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NEUTRON REACTIONS ON U-239

(U)

Donald G. Gardner

April 24, 1975

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NEUTRON REACTIONS ON U-239^{*}

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April 24, 1975

SUMMARY

Calculations were made of the major reactions induced by neutrons in the energy range of 10 ev to 2.5 MeV incident on ^{239}U . Both the $23.5\text{ m } 5/2^+$ ground state and the $0.78\text{ }\mu\text{s } 1/2^+$ isomeric state of ^{239}U were considered as targets. The bulk of the calculations were performed with the COMNUC and UHL statistical model codes using Moldauer's optical-model parameters, although a rough correction for direct reactions was also made. Specifically, the total, shape elastic, compound elastic, inelastic, capture, and fission cross sections are presented in tabular and graphic form over the specified neutron energy range. In addition, the fission cross sections were tentatively extrapolated down to thermal energy where they are compared with an unpublished measurement. For neutron energies above 500 keV the fission calculations are compared with predictions derived from published experimental measurements of the (t,pf) reaction on ^{238}U .

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INTRODUCTION

The isotope ^{239}U will be formed by neutron capture when ^{238}U is exposed to a flux of neutrons. From consideration of systematics, it is expected that the fission barrier in ^{240}U will be somewhat lower than the neutron separation energy, which implies that ^{239}U will undergo fission with thermal neutrons, as opposed to ^{238}U which has a fission threshold around 1 MeV. To ensure the proper interpretation of nuclear events in which large amounts of ^{238}U are involved it is important to estimate the production and the subsequent fission of ^{239}U .

Unfortunately, the ground state half-life of ^{239}U is only 23.54 min. The 134-keV isomer has the even shorter half-life of 0.78 μs . Direct measurements of the fission cross section do not seem to have been published, although an old, unpublished value of 14 ± 3 b for pile neutrons is cited in Reference 1. More recently² an estimation of the $^{239}\text{U}(\text{n}, \text{fission})$ cross section was given for neutrons in the range 0.5 to 2.25 MeV. Here the fission probability was measured for the reaction $^{238}\text{U}(\text{t}, \text{p fission})$ with tritons around 18 MeV in energy. From the Q-value for the (t,p) reaction the excitation energy of the fissioning ^{240}U nucleus was determined. The cross section for formation of such a ^{240}U nucleus by neutron capture on ^{239}U was obtained from an optical-model calculation. The product of the formation cross section and the ^{240}U fission probability was assumed to yield the (n,fission) cross section for ^{239}U .

PRESENT CALCULATION

This report discusses a preliminary attempt to calculate all of the important reactions induced by neutrons reacting with ^{239}U both in its ground state and in its isomeric state. Neutrons in the energy range 10 ev to 2.5 MeV were considered, and

the fission results were extrapolated down to thermal energy. The two principle computer codes that were used were COMNUC³ and an unnamed code by M. Uhl.⁴ These are both statistical model codes. A rough estimate of the direct reaction contribution was made using the FOURPLUS code⁵ of C. Dunford. For the optical-model calculations required to compute the neutron transmission coefficients, the optical-potential parameters of Moldauer⁶ were used. The radiation widths for ^{239}U and ^{240}U were estimated using a simple model⁷ built into the COMNUC code. For the energy dependence of the radiation width we assumed the Brink-Axel giant dipole formalism. The double-hump giant dipole resonance had the following parameters: energy and width of first peak were 10.96 MeV and 2.90 MeV, energy and width of second peak were 14.04 MeV and 4.52 MeV, and the ratio of second-peak to first-peak height was 1.23. The same parameters were used for both ^{239}U and ^{240}U , while the radiation widths calculated by the codes were 36 and 30 mv for ^{240}U and ^{239}U , respectively.

Of great importance to any calculation such as this are the low-lying nuclear levels in the target and the compound nuclei.⁸ These are given in Tables I and II.

