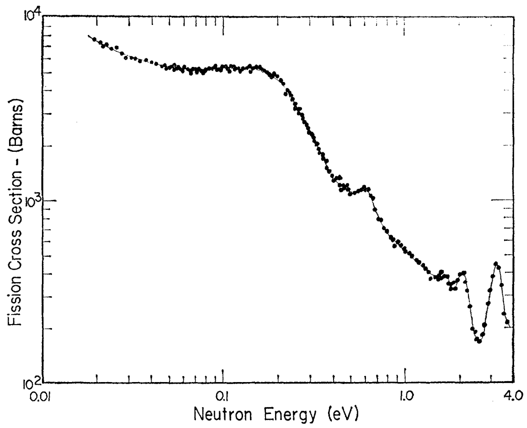

Fig. 3. The fission cross section of Am^{242m}. The data have been corrected for the Am^{241} contaminant.

Two measurements of the thermal-neutron fission cross section have been reported, one by Hulet *et al.*,[1] where the fission rate in Am^{242m} was compared with that of Pu^{239}, and the other by Wolfsberg *et al.*,[2] where the standard material was U^{235}. In both experiments the absolute number of atoms of Am^{242m} in the samples was determined from measured relative mass abundances of the isotopes 241, 242*m*, and 243 and measurements of the absolute amount of Am^{241} α activity. Recent measurements[8] have shown the Am^{241} α half-life to be 433 yr, whereas Hulet and Wolfsberg used values of 461 and 458 yr, respectively, in their calculations. Corrections are also required to the values for the thermal-neutron fission cross sections of Pu^{239} and U^{235} assumed by these experimenters. In the case of Hulet's results, the value originally assumed for Pu^{239}, 806 b, should be reduced to 787 b, according to the most recent recommended cross section data[9] for Pu^{239}. Values for the fission cross section at 0.0253 eV, as derived from the Hulet and Wolfsberg data, are found to be 6010±500 and 6830±300 b, respectively. A weighted average, 6600±300 b, has been used in our normalization. The data below 4 eV are shown in Fig. 3. The contribution of the Am^{241} has been removed using previously measured data.[10]

For the intermediate-energy measurements, data were

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[7] J. A. Harvey and J. F. Sanders, *Progress in Nuclear Energy, Series I, Physics and Mathematics*, edited by R. A. Charpie, J. Horowitz, D. J. Hughes, and D. J. Littler (Pergamon Press, Inc., New York, 1956), Vol. I, p. 6.

[8] F. L. Oetting and S. R. Gunn J. Inorg. Nucl. Chem. **29**, 2659 (1967); R. E. Stone and E. K. Hulet (unpublished).

[9] Brookhaven National Laboratory Report No. 325 (U. S. Government Printing Office, Washington, D. C., 1965), 2nd ed., Suppl. 2.

[10] C. D. Bowman, M. S. Coops, G. F. Auchampaugh, and S. C. Fultz, Phys. Rev. **137**, B326 (1965).

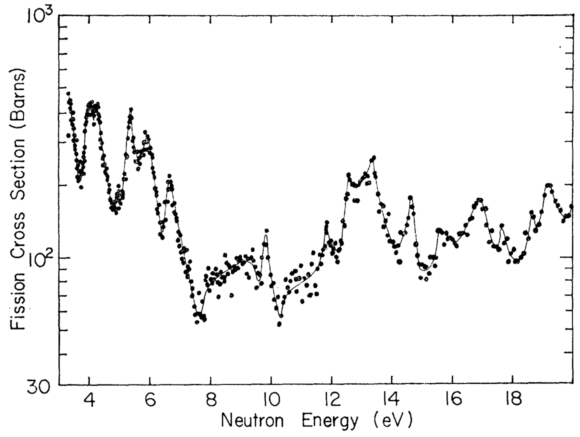

FIG. 4. The fission cross section of Am^{242m}. The data have not been corrected for the Am^{241} contaminant.

