Isomeric Cross-Section Ratios in (n,γ) Reactions*

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Isomeric cross-section ratios for (n,γ) reactions have been measured for the even-even target nuclei Te^{120}, Te^{130}, Ce^{138}, Pt^{196}, and Hg^{196}. In addition, cross sections for $Pt^{194}(n,\gamma)Pt^{195m}$ and $Pt^{192}(n,\gamma)Pt^{193m}$ reactions have also been measured. It is found that isomeric cross-section ratios ($\sigma_{\text{low spin}}/\sigma_{\text{high spin}}$) tend to increase at the magic numbers of neutrons as well as protons. Away from the magic numbers, these ratios obey an empirical rule which states, "The isomeric cross-section ratios for various isotopes in the same element remain approximately the same provided the spins of the compound nuclei and the isomeric states are the same for all the isotopes." This rule applies to even-even target nuclei. On the basis of this new empirical rule, the cross sections for the production of some of the isomeric states have been estimated. Multiplicity factors (i.e., the number of γ rays emitted per neutron capture by target nuclei) have been calculated for $A<100$, using capture γ-ray spectra of Groshev *et al.* Theoretical calculations of the isomeric cross-section ratios are performed using the spin dependence of the nuclear level density expression of Bloch. Experimental values of the isomeric cross-section ratios are compared with the theoretical values and the results are discussed.

INTRODUCTION

WHEN a slow neutron is captured by a target nucleus X, it gives rise to an excited nucleus $X+n$. The excitation energy of the compound nucleus $(X+n)$ is equal to the binding energy of the last neutron in $X+n$. This excited nucleus reverts to the ground state in a very short time ($\sim 10^{-13}$ sec), normally by the emission of gamma rays if no other channels of decay are available. The γ-ray spectra from these excited nuclei are quite complex. It was first found by Muehlhause[1] that the average number of γ rays emitted by the excited nucleus before it de-excites to the ground state varies between 2 and 4. If we have now two low-lying levels with a large spin difference, then each of these low-lying levels has a certain probability of being populated by the γ-ray cascade. The ratio of the population of these isomeric states is called the isomeric cross-section ratio.[2] der Mateosian and Goldhaber[3] studied isomeric cross-section ratios and found that the ratio of the cross sections for the production of the two isomeric states by slow neutron capture is such that the isomeric state with spin closer to that of the compound nucleus is favored.

Huizenga and Vandenbosch[4] have made calculations concerning isomeric cross-section ratios. In doing so they assumed a spin dependence of the level density given by Bethe[5] and Bloch,[6] which is of the form

$$\rho(J)=\rho(0)(2J+1)e^{-J(J+1)/2\sigma^2}, \quad (1)$$

where $\rho(0)$ is the density of the levels with spin zero, $\rho(J)$ is the density of the levels with spin J, and σ is a parameter[7] which determines the spin dependence of the level density. In their calculation both σ and the multiplicity factor ν (i.e., the average number of γ rays emitted in the process of the de-excitation of the compound nucleus) are variables. By changing the values of these two variables separately from 3 to 5, they were able to show that calculated values of the isomeric cross-section ratios are close to the experimental value.

We have measured the isomeric cross-section ratios for Te^{120}, Te^{130}, Ce^{138}, Pt^{196}, and Hg^{196}. The even-even target nuclei were chosen to avoid the ambiguity in spin of the compound nucleus. Thus, in each of these cases the compound nucleus has a spin and parity of $\frac{1}{2}^+$. The study of the isomeric cross-section ratios for even-even target nuclei shows that the ratio of the cross section for the production of the isomeric state with lower spin to the isomeric state with higher spin, has a large value at the magic numbers. Also away from the magic numbers, it is found that this ratio stays approximately the same for various isotopes in the same element provided the spins of the compound nucleus and the isomeric states are the same for all the isotopes. This statement applies only to even-even target nuclei. On the basis of this rule it is possible to estimate the cross section for the production of certain isomeric states.

We have also made some calculations concerning isomeric cross-section ratios. In doing so, the values of the multiplicity ν have been taken for some of the cases from the data of Groshev *et al.*[8]

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[1] C. O. Muehlhause, Phys. Rev. **79**, 277 (1950).

[2] E. Segrè and A. C. Helmholz, Revs. Modern Phys. **21**, 271 (1949); M. Goldhaber and R. D. Hill, ibid. **24**, 179 (1952).

[3] E. der Mateosian and M. Goldhaber, Phys. Rev. **108**, 766 (1957).

[4] J. R. Huizenga and R. Vandenbosch, Phys. Rev. **120**, 1305 (1960); R. Vandenbosch and J. R. Huizenga, *ibid.* **120**, 1313 (1960).

[5] H. A. Bethe, Revs. Modern Phys. **9**, 84 (1937).

[6] C. Bloch, Phys. Rev. **93**, 1094 (1954).