In order to calculate the (n,γ) competition and the inelastic scattering to the continuum of levels in ^{239}U and ^{240}U above those listed in Tables I and II, it was necessary to employ a level-density expression. A combined constant-temperature and Fermi-gas prescription was used, as described by Gilbert and Cameron⁹ and by Cook and co-workers.¹⁰ No attempt was made here to improve on these parameters.

The COMNUC code permits the use only of a single-hump fission barrier, and computes the transmission through the barrier as a function of energy in the usual Hill-Wheeler formalism. The principal difficulty is to describe the discrete fission channels in terms of spin, parity, barrier energy, and barrier curvature. The code is limited to 20 discrete channels, above which a continuum of fission channels is used in the same manner that a level-density expression is used to compute a continuum of nuclear levels.

TABLE I

Nuclear Level Structure and Gamma-Ray Decay Modes of ^{239}U

Level No.	Level Energy (MeV)	$J^\pi(K)$	Primary Gamma-Ray Decay Modes Final Level energy(% branch)	$T_{1/2}$
1	0.0	$5/2^+ (5/2)$	-----	23.54 m
2	.043	$7/2^+ (5/2)$	0.0 (100%)	
3	.097	$9/2^+ (5/2)$	0.0(70%), .043 (30%)	
4	.134	$1/2^+ (1/2)$	0.0(100%)	.78 μs
5	.146	$3/2^+ (1/2)$	.134(100%)	
6	.165	$11/2^+ (5/2)$	.043(95%), .097(5%)	
7	.173	$7/2^+ (7/2)$	0.0(100%)	
8	.194	$5/2^+ (1/2)$	.133(100%)	
9	.195	$7/2^- (7/2)$	0.0(100%)	
10	.220	$7/2^+ (1/2)$	.145(100%)	
11	.229	$9/2^+ (7/2)$	0.0(40%), .043(10%), .173(50%)	
12	.234	$13/2^+ (5/2)$	.097(95%), .165(5%)	
13	.240	$9/2^- (7/2)$	.043(75%), .097(25%)	
14	.295	$11/2^- (7/2)$	.097(80%), .165(20%)	
15	.300	$11/2^+ (7/2)$	.173(100%)	
16	.307	$9/2^+ (1/2)$	.193(70%), .220(30%)	
17	.314	$15/2^+ (5/2)$	.165(100%)	
18	.341	$11/2^+ (1/2)$	.220(100%)	
19	.359	$9/2^+ (9/2)$	.173(100%)	
20	.360	$13/2^- (7/2)$	.165(80%), .234(20%)	

TABLE II
Nuclear Level Structure of ^{240}U

Level No.	Level Energy (MeV)	$J^\pi(K)$	Level No.	Level Energy (MeV)	$J^\pi(K)$
1	0.0	$0^+(0)$	11	1.040	$0^+(0)$
2	.045	$2^+(0)$	12	1.048	$9^-(0)$
3	.151	$4^+(0)$	13	1.078	$2^+(0)$
4	.311	$6^+(0)$	14	1.080	$2^-(2)$
5	.527	$8^+(0)$	15	1.109	$12^+(0)$
6	.674	$1^-(0)$	16	1.112	$2^+(2)$
7	.716	$3^-(0)$	17	1.113	$3^-(2)$
8	.793	$5^-(0)$	18	1.154	$3^+(2)$
9	.795	$10^+(0)$	19	1.158	$4^-(2)$
10	.903	$7^-(0)$	20	1.166	$4^+(0)$

Figure 1 illustrates the general situation for an excited ^{240}U nucleus. The principal types of competition at moderate energies are neutron emission, γ -ray emission, and fission. Discrete levels are shown for ^{239}U and ^{240}U , above which in each case the continuum of levels exists which is described by the level-density formulae. The symbol S_n represents the neutron separation energy in ^{240}U . To the right is a potential energy curve for ^{240}U , as a function of energy in the single-hump approximation. The symbol E_B denotes the ground-state fission barrier. Above the top of the barrier the ^{240}U nucleus can exist in a number of different excited vibrational and rotational states which may also fission. Soon the density of such states becomes sufficiently high that they may be adequately described by a continuum, of similar form as in the level-density case.