recorded for the Am mixture, Pu^{239}, and the BF_3 proportional counter which was used as a flux monitor. A manganese absorber in the beam during the measurement allowed us to determine the background at 335 eV. The energy dependence of the cross section in the neighborhood of that resonance was determined by removing the manganese filter for a short time. The time-independent portion of this background was determined with the delayed scaler, as described earlier. Measurements of the time or energy dependence of the background were carried out in a separate run with a Ta foil also included. The total background correction was 30% in the valley at 7.5 eV, but became less important as the energy increased. The data were normalized to the 3.3-eV resonance in Am^{242m} of the low-energy measurements. The results are shown in Figs. 4–6. No Am^{241} correction was applied to these data above 3.7 eV, and therefore we refer to the data of these figures as the cross section of the mixture. However, below 100 eV the average Am^{241} fission cross section is only about 1% of that for Am^{242m}, so that the corrections are small except at the peaks of the unusually large Am^{241} resonances. Since measurements of the same energy resolution were not available and the corrections were small, no correction was applied.

Between 100 eV and 300 keV, the Am^{241} cross section is expected[11] to decrease smoothly to a measured value at the foot of the threshold of about 30 mb. Therefore, in this region, the contributions of Am^{241} to the cross section of the mixture also are expected to be small enough to be neglected, compared to other sources of error. However, the measurements of Seeger *et al.*[4] indicate an anomalous behavior for Am^{241}. The cross section appears to increase to a value of about 1.5 b at a few hundred eV and to remain essentially flat to 20 keV, where the cross section suddenly drops to a value of about 30 mb at 70 keV. Such a behavior has not been observed in any other nucleus and is not consistent with the current theory[11] of subthreshold fission. Since Seeger *et al.*[4] point out that there may have been experimental difficulties in the data in this energy region, we have chosen not to correct the cross section of the mixture for the Am^{241} contaminant over the energy interval from 3.3 eV to 300 keV.

For the high-energy measurements, time spectra were recorded for all four foils. A portion of the raw time spectra is shown in Fig. 7. The peaks in all four spectra at low channel numbers result from photofission induced by the γ flash from the accelerator. These peaks serve to measure the zero time and the time resolution. The broad maxima observed at later times arise from fission induced by the essentially unmoderated portion of the neutron boil-off spectrum. The low-energy (high channel number) side of the maxima for Am^{241} and U^{238} foils are truncated due to the existence of a threshold for fission in these nuclei. A long tail in the Pu^{239} and Am mixture indicates considerable cross section in the keV region. The unnormalized cross sections of Am^{241}, U^{238}, and the Am mixture were determined in the region from 1 keV to 6 MeV, using the known Pu^{239} fission cross section[12] as the flux monitor. The cross section for the mixture was normalized in the 1.0- to 2.5-keV region, where it overlapped the intermediate data.

In the region above 300 keV, a large correction is required for the Am^{241} contaminant owing to a threshold for fission at 500 keV. The Am^{241} fission cross section, therefore, must be known with as high a degree of

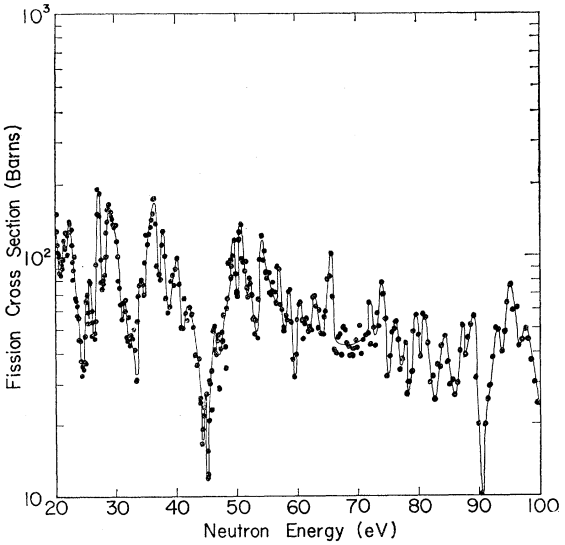

FIG. 5. The fission cross section of Am^{242m}. The data have not been corrected for the Am^{241} contaminant. The deep minimum at 91 eV is attributed to the influence of the Cd filter.

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[11] E. R. Rae, in *Proceedings of the Symposium on the Physics and Chemistry of Fission, Salzburg, 1965* (International Atomic Energy Agency, Vienna, 1965), Vol. I, p. 187.