[7] The symbol σ for the spin dependence of the level density should not be confused with the same symbol σ used for the cross section. The symbol σ when used for the cross section will always be followed by a g (meaning ground state) or m (meaning metastable state) or the lifetime of the activity involved.

[8] L. V. Groshev, V. N. Lutsenko, A. M. Demidov, and V. I. Pelekhov, *Atlas of γ-Ray Spectra from Radiative Capture of Thermal Neutrons* (Pergamon Press, New York, 1959); L. V. Groshev, A. M. Demidov, V. N. Lutsenko, and V. I. Pelekhov, in *Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy* (United Nations, Geneva, 1958), Vol. 15, p. 138.

EXPERIMENTAL PROCEDURE

The cross sections for the cases studied were measured by counting the disintegration rate of the sample in a fixed geometry. A $1\frac{1}{2}$- $\times 1\frac{1}{2}$-in. NaI(Tl) crystal was used for the detection of the γ rays. The efficiency of the crystal (intrinsic efficiency of detection $\times$ geometry factor) for various energies of the γ rays was determined by performing γ-γ and β-γ coincidences using the following standard sources: Na^{22}, Sn^{117}, Ce^{141}, Tm^{170}, Au^{198}, and Bi^{207}. The errors involved in the measurement of the cross sections are discussed in detail by Sehgal *et al.*[9] In most of the cases enriched isotopes[10] were used for measuring the isomeric cross-section ratios. The irradiations of the samples were made using the Brookhaven Graphite Research reactor. For Pt, Hg, and Te isotopes, the irradiations were made in the thermal column. In other cases, the irradiations were made at places where the cadmium ratio for maganese was very high. The isomeric cross-section ratio measured in such a flux should not as a rule be different from one measured in the thermal flux, because this cross-section ratio depends mostly upon the spins of the isomeric states involved, and the multiplicity of the γ-ray cascade and the spin of the compound nucleus formed. Since the contribution of the p-wave neutrons in such a flux is almost zero, the spin of the compound nucleus formed for the cases studied should not change from $\frac{1}{2}$.

To measure the isomeric cross section, the following well-known expression was used:

$$(nv)N\sigma_m=\frac{(dn/dt)_{t_2}e^{\lambda t_2}}{1-e^{-\lambda t_1}}, \qquad (2)$$

where (nv) is the flux of the neutrons at the point of irradiation of the sample; N is the total number of nuclei irradiated in the isotope; σ_m is the isomeric cross section for the isotope under consideration; t_1 is the time of irradiation of the sample; $(dn/dt)_{t_2}$ is the disintegration rate of the radioactive isotope at time t_2 after the sample is removed from the pile; and λ is the decay constant of the radioactive isotope formed by the absorption of the neutron by the initial isotope. From the counting rate of the sample, one can find the absolute disintegration rate $(dn/dt)_{t_2}$, knowing the efficiency of the crystal (intrinsic efficiency of detection $\times$ geometry factor). In cases when the isomeric cross-section ratio is measured, the neutron flux (nv) gets canceled. In other cases when the cross section for the isomeric state (σ_m) is measured separately, the neutron flux was calibrated either by taking Au^{197} or Al^{27} as the standard substance.

The cross section for $Ce^{138}(n,\gamma)Ce^{139}$ reaction was measured by irradiating enriched Ce^{138} with slow neutrons. The sample was then allowed to decay for about 13 days, so that all short-lifetime activities became weak. The 145-keV γ ray in Ce^{141} ($T_{1/2}=33$days) was very strong and was unresolved from the 166-keV γ-ray peak due to Ce^{139} ($T_{1/2}=140$ days). To find the Ce^{139} ($T_{1/2}=140$ days) disintegration rate, K x ray—166 keV γ-ray coincidences were performed. From the coincidence counts under the 166-keV γ-ray peak, the absolute disintegration rate N was determined from the equation

$$N_c=N(kf_K\epsilon_K)\gamma_{166}\epsilon_\gamma,$$

where N_c is the coincidence counting rate between the K x ray and the 166-keV γ ray, ϵ_K and ϵ_γ are the efficiencies for the two crystals for the K x ray and 166-keV γ ray, respectively, f_K is the fluorescent yield for the K x ray and k is the fraction of K-electron capture in the decay of Ce^{139} to La^{139}; γ_{166} is the fraction of the unconverted 166-keV γ ray. The cross section for $Ce^{138}(n,\gamma)Ce^{139}$ was compared with the cross section for $Ce^{140}(n,\gamma)Ce^{141}$ and a value of 2.1 ± 0.2 was obtained for $\sigma_{138}/\sigma_{140}$. Taking $\sigma_{140}=0.31\pm0.1$ b,[11] the value of σ_{138} was found to be 0.65 ± 0.22 b. This value was also compared to the cross section for $Sn^{116}(n,\gamma)Sn^{117m}$ ($T_{1/2}=14$ days), and a value of 108 was obtained for $\sigma_{Ce^{138}}/\sigma_{Sn^{116}}$. The cross section for the 55-sec activity of Ce^{139} was measured using $Al^{27}(n,\gamma)$ as a standard, and a value of 18 ± 5 mb was obtained.

