Angular Momentum Effects in Charged-Particle Reactions Producing the Isomer Pair ^{119m}Te-^{119g}Te*

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The effect of angular momentum on compound-nucleus reactions was investigated by measuring the formation cross-section ratios of the isomers of tellurium-119. Nine reactions were studied. Five proceeded via the compound nucleus ^{122*}Te, and two each via the compound nuclei ^{121*}Te and ^{123*}Te. Projectiles ranging in size from ^{3}He to ^{18}O were employed. The experimentally determined ratios (upper-state to lower-state) varied from about 0.75 to 25. The expected increase of ratio with energy and projectile size was verified. An apparent direct interaction of ^{7}Li projectiles was observed. Calculations of a simple type which considered only the angular momentum distribution of the compound nucleus, and calculations of the Huizenga-Vandenbosh type were performed for the reactions studied.

I. INTRODUCTION

MANY investigators have studied the effects of compound-nucleus angular momentum on the production ratio of isomeric pairs. However, in none of these investigations (with the exception of Kiefer's work done in this laboratory) has the compound nucleus leading to the isomers been produced by more than two paths,[1] and relatively heavy projectiles have been employed in only a few.[1–4] In the present investigation, the isomer ratio (^{119m}Te/^{119g}Te) as a function of the projectile energy was determined for the following reactions:

$$^{3}\mathrm{He}+^{119}\mathrm{Sn}\rightarrow{}^{122*}\mathrm{Te}\rightarrow{}^{119g,m}\mathrm{Te}+3n,$$

$$^{4}\mathrm{He}+^{118}\mathrm{Sn}\rightarrow{}^{112*}\mathrm{Te}\rightarrow{}^{119g,m}\mathrm{Te}+3n,$$

$$^{7}\mathrm{Li}+^{115}\mathrm{In}\rightarrow{}^{122*}\mathrm{Te}\rightarrow{}^{119g,m}\mathrm{Te}+3n,$$

$$^{12}\mathrm{C}+^{110}\mathrm{Pd}\rightarrow{}^{122*}\mathrm{Te}\rightarrow{}^{119g,m}\mathrm{Te}+3n,$$

$$^{18}\mathrm{O}+^{104}\mathrm{Ru}\rightarrow{}^{122*}\mathrm{Te}\rightarrow{}^{119g,m}\mathrm{Te}+3n,$$

$$^{3}\mathrm{He}+^{118}\mathrm{Sn}\rightarrow{}^{121*}\mathrm{Te}\rightarrow{}^{119g,m}\mathrm{Te}+2n,$$

$$^{4}\mathrm{He}+^{117}\mathrm{Sn}\rightarrow{}^{121*}\mathrm{Te}\rightarrow{}^{119g,m}\mathrm{Te}+2n,$$

$$^{3}\mathrm{He}+^{120}\mathrm{Sn}\rightarrow{}^{123*}\mathrm{Te}\rightarrow{}^{119g,m}\mathrm{Te}+4n,$$

$$^{4}\mathrm{He}+^{119}\mathrm{Sn}\rightarrow{}^{123*}\mathrm{Te}\rightarrow{}^{119g,m}\mathrm{Te}+4n.$$

Five reactions proceed via the compound nucleus ^{122*}Te. Two reactions proceed through the compound nucleus ^{123*}Te, and two through ^{121*}Te. Because of variation in projectile size, the different reactions produce compound nuclei with similar excitation energies but which differ widely in angular momentum.

Two methods of calculating isomer ratios were employed. The first was a simple method which considers only the angular momentum distribution of the compound nucleus.[5] The second employed the Huizenga-Vandenbosch formalism.[6] Very little work has been reported in which this type of calculation has been applied to heavy projectiles.

II. EXPERIMENTAL PROCEDURE

A γ-ray scintillation counting technique was used. The detector was a standard 3×3-in. cylinder of thallium-activated sodium iodide with an integrally aligned photomultiplier, coupled to a pulse-height analyzer. Stacked foil target assemblies were used in all irradiations. Energies were calculated from the range-energy data of Northcliffe,[7] Hubbard,[8] and Sternheimer.[9] All targets except those of ^{115}In were prepared by electroplating the particular enriched isotope upon a thin copper, nickel, or gold-backing foil. The ^{115}In targets were prepared by evaporation of natural indium (95.8% ^{115}In) under vacuum onto aluminum.