[12] R. E. Coté, L. M. Bollinger, J. M. LeBlanc, and G. E. Thomas, in *Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958* (United Nations, Geneva, 1958), Vol. 15, p. 127.

accuracy as possible. The unnormalized cross section for Am^{241} was obtained using the Pu^{239} as a flux monitor, and the absolute cross section was determined in the following way. During these high-energy measurements, data were simultaneously recorded for Am^{241} near its 5.48-eV resonance and for Pu^{239} near its 7.85-eV resonance. The energy dependence of the flux from 5.48 to 7.85 also was measured. The area of both resonances in barn-eV is known.[10,12] Therefore, the ratio of the counting rate per barn of Am^{241} cross section to the counting rate per barn of Pu^{239} cross section can be determined. The ratio is independent of the energy. With this ratio and the known cross section of Pu^{239}, an absolute cross section for Am^{241} was obtained in the MeV region. The value of the Am^{241} fission cross section at 2.5 MeV was found to be 1.96 ± 0.2 b. The effect of the recent change in the half-life for Am^{241} increases the cross section data of Ref. 10 by 6% and the influence of this change has been considered in obtaining our value. Our value agrees with the value of 1.95 ± 0.2 b obtained by Kazavinova *et al.*[13] at the same energy. While the latter value was similarly influenced by the change in the Am^{241} half-life, the effects were almost exactly compensated by a change[9] in the value of the U^{238} fission cross section at 2.5 MeV, to which the Am^{241} measurement was referred. The Am^{241} fission cross section was normalized to a value of 1.96 ± 0.14 b at 2.5 MeV. The error of 0.14 b was deduced from the 0.2-b error of the two indendent measurements.

The cross section for the isotopic mixture, $\sigma_{\text{mixture}}=\sigma_{f\ 242m}+4\sigma_{f\ 241}$, can be normalized from 1–3 keV, where the high-energy data overlaps the intermediate-energy measurements. Unfortunately, the accuracy in this normalization is limited to ±10%, owing to poor statistics in the higher-energy data. This translates into a ±50% error in the Am^{242m} fission cross section in the MeV region after subtractions of the contributions of the Am^{241} contaminant.

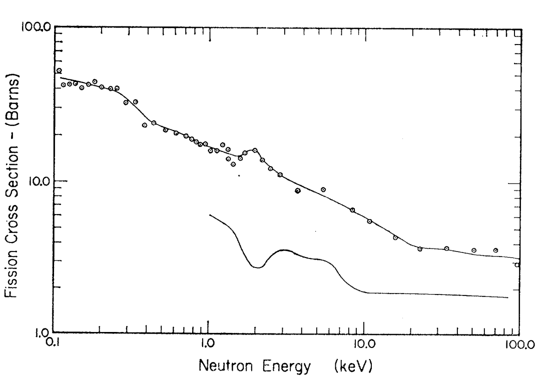

FIG. 6 The fission cross section of Am^{242m} between 0.1 and 100 keV. The solid line is the Pu^{239} fission cross section used as the flux monitor for the Am^{242m} in the high-energy measurements.