For ^{240}U at the top of the fission barrier one would expect to find the same type of vibrational bands as in the unexcited nucleus: $K^\pi = 0^+, 0^-, 1^-,$ and 2^+ . Cramer¹¹ has attempted to locate the position of these bands in a number of fissioning nuclei, including ^{240}U . He again employed the (t,pf) reaction and observed not only the fission event but also the angular distribution of the direct reaction proton. He reported the fission barrier height to be 5.7 MeV, which is somewhat larger than predicted by Viola and Wilkins¹², but in agreement with other estimates.¹³ The positions above the barrier of the band heads for $K^\pi = 2^+, 0^-, 1^-,$ and 2^- were also given, and it was assumed that the $K^\pi = 0^+$ band head coincided with the top of the barrier.

The bands were built upon the band heads using the expression:

$$\Delta E^*(J, K_i^\pi) = \Delta E^*(K_i^\pi) + [J(J+1) - K_i^2] E_r,$$

where $E_r = \hbar^2/2I$.

Here $\Delta E^*(K_i^\pi)$ is the position of the band head above the barrier, and E_r is the rotational energy constant, which includes the moment of inertia I . In the present

Fig. 1. Neutron and gamma-ray emission as competition to fission process in ^{240}U . (S_n is the neutron separation energy and E_B is the lowest fission barrier. A continuum of nuclear levels or fission channels is denoted by a shaded area.)

calculations E_r was taken as 0.005 MeV. In the continuum, the angular momentum dependence of the barrier height was taken as merely $J(J+1)E_r$, because there was no way to include K^2 in the level density expression. For all of the fission barriers used here, the barrier curvature $\hbar\omega$ was taken to be 0.5 MeV.

The COMNUC code can handle up to 20 discrete fission channels, above which a continuum is used. The channels used here are given in Table III, and the continuum was allowed to begin at 0.7 MeV above the ground-state fission barrier after the last discrete channel. The barrier energies in Table III are the energies of the discrete channels above the 5.7-MeV ground state barrier. It is not unreasonable to expect the fissioning nucleus at the saddle point to be less symmetric and, therefore, to have a higher density of states than the nucleus in its less deformed ground state. To compensate for this we have increased the level density parameters used to compute the density of fission channels by 15%. A discussion of this increase will be given in reference to Figure 10.

RESULTS

Statistical model calculations were carried out for incident neutrons in the energy range 10 ev to 2.5 MeV. Above about 0.3 MeV, direct inelastic neutron scattering begins to be significant, and it becomes necessary to accordingly reduce the compound-nuclear formation cross section. Because the present calculations are of a preliminary nature, a detailed coupled-channel calculation for the target ^{239}U was not made. Instead, an older calculation for ^{238}U was employed. For the present purpose it is felt that this would be adequate. However, for energies of 0.3 MeV and above both the uncorrected and the corrected cross sections will be listed. A plot of the correction factor versus energy appears in Figure 2.

Fig. 2. Direct-reaction correction factor, used to reduce the compound nucleus formation cross section as calculated with a spherical optical model and Moldauer's parameters.

TABLE III
Discrete Fission Channels For ^{240}U

Channel No.	Energy Above Barrier (MeV) ^a	$J^\pi(K^\pi)$	Channel No.	Energy Above Barrier (MeV) ^a	$J^\pi(K^\pi)$
1	0.0	$0^+(0^+)$	11	.48	$4^+(2^+)$
2	.03	$2^+(0^+)$	12	.52	$7^-(0^-)$
3	.10	$4^+(0^+)$	13	.53	$5^+(2^+)$
4	.21	$6^+(0^+)$	14	.56	$1^-(1^-)$
5	.25	$1^-(0^-)$	15	.58	$2^-(1^-)$
6	.30	$3^-(0^-)$	16	.59	$6^+(2^+)$
7	.36	$8^+(0^+)$	17	.61	$3^-(1^-)$
8	.39	$5^-(0^-)$	18	.65	$4^-(1^-)$
9	.41	$2^+(2^+)$	19	.66	$7^+(2^+)$
10	.44	$3^+(2^+)$	20	.70	$5^-(1^-)$

^aIn all cases the barrier curvature $\hbar\omega$ was assumed to be 0.5 MeV.