The determination of an isomer ratio usually depends upon an accurate knowledge of the decay scheme of each isomer. Any ambiguities in the decay scheme result in uncertainties in the isomeric ratios. The isomer pair ^{119m,g}Te offers a particular advantage in this respect, in that it is possible to determine the ratios without recourse to details of the decay scheme. Pure ground-state ^{119g}Te (spin $\frac{1}{2}$ and experimentally determined half-life of 16.7 h) was produced by bombardment of KI with 240-MeV protons. Such a bombardment produces ^{119}I which decays exclusively to the ground-state isomer of tellurium-119. A conven-

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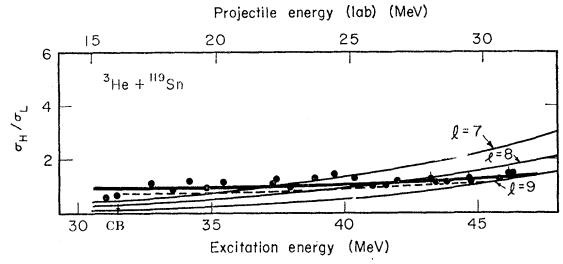
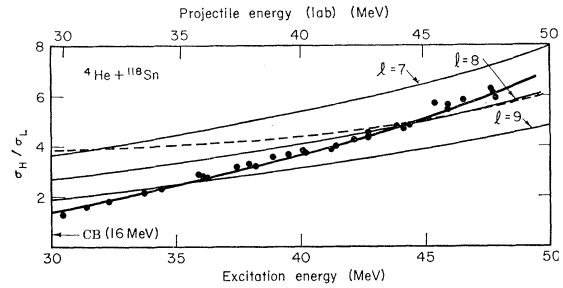


(a)



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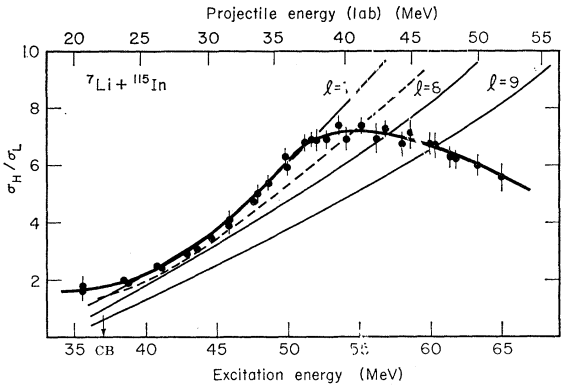

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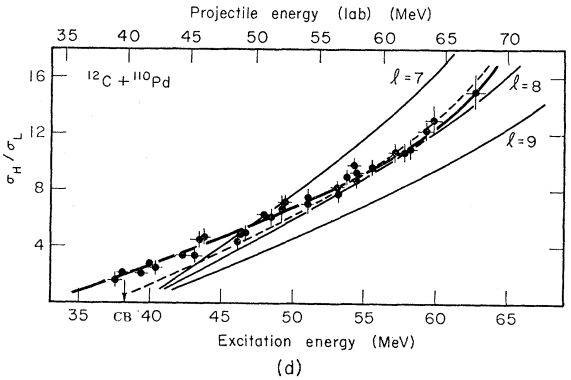

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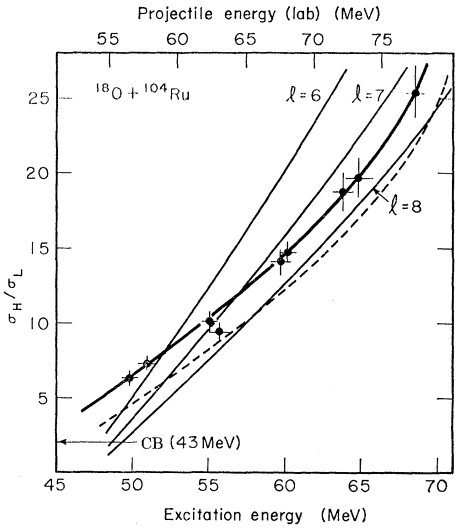