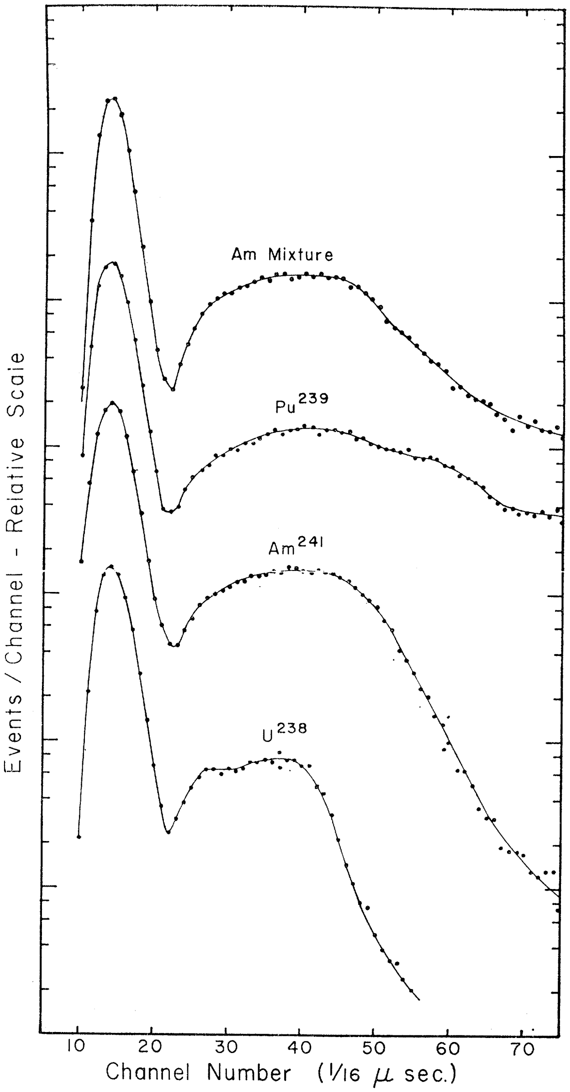

FIG. 7. Time spectra for the high-energy measurements. The more narrow peak of the curves arises from photofission induced by the γ flash from the accelerator. The broad maximum of the curves arises from the boil-off spectrum of neutrons from the (γ,n) and (γ,f) reactions in the neutron source.

However, the correction of the data for the Am^{241} also provides information on the normalization of the mixture. This subtraction was accomplished in accordance with the relationship

$$\sigma_{242m}=\sigma_{\text{mixture}}\left(\frac{\text{total Am atoms}}{\text{Am}^{242m}\text{ atoms}}\right)-4\sigma_{241}. \tag{1}$$

If the cross section of the mixture has not been normalized properly at a few keV, the cross section will show a step up or down at the position of the Am^{241} fission threshold after the subtraction of the Am^{241} from the Am^{242m}. We have chosen to adjust the normalization to the intermediate data such that the cross section for Am^{242m} is smooth across the Am^{241} threshold. The

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[13] M. I. Kazarinova, Yu. S. Zamyatin, V. M. Gorbachev, At. Energ. (USSR) 8, 139 (1960).

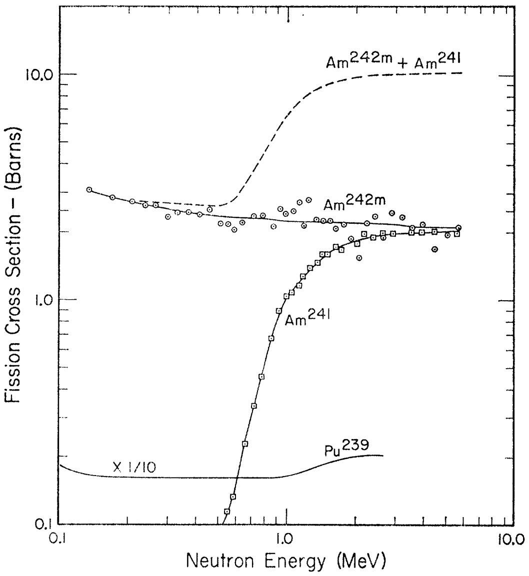

FIG. 8. Cross-section results in the MeV region. The dashed line is the cross section of the Am mixture (Am^{242}+4 Am^{241}). The data denoted by the rectangular points are the results for Am^{241}. The circles give the fission cross section for Am^{242m} after the correction for the Am^{241} contribution has been applied to the mixture. The solid curve is the Pu^{239} cross section which was assumed for the data reduction.

adjustment required to the normalization at a few keV is well within the ±10% error obtained on the basis of that normalization alone. The cross section for Am^{242m} at 2.5 MeV which results is 2.2±0.6 b. The error is four times the uncertainty of the Am^{241} fission cross section at that energy. Owing to the large subtraction for Am^{241} required for the sample, we feel that it would be very difficult to improve on the accuracy of the MeV cross section without samples of higher isotopic purity in Am^{242m}.

The slope of the Am^{241} fission cross section across the threshold is not as high as that reported in earlier measurements. We attribute this primarily to our much poorer resolution.