Both the ground state of ^{239}U and the $1/2^+$ isomer at 0.134 MeV were used as targets. It is felt that the isomeric results are as trustworthy as the ground state results because the fission channels were calculated rather than merely being extracted from experimental data for the ground state alone. As it turned out, there is not a great deal of difference in the fission cross sections between the two targets. However, for completeness we have also estimated the cross section for forming the isomer, both by neutron capture on ^{238}U and also by inelastic scattering from the ground state of ^{239}U . Table IV lists the total $^{238}\text{U}(\text{n,capture})$ cross sections that were assumed here, the fraction of the total capture cross section that produces the $1/2^+$ isomer in ^{239}U , and the deduced $^{238}\text{gsU}(\text{n,capture})^{239\text{mU}}$ excitation function. The results are also displayed in Figure 3. The total $^{238}\text{U}(\text{n,capture})$ excitation used here was derived from an earlier calculation, and, therefore, may not represent the current state of knowledge. If necessary, the fractions in Table IV may be applied to the best experimental $^{238}\text{U}(\text{n,capture})$ data to get an even better estimate for the production of the ^{239}U isomer.

The isomer in ^{239}U may also be formed by inelastic scattering from the ground state. Table V gives an estimate of this excitation function. The results also appear in Figure 4.

In the following four tables we present the major results of the ^{239}U calculations. The results are shown for both the ground state and the isomer of ^{239}U , and both with and without the correction for direct reactions. Some of the results are displayed in Figures 5-8.

Fig. 3. Neutron capture cross sections for ^{238}U .

Fig. 4. Excitation function for the population of the $1/2^+$ isomer in ^{239}U by inelastic scattering from the ground state.

Fig. 5. Elastic scattering and total neutron cross sections for ground state of ^{239}U .

Fig. 6. Compound elastic and inelastic neutron cross sections for ground state and isomeric state of ^{239}U .

Fig. 7. Neutron capture cross sections for ground state and isomeric state of ^{239}U .

Fig. 8. Neutron fission cross sections for ground state and isomeric state of ^{239}U .

TABLE IV
 Estimate of the ^{238}gsU (n,capture) Excitation Function
 for the Production of the $1/2^+$ Isomer in ^{239}U

En (MeV)	Assumed Total ^{238}U Capture Cross Section (b)	Fraction Leading to ^{239}U Isomer	Cross Section to Form Isomer (b)
.001	2.605	.540	1.407
.003	1.451	.540	.784
.006	1.121	.540	.605
.01	.9414	.538	.506
.03	.5911	.536	.317
.06	.3570	.530	.189
.1	.2266	.524	.119
.2	.1555	.504	.078
.3	.1405	.488	.069
.4	.1398	.468	.065
.6	.1583	.434	.069
.8	.1494	.404	.060
1.	.1609	.376	.060
1.2	.1180	.352	.042
1.4	.0796	.335	.027
1.6	.0560	.324	.018
1.8	.0416	.316	.013
2.	.0313	.308	.0096
2.5	.0162	.290	.0047

TABLE V

Estimate of the Production of the ^{239}U Isomer
by Inelastic Scattering from the Ground State

<u>En (MeV)</u>	<u>Fraction of Inelastic Scattering Leading to Isomer</u>	<u>Inelastic Scattering Cross Section for Production of Isomer (b)</u>
.15	.15	.10
.20	.27	.37
.30	.36	.72
.40	.38	.81
.50	.38	.82
.60	.36	.77
.70	.30	.64
.80	.28	.59
1.00	.25	.53
1.25	.22	.46
1.50	.20	.40
1.75	.20	.39
2.00	.20	.38
2.25	.20	.35
2.50	.20	.34