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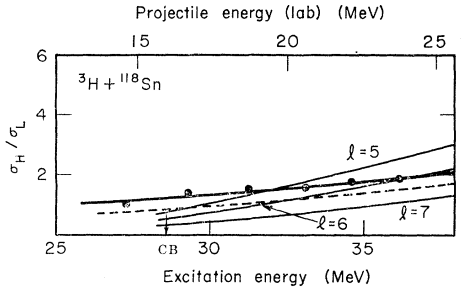
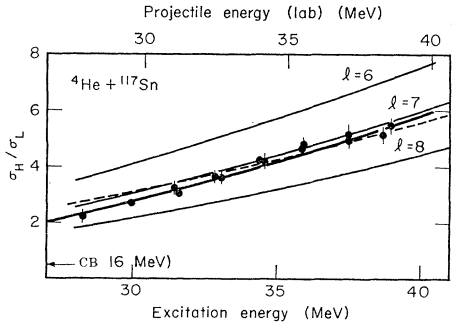


(f)



(g)

FIG. 1. Isomer ratios as a function of the excitation energy of the compound nucleus. The experimental results are given by the points and the heavy solid line. The light solid lines give the results of the simple angular-momentum partition model for partition at the l indicated. The dashed curves give the results of the Vandenbosch-Huizenga calculations. CB indicates the approximate position of the Coulomb barrier.

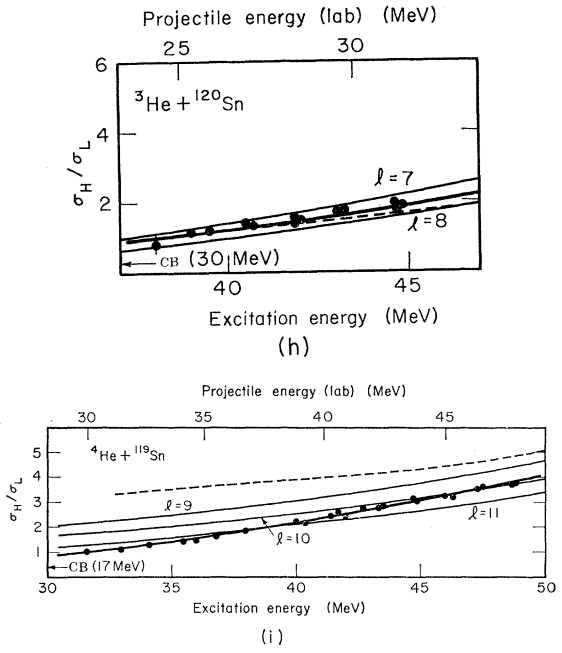


FIG. 1. (*Continued*)

iently measured γ ray of pure ^{119g}Te, thus obtained, was counted and then a timed separation of the ^{119}Sb daughter was performed. By means of the daughter sample (of known chemical yield) it was possible to relate the chosen γ-ray activity of the ^{119g}Te to a measured activity of the separated ^{119}Sb. The same type of procedure was carried out for the upper state isomer, ^{119m}Te (spin 11/2 and half-life 4.7 day). Pure ^{119m}Te was obtained by α-particle bombardment of tin. In such bombardments, both tellurium isomers are formed, but since there is no isomeric transition, the shorter-lived ground-state isomer was allowed to decay away and the remaining ^{119m}Te then chemically purified before the timed separation of the ^{119}Sb daughter. By this procedure the selected γ-ray activity of each isomer was related to a measured activity of the same ^{119}Sb daughter, and it was thus possible to specify the isomeric ratio in terms of the ratio of counting rates of the two chosen γ rays without regard to counting efficiencies or details of the decay schemes.

III. EXPERIMENTAL RESULTS

The experimentally determined formation cross-section ratios for the tellurium-119 isomers are plotted (as the solid dots and heavy lines) in Figs. 1(a)–1(i) as a function of the laboratory projectile energy and the compound nucleus excitation energy. Compound nucleus excitation energies were calculated from Seeger's mass tables.[10] The limits of error include standard deviations of the counting rates, uncertainties in the background subtraction, and the beam-energy spread.