During these measurements, concurrent experiments were under way at Los Alamos Scientific Laboratory, using a nuclear explosion as a neutron source for a time-of-flight experiment.[4] The experiments overlapped from 20 eV to 1 MeV. The cross section of the mixture obtained from the two experiments agree to within 15% over almost the full energy range when the same value for the Am^{241} half-life is used in both experiments. The cross section for Am^{242m} is significantly different in the kilovolt region, owing to large corrections for the unusual behavior of the Am^{241} fission cross section obtained in their measurement which they applied to their data.

TABLE II. Fission resonance integrals.[a]

Nucleus	$\int_{0.5\,\mathrm{eV}}^{\infty} [\sigma(E)/E]dE$ (b)
Am^{242m}	1570
U^{233}	780
U^{235}	280
Pu^{239}	288
Pu^{241}	573

[a] Data from Ref. 14.

IV. ANALYSIS AND RESULTS

One of the more interesting questions raised earlier in this paper regarded the degree of persistence into the epithermal range of the high thermal-fission cross section systematically observed for odd-odd nuclides. A cursory comparison of the fission cross section of Am^{242m} with that of the other thermally fissile nuclides which have been measured clearly shows that the Am^{242m} cross section is considerably larger, on the whole, in the epithermal region than any of these cross sections. For example, the average cross section at 100 eV for Am^{242m} is 45 b, which is roughly a factor of 2 higher than the highest of the other fissile targets. The comparison with other nuclides can also be made in terms of the fission resonance integral defined as

$$\int_a^{\infty} (\sigma/E)dE\,.$$

Values for this quantity have been tabulated[14] for $a=0.5$ eV, and some of these are reproduced here in Table II for purposes of comparison. The value for Am^{242m} is obtained by integration of our cross section data and is a factor of 2 higher than the largest of the other fission cross sections measured to date.

The average fission cross section can be expressed in terms of average parameters when the Breit-Wigner formula is averaged over many resonances; and, if we restrict ourselves to the energy regions where only s-wave neutron interactions are important, the cross section takes the form

$$\langle\sigma_f\rangle = 2\pi^2\bar{\lambda}^2 g(\sqrt{E})\langle\Gamma_n^0/D\rangle\langle\Gamma_f/\Gamma\rangle\,, \quad \text{with} \quad g=(2J+1)/2(2I+1)\,, \qquad (2)$$

where $\bar{\lambda}$ is the wavelength of the neutron divided by 2π, E is the neutron energy in eV, I is the spin of the target, J is the spin of the compound nucleus, $\langle\Gamma_n^0/D\rangle$ is the s-wave neutron strength function, and $\langle\Gamma_f/\Gamma\rangle$ is the average ratio of fission width to total width for the resonances. It is clear that values for the product of the last two quantities can be obtained with a $1/V$ fit to the average cross section. Such a fit to the data below 1000 eV gives $\bar{\sigma}_f=(505\ \mathrm{b\ eV}^{1/2})/\sqrt{E}$. For Am^{242m} $I^{\pi}=5^-$, so that g values of 0.454 and 0.545 are associated with $J=\frac{9}{2}$ and $\frac{11}{2}$, respectively. With the approximation of $g=\frac{1}{2}$, we find a value for the product $\langle\Gamma_n^0/D\rangle\langle\Gamma_f/\Gamma\rangle$ per spin state of 1.25×10^{-4}. This value

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[14] M. K. Drake, Nucleonics 24, 108 (1966).

is a lower limit to the neutron strength function since $\langle\Gamma_f/\Gamma\rangle<1$. A comparison with neighboring nuclei[15] indicates that this quantity is not abnormally large.

Additional information on the quantities $\langle\Gamma_n{}^0/D\rangle$ and $\langle\Gamma_f\Gamma\rangle$ can be obtained from a multilevel fit to the cross section. It is probably not meaningful to attempt to fit these data above about 3.8 eV, since the data are less accurate above that energy and corrections for the contributions of the Am^{241} contaminant to the data could not be made. In Fig. 9 we have plotted the data $\sigma_f/\sqrt{E}$ below 3.8 eV, where Am^{241} cross section corrections have been applied. The dominant feature of the figure is the very large resonance at 0.173 eV. The quantity $\sigma_f\sqrt{E}$ at the peak of this resonance appears to be larger than that of any other resonance observed over the full energy range of the experiment. It is, perhaps, surprising to note that the resonance appears to be almost symmetric, suggesting little evidence of interference with other levels.