TABLE VI
Calculated Cross Sections for Ground State of ^{239}U ,
Without Direct-Reaction Correction

En (MeV)	Total (b)	Elastic (b)		Inelastic (b)	Capture (b)	Fission (b)
		Shape	Compound			
.00001	102.6	10.17	1.763		50.56	40.14
.00002	75.51	10.17	1.733		35.40	28.26
.00003	63.53	10.17	1.711		28.69	23.00
.00005	51.52	10.16	1.678		21.98	17.73
.00007	45.13	10.16	1.652		18.42	14.93
.0001	39.44	10.15	1.620		15.26	12.43
.0002	30.92	10.14	1.547		10.55	8.701
.0003	27.15	10.13	1.497		8.485	7.057
.0005	23.39	10.11	1.424		6.451	5.419
.0007	21.41	10.11	1.372		5.382	4.552
.001	19.65	10.10	1.312		4.454	3.787
.002	17.05	10.06	1.186		3.139	2.670
.003	15.93	10.02	1.112		2.605	2.194
.005	14.85	9.959	1.026		2.123	1.742
.007	14.30	9.905	.9825		1.897	1.517
.01	13.84	9.831	.9600		1.717	1.332
.02	13.22	9.618	1.040		1.464	1.095
.03	12.97	9.434	1.198		1.332	1.011
.05	12.73	9.115	1.487	.0779	1.117	.9310
.07	12.56	8.836	1.675	.2294	.9349	.8823
.1	12.32	8.469	1.845	.4031	.7592	.8405

TABLE VI (Cont.)

.15	11.89	7.952	1.889	.6948	.5679	.7908
.2	11.45	7.514	1.090	1.376	.4367	1.032
.3	10.56	6.782	.6562	2.037	.2503	.8348
.4	9.747	6.173	.4781	2.175	.1873	.7327
.5	9.039	5.651	.3578	2.231	.1539	.6441
.6	8.442	5.201	.2698	2.268	.1332	.5681
.7	7.949	4.813	.2048	2.296	.1188	.5137
.8	7.549	4.483	.1598	2.312	.1100	.4804
1.0	6.976	3.976	.1028	2.344	.0985	.4474
1.25	6.564	3.587	.0636	2.373	.0873	.4398
1.5	6.357	3.411	.0394	2.367	.0742	.4446
1.75	6.270	3.389	.0238	2.322	.0610	.4462
2.0	6.258	3.469	.0139	2.247	.0484	.4460
2.25	6.295	3.609	.0078	2.161	.0370	.4440
2.5	6.367	3.779	.0043	2.075	.0276	.4430

TABLE VII
Calculated Cross Sections for Ground State of ^{239}U ,
With Direct-Reaction Correction

<u>En</u> <u>(MeV)</u>	<u>Compound</u> <u>Elastic (b)</u>	<u>Inelastic</u> <u>(b)</u>	<u>Capture</u> <u>(b)</u>	<u>Fission</u> <u>(b)</u>
.3	.650	2.107	.248	.827
.4	.468	2.262	.183	.718
.5	.344	2.326	.148	.618
.6	.254	2.357	.125	.534
.7	.191	2.405	.111	.478
.8	.146	2.427	.101	.439
1.0	.092	2.478	.088	.400
1.25	.056	2.526	.076	.385
1.5	.034	2.541	.064	.383
1.75	.020	2.524	.052	.379
2.0	.012	2.456	.040	.372
2.25	.0064	2.388	.030	.366
2.5	.0035	2.296	.022	.359

TABLE VIII
Calculated Cross Sections for Isomeric State of ^{239}U ,
without Direct-Reaction Correction