The isomeric cross-section ratio for Pt^{196} was measured by irradiating enriched Pt^{196} (65.5%). The 86-min activity due to Pt^{197m} was measured by the K x ray due to the K conversion of the M_4 343-keV γ ray. The Pt^{197} ($T_{1/2}=17$ h) activity was measured by the unconverted 77-keV γ ray in Au^{197}. To calculate the cross section the decay scheme of Pt^{197m} was studied.[12] The ratio of the cross section for the ground state to that for the metastable state was thus obtained: $\sigma_g/\sigma_m=15.7\pm2.4$. This ratio was also checked by measuring the total beta activity of Pt^{197m} with an anthracene crystal and comparing it with the beta activity of Pt^{197}. After applying the proper corrections, a ratio of 13.6 ± 3.0 was obtained for σ_g/σ_m. This value is essentially in agreement with the above value. Taking the value of $\sigma_g=0.8\pm0.1$ b from the results of Seren *et al.*,[11] a value of 50 ± 10 mb was obtained for σ_m.

The cross section for $Pt^{194}(n,\gamma)Pt^{195m}$ ($T_{1/2}=3.8$ days) was measured relative to that for Au^{197} and a value of 83 mb was obtained. The cross section for Au^{197} was taken as 97 b. In Pt^{195m} the relative branching of the 129-keV γ ray and 31-keV γ ray from the level at 129 keV was determined to be 58 and 42%, respectively. This was done from the intensity of the unconverted 129-keV (E2) and 99-keV (M1) γ rays. The cross section was measured by counting the total

[9] M. L. Sehgal, H. S. Hans, and P. S. Gill, Nuclear Phys. **12**, 261 (1959).

[10] Obtained from the Stable Isotopes Division, Oak Ridge, Tennessee.

[11] *Neutron Cross Sections*, compiled by D. J. Hughes and R. B. Schwartz, Brookhaven National Laboratory Report BNL-325 (Superintendent of Documents, U. S. Government Printing Office, Washington, D. C., 1958), 2nd ed. and Suppl. No. 1.

[12] M. L. Sehgal and G. T. Emery (to be published).

number of K x rays and a value of 83 mb was obtained. When measured by means of the unconverted 99-keV γ ray a value of 92 mb was found. A mean value of 87 ± 13 mb was thus obtained for the $Pt^{194}(n,\gamma)Pt^{195m}$ cross section.

The cross section for $Pt^{192}(n,\gamma)Pt^{193m}$ was measured by irradiating enriched Pt^{192} (15.4%). A half-life of 4.7 days was obtained by following the activity under the K x-ray peak. The cross section was measured by means of the K x-ray peak as well as the unconverted 135-keV γ ray. A mean value of 2.2 ± 0.8 b was obtained for the above cross section, when measured relative to that of Au^{197}.

The isomeric cross-section ratio for Te^{130} was measured using 93.5% enriched isotope. The percentage of the isomeric transition from the 1.2-day state to the 25-min ground state was taken as 18%.[13] The ratio of the 145-keV γ ray to the beta particles for the 25-min activity was taken as equal to 1.[14] This gave a value of 6.8 ± 1.5 for the isomeric cross-section ratio σ_g/σ_m. The cross section for the ground state ($T_{1/2}=25$ min) is measured as 0.27 ± 0.06 b and that for the metastable state ($T_{1/2}=30$ h) as 40 ± 10 mb. These cross sections were measured relative to that of Au^{197}, whose cross section was taken equal to 97 b.

In the case of Te^{120}, a value of 6.2 ± 1.5 was obtained for the isomeric cross-section ratio σ_g/σ_m. Taking 1.1 b as the value of the cross section[11] for $Te^{122}(n,\gamma)Te^{123}$ ($T_{1/2}=110$ days), a value of 340 ± 60 mb was obtained for Te^{121m} ($T_{1/2}=154$ days) and 2.0 ± 0.3 b for Te^{121} ($T_{1/2}=17$ days).

The isomeric cross-section ratio in the case of Hg^{196} was measured by irradiating the sample in the thermal column. The cross section for Hg^{197m} ($T_{1/2}=24$ h) was measured through the 133- and 164-keV γ rays, whereas the cross section for Hg^{197} ($T_{1/2}=65$ h) was measured through the K x ray due to K-electron capture of Hg^{197}. The L/K electron capture ratio in this case was taken as 0.15. The ratio of $\sigma_{65\text{ h}}$ to $\sigma_{24\text{ h}}$ was found to be 36 ± 6. Huizenga and Vandenbosch[4] have reported a value of 22 ± 4 for the same ratio. These values are quite high in comparison with the previous measurement,[9] made with a well-type NaI(Tl) crystal. In the earlier measurement the cross section for the 24-h activity was measured by means of the 133-keV γ-ray photopeak, which also included the sum peak due to the 77-keV γ ray and K x ray from the decay of the ground-state activity. Since no correction for the sum peak was applied, the cross section for the 24-h activity was overestimated.