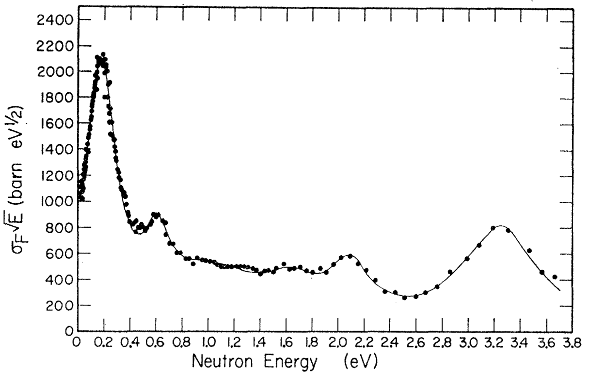

FIG. 9. The quantity $\sigma_f\sqrt{E}$ is shown versus the neutron energy. The data have been corrected for Am^{241}. The solid line is a sum-of-single-levels fit to the data.

Lynn[16] has pointed out that there is little advantage in performing a multilevel fit rather than a sum-of-single-levels fit when the width of the resonances is of the same magnitude as the spacing, and illustrates this with simulated cross sections for U^{235}. Since the width and spacing of levels for Am^{242m} seem to be similar to that for U^{235}, and since the predominant peak at 0.173 eV shows little resonance-resonance interference, we have attempted only the sum-of-single-levels fit. We have fitted the curve with a set of six single levels, as shown by the solid line through the data of Fig. 9. No negative energy level was required to fit this data. This is probably a consequence of the very large resonance at 0.173 eV, which dominates the cross section at lower energy and masks the effects of resonances at negative energy, which are almost certainly much smaller in comparison. The fit appears to deviate from the data somewhat at 0.45 and 1.3 eV, suggesting possible effects of level-level interference. The deviation at 1.3 eV could also be related to uncertainties in correction of the data for the Am^{241} resonance at 1.27 eV.[10] The fit falls below the measured data near the upper energy limit of the figure, since contributions from the wings of higher-energy resonances were neglected. The parameters for the fit are given in Table III. The first column contains the resonance energy, the second column the total width, and the third column the peak cross section. If we assume a capture width of 50 meV, these data give the values for the neutron width in column 6. Bohr and Wheeler[17] have shown that an estimate of the number of fully open channels N can be obtained from the relation $N=2\pi\langle\Gamma_f/D\rangle$. The value obtained from the six resonances is 5.0, suggesting at least two fully open channels per spin state, or even more partially open channels. The single-level fit, therefore, might be more valid than it first appears, since the possibility of two levels falling close enough together and fissioning primarily through the same channel so as to interfere is smaller as the number of channels increases.[18] For purposes of comparison, the value for $2\pi\langle\Gamma_f/D\rangle$ for all other thermally fissile targets is given in Table IV. The value for Am^{242m} is twice as high as the largest of the other isotopes and this must account, in part, for the large fission cross section for Am^{242m} which persists to kilovolt neutron energies.

The value for the strength function per spin state obtained from the resonance fit is $\langle\Gamma_n{}^0/D\rangle=1.8\pm1.1\times10^{-4}$. This value can also be compared with the result from the $1/V$ fit to the epithermal cross section. A value for $\langle\Gamma_f/\Gamma\rangle=0.90$ is obtained from the resonance fit if Γ_γ is assumed to be constant from resonance to resonance and equal to 50 meV. By substituting this value into the expression obtained earlier from the $1/V$ fit $(\langle\Gamma_n{}^0/D\rangle\langle\Gamma_f/\Gamma\rangle=1.25\times10^{-4})$ we find $\langle\Gamma_n{}^0/D\rangle=1.4\times10^{-4}$, in good agreement with the value obtained from the resonance fit alone. The level spacing per spin state D obtained from the single-level fit is $D=1.2\pm0.42$ eV. The value might well be smaller than this, since no corrections for missed levels could be applied. Moore and Simpson[19] plotted the logarithm of the level density

TABLE III. Resonance parameters from shape fit.