En (MeV)	Compound Elastic (b)	Inelastic (b)	Capture (b)	Fission (b)
.00001	3.199	3.776	61.34	23.92
.00002	3.111	2.640	42.67	16.80
.00003	3.048	2.141	34.42	13.65
.00005	2.955	1.645	26.18	10.50
.00007	2.886	1.384	21.81	8.825
.0001	2.804	1.155	17.94	7.337
.0002	2.622	.8238	12.18	5.120
.0003	2.500	.6862	9.666	4.147
.0005	2.333	.5603	7.189	3.185
.0007	2.216	.4955	5.896	2.678
.001	2.085	.4500	4.768	2.235
.002	1.822	.4138	3.150	1.602
.003	1.666	.4206	2.477	1.343
.005	1.477	.4569	1.846	1.108
.007	1.361	.4974	1.536	1.001
.01	1.253	.5540	1.279	.9222
.02	1.035	.8764	.8507	.8336
.03	1.012	1.004	.7043	.8244
.05	.9472	1.308	.5340	.8244
.07	.9824	1.454	.4560	.8292
.1	.6829	1.711	.3885	1.065

TABLE VIII (Cont.)

.15	.7104	1.876	.3972	1.048
.2	.7007	1.924	.2582	1.051
.3	.6002	1.936	.1898	1.053
.4	.4404	2.047	.1358	.9493
.5	.3139	2.109	.1057	.8576
.6	.2268	2.109	.0904	.8126
.7	.1622	2.143	.0781	.7491
.8	.0993	2.176	.0721	.7145
1.0	.0602	2.219	.0664	.6479
1.25	.0355	2.293	.0613	.5745
1.5	.0212	2.310	.0546	.5412
1.75	.0124	2.273	.0463	.5238
2.0	.0071	2.205	.0372	.5090
2.25	.0039	2.119	.0288	.5004
2.50	.0021	2.033	.0216	.4961

TABLE IX

Calculated Cross Sections for Isomeric State of ^{239}U ,
with Direct-Reaction Correction

<u>En</u> <u>(MeV)</u>	<u>Compound</u> <u>Elastic (b)</u>	<u>Inelastic</u> <u>(b)</u>	<u>Capture</u> <u>(b)</u>	<u>Fission</u> <u>(b)</u>
.3	.594	2.007	.188	1.042
.4	.431	2.136	.133	.930
.5	.301	2.209	.102	.823
.6	.213	2.207	.085	.764
.7	.151	2.263	.073	.697
.8	.091	2.303	.066	.654
1.0	.054	2.366	.059	.580
1.25	.031	2.456	.054	.503
1.5	.018	2.492	.047	.465
1.75	.011	2.482	.039	.445
2.0	.0059	2.421	.031	.425
2.25	.0032	2.353	.024	.413
2.5	.0017	2.262	.017	.402

It is of interest to try to extrapolate the present fission calculations down to thermal energy, to see how they compare with the unpublished pile neutron measurement mentioned previously. There is no way of doing such an extrapolation with any accuracy, but it is still of interest to see roughly what cross section might be expected. The procedure used was as follows: the calculated results were extrapolated back to an energy near where the first resonance might be expected; then, the results were decreased by a factor that might reflect a typical resonance in uranium; and, finally, the results were further extrapolated according to $1/v$ to thermal energy.

There is, of course, no way to estimate exactly where the first resonance might be, but somewhere between 0.1 and 1 ev would be reasonable. Actually, in the present case the extrapolation is not too sensitive to this position. We have chosen to decrease the cross section at 1 ev by a factor of 20. This might be good to within a factor of 4. The results are presented in Figure 9, along with the single data point listed in Reference 1. It is difficult to compare the calculations with the measurement because the actual energy distribution of the pile neutrons is unknown. Presumably, it is of a Maxwell-Boltzmann type, with a sizable high-energy tail. The extrapolations are not inconsistent with such an assumption.