The cross section for Hg^{202} when measured relative to that for Au^{197} was determined as 4.6 ± 0.7 b. This value is essentially in agreement with 3.8 ± 0.8 b reported by Lyon,[15] who used Co^{59} as the standard.

[13] A. Badescu, O. M. Kalinkina, K. P. Mitrofanov, A. A. Sorokin, N. V. Forafontov, and V. S. Shpinel, Zhur. Eksp. i Teoret. Fiz. **40**, 91 (1961).

[14] *Nuclear Data Sheets*, National Academy of Sciences, National Research Council (U. S. Government Printing Office, Washington, D. C.).

MULTIPLICITY (ν)

As pointed out earlier, the number of γ rays per neutron capture were first measured experimentally by Muehlhause.[1] He found the value of ν by studying the singles as well as the coincidence counting rate using two anthracene crystals. In evaluating ν, he took a fixed value of the quantity $(\epsilon_1+\epsilon_2)/\epsilon_1\epsilon_2$ for the entire energy spectrum, where ϵ_1 and ϵ_2 are the efficiencies of detection of γ rays for the two anthracene crystals. This assumption is not fully justified, although the values of ν obtained by him are in reasonable agreement with the values obtained by Groshev *et al.*[8] from their capture γ-ray spectra. Groshev *et al.*[8] plotted their capture γ-ray spectra in the form $\nu(E_\gamma)H\rho$ vs energy, with energy expressed in MeV and $H\rho$ expressed in Oe-cm, where $\nu(E_\gamma)$ is the number of γ rays emitted per neutron capture per unit energy range (1 MeV). These authors have calculated the multiplicity factor for nuclei with mass number greater than 100. In the present case, we have calculated the values of ν for $A<100$ using their capture γ-ray spectra. From the capture γ-ray spectrum one can calculate the values of the multiplicity as

$$\nu_1=\int_0^1 \nu(E_\gamma)dE_\gamma=\int_0^1 \nu(E_\gamma)H\rho dE/\langle H\rho\rangle,$$

where ν_1 is the number of γ rays emitted in the energy range 0 to 1 MeV per neutron capture, and $H\rho$ corresponds to the momentum of the electron when the incident energy of the γ ray is E_γ. In the above equation, $\langle H\rho\rangle$ is the average value of the momentum of the electron when the energy of the incident γ ray lies between 0 and 1 MeV. The capture γ-ray spectra have been divided into slices of 1 MeV and the value of ν_i has

TABLE I. Values of the multiplicities for various elements with $A<100$. The values obtained by Muehlhause are also shown for comparison.

Target nucleus	Multiplicity	Muehlhause value
$_{14}Si$	4.0	
$_{15}P$	5.4	
$_{16}S$	3.8	
$_{17}Cl$	4.2	3.1
$_{19}K$	3.5	
$_{20}Ca$	5.7	
$_{21}Sc$	3.6	
$_{22}Ti$	2.8	
$_{23}V$	2.6	2.5
$_{24}Cr$	3.3	2.3
$_{26}Fe$	2.9	1.7
$_{27}Co$	2.9	
$_{28}Ni$	3.0	
$_{29}Cu$	3.0	2.6
$_{30}Zn$	4.4	

[15] W. S. Lyon, Phys. Rev. **82**, 276 (1951).

been determined in each case. The value of the multiplicity ν can then be obtained by adding all the values of ν_i for the entire energy spectrum. Since the capture γ-ray spectra of Groshev *et al.* start from about 0.3 MeV, extrapolation from 0 to 0.3 MeV has been made in all cases by joining the curve smoothly to zero. However, when the energies of the γ rays are small, the conversion coefficients become appreciable, which may falsify the capture spectra in the low-energy region. The values of the multiplicity thus calculated from the capture spectra represent lower limits. The actual values of the multiplicity may be higher by about 10 to 15% or so when transitions of low energy are involved. In addition to this error, there will be a statistical error of about 10% or so. Values of the multiplicities derived in this way have been listed in Table I.