E_0 (eV)	Γ (eV)	σ_0	Γ_n (meV)	$\Gamma_n{}^0$ (meV)	Γ_f (eV)
0.173	0.280	4695	0.213	0.512	0.230
0.61	0.220	575	0.077	0.098	0.170
1.02	1.05	396	0.342	0.339	1.00
1.65	0.450	168	0.108	0.084	0.400
2.09	0.375	266	0.186	0.128	0.325
3.25	0.700	426	0.806	0.447	0.650

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[15] Other values summarized by R. E. Coté, R. F. Barnes, and H. Diamond [Phys. Rev. **134**, B1281 (1964)].

[16] J. E. Lynn, in *Proceedings of the International Conference on the Study of Nuclear Structure with Neutrons, Antwerp* (North-Holland Publishing Co. Amsterdam, 1965), p. 125.

[17] N. Bohr and J. A. Wheeler, Phys. Rev. **56**, 426 (1939).

[18] Erich Vogt, Phys. Rev. **112**, 203 (1958).

[19] M. S. Moore and O. D. Simpson, in Proceedings of the Conference on Neutron Cross-Section Technology, Washington, D. C., 1966, Vol. II, p. 840 (unpublished).

TABLE IV. Comparison of values[a] for $2\pi\langle\Gamma_f/D\rangle$.

Nucleus	$2\pi\langle\Gamma_f/D\rangle$	Reference
Am^{242m}	2.5	This work
U^{232}	0.3	b
U^{233}	1.2	c
U^{235}	0.25	d
Pu^{239}	0.05	e
Pu^{241}	0.85	f

[a] All values quoted per spin state.
[b] G. D. James, Nucl. Phys. **55**, 517 (1964).
[c] H. Nifenecker, J. Phys. (Paris) **25**, 877 (1964).
[d] A. Michaudon, H. Derrien, P. Ribon, and M. Sanche, Nucl. Phys. **69**, 545 (1965).
[e] Reference 12.
[f] M. S. Moore, O. D. Simpson, T. Watanabe, J. E. Russell, and R. W. Hockenbury, Phys. Rev. **135**, B945 (1964).

versus neutron binding energy after correcting for the $2J+1$ dependence of the level density, using the relation $\rho=\rho_0(2J+1)$, where J is the spin of the levels. They find that data for both even-even and even-odd nuclei can be fitted by a single straight line. This line predicts a value of D for Am^{242m} of 1.1 eV, in good agreement with the value of 1.2 obtained from this experiment. Therefore, the spin-independent level density for Am^{242m} probably is not anomalously high but is consistent with other even- and odd-mass nuclides. Of course, the actual level density is higher than most other nuclides since both the excitation energy[20] of the compound nucleus Am^{243} (6.335 MeV) and the target spin[21] $I=5$ are relatively large.

The cross section at 3 MeV of 2.15 b is in good agreement with the empirically-predicted[22] value of 2.2 b.

V. SUMMARY

These measurements indicate that the high fission cross section observed at thermal energies extends into the epithermal neutron energy range, but that at 1 MeV the cross section agrees well with values predicted from empirical systematics. The very large cross section at thermal energy is a consequence of a large resonance located at 0.173 eV. From a sum of single-levels fit to the low-energy resonances and a $1/V$ fit to the epithermal fission cross section, values for D, $2\pi\langle\Gamma_f/D\rangle$, and $\langle\Gamma_n{}^0/D\rangle$ were obtained. The value for $2\pi\langle\Gamma_f/D\rangle$ from the six resonances is unusually large, and this, along with a moderately high strength function, appear to be the primary reasons for the high cross section in the epithermal neutron range. The large value for $2\pi\langle\Gamma_f/D\rangle$ found for this nucleus might be generally characteristic of odd-odd targets and thus might account for the systematically higher thermal fission cross sections for this species which was illustrated in Fig. 1.

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[20] J. H. E. Mattauch, W. Thiele, and A. H. Wapstra, Nucl. Phys. **67**, 1 (1965).

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[22] H. L. Smith, R. K. Smith, and R. L. Henkel, Phys. Rev. **125**, 1329 (1962).