A more interesting comparison may now be made. It was mentioned before that Cramer and Britt² predicted $(n, \text{fission})$ values for ^{239}U based on their (t, pf) measurements on ^{238}U . Figure 10 shows the present calculation along with a modification of their predictions. To be consistent with the present calculations we used the calculated optical-model compound-nucleus formation cross sections from Moldauer's parameters with the fission probabilities of Cramer and Britt. This resulted in somewhat smaller fission cross sections than were listed in their article.

Fig. 9. Extrapolation of the ^{239}U (n,fission) excitation functions down to thermal energy. (Thermal-energy data point is a pile-neutron measurement.¹⁾)

Fig. 10. Comparison between two calculations of ground state $^{239}\text{U}(n,\text{fission})$ excitation function and cross sections inferred from $^{238}\text{U}(t,\text{pf})$ measurements (circles). Solid line resulted from a 15% enhancement of the continuum fission-channel density parameter; dotted line shows results without this enhancement.

For incident neutron energies below about 500 keV, the bulk of the fission cross section is due to the discrete fission channels. Above 500 keV the contribution of the continuum of fission channels starts to become significant. It was mentioned previously that the level density parameter used to compute the density of fission channels in the continuum was increased by 15% over that used to compute the density of nuclear levels in ^{240}U . The magnitude of the increase was estimated by comparing a number of calculations with the fission cross section derived from the Cramer-Britt data. The lower curve in Figure 10 resulted when no increase was made in the level density parameter, while the upper curve includes the 15% increase. A 20% increase caused the calculation to fall above the data points around 2 MeV.

The estimates of the $^{239}\text{U}(n,f)$ cross section based on the (t,pf) measurements are expected to be larger than the actual $^{239}\text{U}(n,f)$ cross section, because a far wider range of angular momenta is carried in by the high-energy tritons than is the case for low-energy neutrons. In Reference 2 the angular momentum distribution transferred by the tritons is shown to be relatively smooth, peaking at $\ell = 4$, and maintaining a significant value from $\ell = 0$ to $\ell = 10$. In the present case, Moldauer's neutron optical-model parameters produce the vastly different distributions shown in Figure 11 for neutron energies of 0.5 and 2.0 MeV. The wider angular-momentum distribution in the triton case will favor fission because the neutron and gamma-ray competition must find high spin states to decay to at low energies in ^{239}U and ^{240}U , respectively. On the other hand we have seen that the continuum fission channels are enhanced over the continuum of nuclear levels, and the high-spin fission channels are only shifted up in effective energy by at most one oscillator width over the low-spin channels. Thus, while such (t,pf) reactions may be used as a guide in estimating (n,f) cross sections, they must be used with care below an equivalent neutron energy of 5 MeV.

Fig. 11. Angular momentum transfer from Moldauer's transmission coefficients.

REFERENCES

1. D. Hughes and R. Schwartz, "Neutron Cross Sections," BNL-325, 2nd edition, July, 1958.
2. J. Cramer and H. Britt, Nucl. Sci. Eng. 41 (1970) 177.
3. C. L. Dunford, "A Unified Model for Analysis of Compound Nucleus Reactions," AI-AEC-12931 (July, 1970).
4. M. Uhl, Acta Physica Austriaca 31 (1970) 245.
5. Unpublished computer program by C. L. Dunford.
6. P. Moldauer, Nucl. Phys. 47 (1963) 65.
7. Unpublished results by D. G. Gardner and C. Gatrouris, Lawrence Livermore Laboratory.
8. Nuclear levels in ^{239}U and ^{240}U supplied by Eugene Henry, Lawrence Livermore Laboratory.
9. A. Gilbert and A. Cameron, Can. J. Phys. 43 (1965) 1446.
10. J. Cook. et al., AAEC/TM 392 (1967).
11. J. Cramer, LA-4198 (1969).
12. V. Viola and B. Wilkins, Nucl. Phys. 82 (1966) 65.
13. H. Pauli and T. Ledergerber, Nucl. Phys. A175 (1971) 545.

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