SPIN FALLOFF PARAMETER (σ)

To find experimentally the approximate value of σ, the spin dependence of the nuclear level density, in various regions, we have taken data on nuclei with mass numbers from 51 to 119 and from 101 to 199 from the Nuclear Data Sheets.[14] The total number of experimentally known levels of each spin in these nuclei (stable as well as radioactive) has been determined and is plotted in Fig. 1. In the region of A between 51 and 119 the value of σ is less than 3, and in the region of A between 101 and 199 there are two maxima with J near

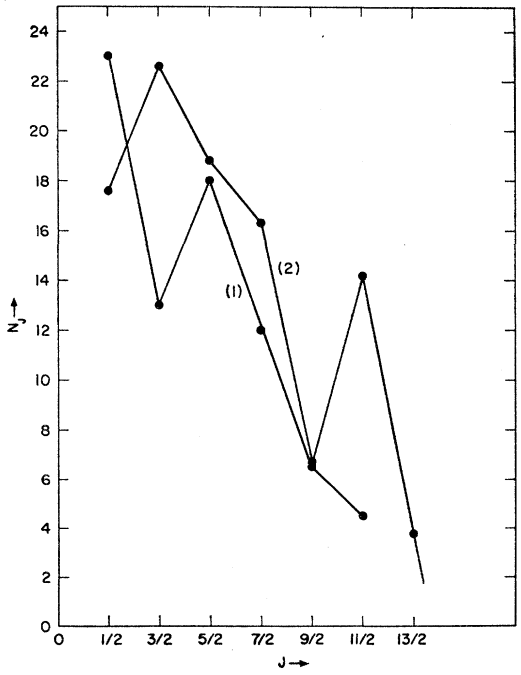

FIG. 1. Plot of N_J (the number of levels with spin J) vs J. Curves (1) and (2) correspond to the mass regions from 51 to 119 and from 101 to 199, respectively. If one determines σ by using the equation $2\sigma^2=\langle J(J+1)\rangle_{\text{av}}$, one obtains $\sigma=2.2$ for curve (1) and $\sigma=2.6$ for curve (2).

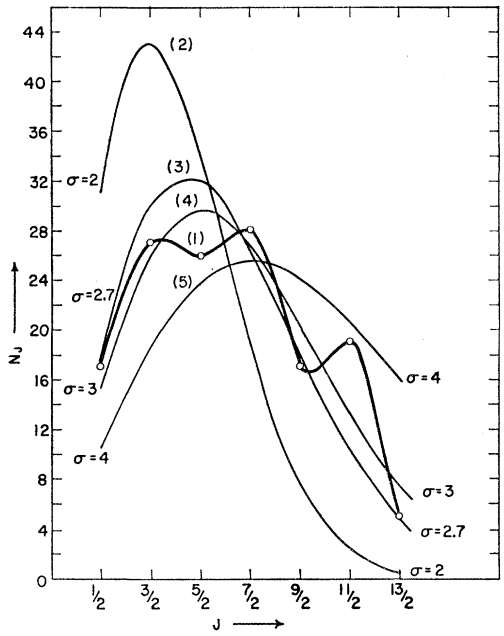

FIG. 2. Plot of N_J (the number of levels with spin J) vs J. Curve (1) corresponds to the Kisslinger and Sorensen results and curves (2), (3), (4), and (5) correspond to Eq. (1) when σ equals 2, 2.7, 3, and 4, respectively. Curves (2), (3), (4), and (5) have been normalized to the same total number of levels as in curve (1). If one determines σ from the Kisslinger and Sorensen results by using equation $2\sigma^2=\langle J(J+1)\rangle_{\text{av}}$, one obtains $\sigma=2.7$.

1.5 and 5.5, which correspond to σ approximately equal to 2 and 6, respectively. It should be pointed out that the value of σ from these curves may be falsified due to the fact that most of these levels are known from radioactive decays, in which case it is sometimes difficult to excite levels with high spins in comparison with levels of lower spins. On the other hand, since a large number of nuclei are considered, it is hoped that such an effect, if it exists, is minimized.

The levels of the odd tin isotopes have been worked out by Kisslinger and Sorensen[16] including the effect of the pairing correlation. They have predicted the levels up to about 2.5 MeV or so. Although the order of the levels predicted by them may not necessarily be correct, the order of the levels is immaterial for finding the spin distribution of the level density. The total number of levels of each spin in Sn^{117}, Sn^{119}, Sn^{121}, Sn^{123}, and Sn^{125} is plotted in Fig. 2. In the same figure, level density curves on the basis of Eq. (1) for σ equal to 2, 2.7, 3, and 4 are also plotted for comparison. A reasonable fit is attained when $\sigma\approx 3$. The level density curve drawn on the basis of the Kisslinger and Sorensen results has some structure; this is probably due to shell effects in this region. Hibdon[17] has studied the angular momenta of a large

[16] L. S. Kisslinger and R. A. Sorensen, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. 32, No. 9 (1960); R. A. Sorensen, Nuclear Phys. **25**, 674 (1961).

[17] C. T. Hibdon, Phys. Rev. **118**, 514 (1960); C. T. Hibdon, Argonne National Laboratory Report ANL-6235 (unpublished), p. 37.

number of virtual levels of Na^{24} and Al^{28} by measuring the neutron total cross section as a function of neutron energy. He found values of σ equal to 1.7 and 2.2 for Al^{28} and Na^{24}, respectively. Thus, we find that the values of the spin falloff parameter σ vary from 1.5 to 3 approximately up to the tin region. Some information also exists on the value of σ from other reaction data,[4] but in calculating the value of σ in those cases, values of the nuclear temperatures have been chosen arbitrarily which may not be valid. However, a value of 4 ± 1 has been obtained[4] for σ around $Z=80$.

DISCUSSION

Isomeric cross-section ratios (cross section for lower spin state to the cross section for higher spin state) are plotted vs A as shown in Fig. 3. It is found that at the magic numbers these cross-section ratios tend to increase. For instance, in the case of Sn^{120}, Sn^{122}, and Sn^{124} the values are quite high in comparison with the Te isotopes. In both Sn^{120}, Sn^{122}, and Sn^{124} and the Te isotopes, $h_{11/2}$ and $d_{3/2}$ states are responsible for giving rise to isomers. In Ce^{136} and Ce^{138}, the spins of the isomeric states are based on the assignments $h_{11/2}$ and $d_{3/2}$, but the isomeric cross-section ratio for Ce^{138} is higher than for Ce^{136}, correlating it with the approach of a closed neutron shell. Again in Pt^{196}, Pt^{198}, and Hg^{196} the competing spins are 5/2 and 13/2, but the isomeric cross-section ratio for Hg^{196} is quite high in comparison with the isomeric cross-section ratios for Pt^{196} and Pt^{198} because of the approach of a proton magic number. Another interesting feature of Fig. 3 is that away from the magic numbers the isomeric cross-section ratios stay approximately the same within the same element provided the spins of the isomeric states remain the same, as is true in the cases of Te, Pt, Ge, and Se isotopes. This fact helps one to estimate the cross section for one of the isomeric states when the cross section for the other isomeric state is known, and provided the isomeric cross-section ratio for another isotope in the same element is known. On the basis of this empirical rule, cross sections for certain states are given in Table II. In the same table the cross section for the production of the metastable state and the total neutron absorption cross sections are also given for comparison.

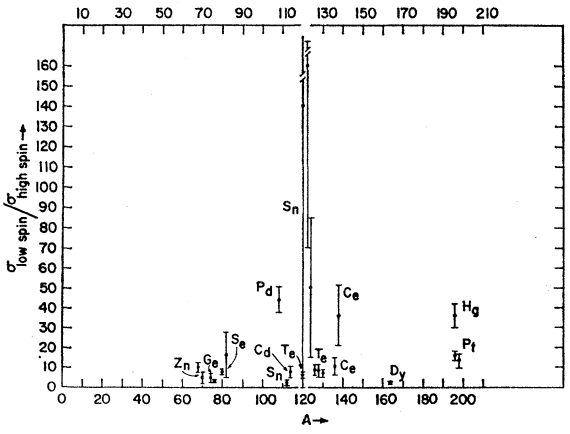

FIG. 3. Plot of the isomeric cross-section ratios ($\sigma_{\text{low spin}}/\sigma_{\text{high spin}}$) vs A of the target nuclei. The references for the data are listed in Table III.

TABLE II. Estimated cross section for the production of ground-state reaction on the basis of the new semiempirical rule. The cross section for the isomeric state and the total absorption cross section are also given for comparison.

Target nuclei	Estimated cross section in barns for the production of ground state	Isomeric cross section in barns	Total absorption cross section in barns
Se^{76}	56±28	7±3	85±7
Cd^{110}	1.5±0.9	0.2±0.1	not known
Cd^{112}	0.23±0.15	0.03±0.015	not known
Te^{122}	7.7±4.2	1.1±0.5	2.8±0.9
Te^{124}	35±24	5±3	6.8±1.3
Pt^{192}	33±14	2.2±0.8	8±8
Pt^{194}	1.3±0.4	0.087±0.013	1.2±0.9

It is interesting to compare the experimental values of the isomeric cross-section ratios with the theoretical values obtained by assuming a spin distribution of the level density given in Eq. (1). Theoretical calculations of this nature were first performed by Huizenga and Vandenbosch.[4] In calculating these isomeric cross-section ratios the following assumptions were made: (1) The γ-ray cascade from the compound nucleus is believed to be a pure dipole radiation.[18–20] (2) When the compound nucleus with spin J_c decays to levels with spin (J_c-1), J_c, and (J_c+1), it is again assumed that the density of the levels with different spins is quite high, so that all these levels are available at practically the same energy. In other words, the energies of the γ rays which populate these three levels of different spins are the same. In calculating the theoretical values of the isomeric cross-section ratios, one is required to know the values of ν and σ, the spin falloff parameter which appears in Eq. (1). If one of these parameters is known, the other can be determined by comparing the experimental values of the isomeric cross-section ratios with the theoretical values. Unfortunately, the values of the multiplicity ν for individual isotopes which give rise to isomers (by neutron absorption) is not known in most cases. However, there exists some information on the values of the multiplicities for various elements; these values are around 4. In Table III are compared the experimental values of the isomeric cross-section ratios with the theoretical values. As is clear from this table, the theoretical values of the

[18] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1952).
[19] B. B. Kinsey and G. A. Bartholomew, Phys. Rev. **93**, 1260 (1959).
[20] G. A. Bartholomew, P. I. Campion, I. W. Knowles, and G. Manning, Paper presented at the colloquium on Nuclear Interaction of Neutrons, International Union of Pure and Applied Physics, New York, September, 1957 (unpublished).

TABLE III. Comparison of theoretical values of the isomeric cross-section ratios ($\sigma_{\text{low spin}}/\sigma_{\text{high spin}}$) with the experimental values. The theoretical values are calculated only for selected values of the parameter ν.

Target nucleus	Competing levels	Theoretical values $\sigma_{\text{low spin}}/\sigma_{\text{high spin}}$	Experimental values $\sigma_{\text{low spin}}/\sigma_{\text{high spin}}$
		$\sigma=1.75$ $\nu=4$ 15.6, $\nu=5$ 11.9; $\sigma=2$ $\nu=4$ 8.7, $\nu=5$ 6.4	
Zn^{68}	1/2–9/2		10.3 ± 2.3[g]
Zn^{70}	1/2–9/2		5 ± 3[a]
		$\sigma=1.3$ $\nu=4$ 13.3, $\nu=5$ 11.6; $\sigma=1.5$ $\nu=4$ 6.7, $\nu=5$ 5.62; $\sigma=1.75$ $\nu=4$ 4.1, $\nu=5$ 3.3; $\sigma=2$ $\nu=4$ 3.0, $\nu=5$ 2.3	
Ge^{74}	1/2–7/2		5.2 ± 2.3[g]
Ge^{76}	1/2–7/2		3.2 ± 0.4[b]
Se^{80}	1/2–7/2		7.7 ± 0.8[c]
Se^{82}	1/2–7/2		16.5 ± 11.5[g]
Dy^{164}	1/2–7/2		2.2 ± 0.3[g]
Sn^{112}	1/2–7/2		2.3 ± 0.9[d]
		$\sigma=3$ $\nu=5$ 43.4	
Pd^{108}	5/2–11/2		44.4 ± 6.2[c]
		$\sigma=2$ $\nu=4$ 26.4, $\nu=5$ 16.0; $\sigma=2.5$ $\nu=4$ 14.6, $\nu=5$ 8.3	
Cd^{114}	1/2–11/2		7.8 ± 2.7[g]
		$\sigma=2$ $\nu=4$ 148.2, $\nu=5$ 67.5; $\sigma=3$ $\nu=4$ 28, $\nu=5$ 12.8; $\sigma=4$ $\nu=4$ 17.1, $\nu=5$ 7.8; $\sigma=5$ $\nu=4$ 13.9, $\nu=5$ 6.3	
Sn^{120}	3/2–11/2		140 ± 140[g]
Sn^{122}	3/2–11/2		160 ± 90[g]
Sn^{124}	3/2–11/2		50 ± 35[g]
Te^{120}	3/2–11/2		6.2 ± 1.5[f]
Te^{126}	3/2–11/2		8.8 ± 2.9[g]
Te^{128}	3/2–11/2		8.6 ± 3.3[g]
Te^{130}	3/2–11/2		6.8 ± 1.5[f]
Ce^{136}	3/2–11/2		10.5 ± 4.4[g]
Ce^{138}	3/2–11/2		36.1 ± 15.8[f]
		$\sigma=5$ $\nu=5$ 44.1, $\nu=6$ 18.0; $\sigma=6$ $\nu=5$ 37.4, $\nu=6$ 15.2; $\sigma=8$ $\nu=5$ 32.0, $\nu=6$ 13.0	
Hg^{196}	5/2–13/2		36 ± 6[f]
Pt^{196}	5/2–13/2		14.6 ± 2.5[f]
Pt^{198}	5/2–13/2		12.8 ± 3.3[e]

[a] T. T. Thwaites and W. W. Pratt, Phys. Rev. **124**, 1526 (1961).
[b] W. S. Lyon and J. S. Eldridge, Phys. Rev. **107**, 1056 (1957).
[c] C. T. Bishop, Argonne National Laboratory Report ANL-6405, 1961 (unpublished).
[d] M. Schmorak, G. T. Emery, and G. Scharff-Goldhaber, Phys. Rev. **124**, 1186 (1961).
[e] M. A. Wahlgren, Atomic Energy Commission Report TID-11807, 1961 (unpublished).
[f] Present measurements.
[g] See reference 11.

isomeric cross-section ratios depend very strongly upon the values of the multiplicity ν, especially when high spins like 11/2 and 13/2 are involved. It is, therefore, not desirable to conclude from these calculations any quantitative information concerning the spin falloff parameter σ. On the other hand, if one makes an assumption that the values of the multiplicity ν lie between 4 and 5 for all the cases in Table III, one finds that the spin falloff parameter σ has a tendency to increase with A.

It should be remarked that the shell effects in the isomeric cross-section ratios may be either due to a decrease in the value of the multiplicity ν or an increase in the value of σ at the magic numbers. In the cases of Ca^{40}, K^{39}, V^{51}, Cr, and Ni, the values of the multiplicities are 5.7, 3.5, 2.6, 3.3, and 3.0, respectively. In all these cases there is either a proton or a neutron magic number. The values of the multiplicities in the neighboring elements Cl, Sc, Ti, Fe, Cu, and Zn are 4.2, 3.6, 2.8, 2.9, 3.0, and 4.4, respectively. By comparing these two sets of nuclei, we find that there is practically no drop in the value of the multiplicity for the closed-shell

nuclei. Now, if we assume that this argument also holds true for those closed-shell nuclei which give rise to isomers, then we find that there should not be any decrease in the value of the multiplicity at the closed shell. This fact then leads us to the conclusion that the shell effects in the isomeric cross-section ratios are probably due to the spin falloff parameter σ and not to multiplicity changes.

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Total Cross Sections for Fission of U^{238} Induced by He^4 and Heavy Ions*

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The total fission cross sections have been measured for bombardment of U^{238} with He^4, B^{11}, C^{12}, N^{14}, O^{16}, and Ne^{20} ions at energies up to 10.4 MeV/nucleon. Because of the high fissionability of these systems, it is assumed that the fission cross section is equal to the total reaction cross section for heavy-ion reactions. The data have been compared with the theoretical cross-section calculations of Thomas, assuming (1) a square-well nuclear potential, and (2) a parabolic approximation to the real part of the optical potential. At energies well above the Coulomb barrier, the data are well represented using a square-well potential and $r_0=1.50$F. Near the barrier, however, the agreement is poor. With the parabolic approximation, the entire excitation function can be generally reproduced except in the case of Ne^{20}. For the He^4 data, these calculations used a well depth $V_0=-67$ MeV, a nuclear radius $r_0=1.17$F, and a diffuseness parameter $d=0.574$F. These values for heavy ions were $V_0=-70$ MeV, $r_0=1.23$ to 1.26F, and $d=0.50$ to 0.44F, r_0 increasing and d decreasing as a function of increasing heavy-ion mass.

I. INTRODUCTION

THE measurement of total reaction cross sections provides a valuable means of investigating the basic characteristics of nuclear structure. From such information, one is able to derive a greater understanding of the range of the nuclear potential and its corresponding shape at the nuclear surface. In this paper we define the total reaction cross section to be the sum of all processes in which the incident particle is absorbed or scattered into a reaction channel other than the entrance channel; i.e., it includes all nuclear reactions except shape elastic scattering.[1]

Because of the many competing nuclear processes, total reaction cross sections are generally difficult to measure. Zucker has suggested that the low incident velocity of heavy ions should enhance the probability for compound-nucleus formation at the expense of direct interaction.[2] As a consequence, one would expect the determination of total reaction cross sections from heavy-ion bombardments to be simplified somewhat, in comparison with those involving lighter charged particles ($A \leqslant 4$).

Total reaction cross sections for heavy ions have been calculated from elastic-scattering data.[3,4] Experiments are currently in progress to measure σ_R directly by a beam-attenuation method.[5] The attenuation experiments, as well as several other studies,[6–8] have revealed that the compound-nucleus picture for heavy-ion reactions is much too simple. Instead, these reactions are quite complex—largely due to the occurrence of nuclear surface reactions. Surface reactions presumably take place among the high l-wave impact parameters that lie between those which lead to pure Coulomb scattering and those which lead to complete amalgamation of the target and projectile.[8] The projectile, although partially deflected by the Coulomb field, comes into approximate tangential contact with the target—resulting in inelastic scattering, nucleon transfer, or breakup of the projectile. These may occur in abundances representing as much as 45% of the total reaction cross section.[6–11]

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[1] B. B. Kinsey, in *Handbuch der Physik*, edited by S. Flügge (Springer-Verlag, Berlin, 1957), Vol. 40, p. 208.

[2] A. Zucker, Ann. Rev. Nuclear Sci. **10**, 27 (1960).

[3] E. Goldberg and H. L. Reynolds, Phys. Rev. **112**, 1981 (1958).

[4] Jonas Alster, Ph.D. thesis, Lawrence Radiation Laboratory Report UCRL-9650, 1961 (unpublished).

[5] B. Wilkins and G. Igo, Bull. Am. Phys. Soc. **6**, 338 (1961).

[6] T. Sikkeland, E. L. Haines, and V. E. Viola, Jr., Phys Rev. **125**, 1350 (1962).

[7] H. C. Britt and A. R. Quinton, Phys. Rev. **124**, 877 (1961).

[8] R. Kaufmann and R. Wolfgang, Phys. Rev. **121**, 192 (1961).

[9] T. Sikkeland, S. Thompson, and A. Ghiorso, Phys. Rev. **112**, 543 (1958).

[10] A. Ghiorso and T. Sikkeland, in *Proceedings of the Second United Nations International Conference on the Peaceful Uses of*