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It will be noticed that in all cases except the ^{7}Li reaction, the isomer ratio continuously increases with projectile energy. This increase in ratio corresponds to an increasing angular momentum of the compound nucleus system. For the ^{7}Li reaction, the ratio increases with projectile energy up to an energy of about 40 MeV, and then falls off. This effect probably can be attributed to the onset of a direct interaction mechanism. From a classical point of view, compound nuclei resulting from nearly head-on collisions correspond to small amounts of angular momentum transfer, while collisions that bring into a compound nucleus the greatest amount of angular momentum are those which have a grazing trajectory. Hence, if the grazing trajectory collisions do not result in the formation of a compound nucleus, the highest-angular-momentum states will be missing in the compound system. Such a decrease in angular momentum would result in a reduction of the isomer ratio.

A number of investigations have shown that under certain conditions the ^{7}Li nucleus may be considered to consist of an α and a triton cluster.[11–16] On the basis of such a model, reactions of the type ^{115}In(^{7}Li, ^{4}He)^{118}Sn may be visualized as stripping reactions, in which the triton is absorbed into the target nucleus and the α particle goes on by. The decrease in isomer ratio with energy observed in this investigation is probably attributable to competition from direct interactions of this type.

IV. CALCULATIONS AND DISCUSSION

Undoubtedly there exists a relationship between the angular momentum of a compound nucleus and the relative amounts of isomers formed through its decay. Accordingly, compound nucleus angular momentum distributions were calculated by the procedure suggested by Thomas.[17] This model envokes a diffuse well approximated at the barrier by a parabola, with height and second derivative matching at the maximum.

The simplest approach for the prediction of isomeric ratios is to assume that there exists some sharp cutoff in the angular momentum distribution such that all compound nuclei with angular momentum equal to or less than a chosen l yield the low-spin isomer, whereas all compound nuclei with angular momentum greater than the cutoff l yield the high-spin isomer.[5] In accordance with this approach, the isomer ratios

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were computed by application of the equation

$$\sigma_H/\sigma_L = \sum_{l=c+1}^{m} \sigma_l / \sum_{l=0}^{c} \sigma_l.$$

In the equation, σ_l is the cross section for formation of a compound nucleus of angular momentum l, c is the arbitrarily chosen cutoff l, and m is the maximum value of l provided by the Thomas calculation.[17] The computation was carried out over the range of energies experimentally studied and for various values of c. For each reaction, there was thereby generated a family of curves of predicted isomer ratios. Figures 1(a)–1(i) illustrate the results (light lines with designated cutoff l) and compares them with the experimentally determined ratios. It is interesting to note that for all of the reactions proceeding through the compound nucleus ^{122*}Te [Figs. (1a) through 1(e)], the isomer ratio at higher excitation energies is quite accurately predicted by a cutoff angular momentum value of about 8. In the vicinity of the Coulomb barrier the analysis predicts ratios that are lower than those experimentally determined. However, Viola *et al.*[18] have shown that in the vicinity of the Coulomb barrier the Thomas[17] calculation probably underpredicts the amount of angular momentum of the compound system. Correction for this effect would increase the calculated ratios in the vicinity of the Coulomb barrier and improve the agreement with experiment. Comparison of the ^{4}He reactions in Figs. 1(g), 1(b), and 1(i) clearly shows the effects of neutron emission. In the $2n$, $3n$, and $4n$ reactions the experimental curves fall successively above, at, and below the $l=8$ cutoff line as would be expected, since each neutron carried off considerable angular momentum. The same trend, although less definite is shown in the ^{3}He reactions in Figs. 1(f), 1(a), and 1(h).

Calculations were also performed using the method of Huizenga and Vandenbosch.[6] This calculation, which follows the formation and de-excitation of the compound nucleus in considerable detail, takes into account the intrinsic spins of the target and projectile, the kinetic energy of the projectile, the emission of neutrons, and the γ-ray cascade. Charged-particle emission is neglected, and it is assumed that all neutrons are emitted before the γ-ray cascade begins. After each step in the de-excitation, a spin distribution is computed and it is assumed that the last γ ray emitted populates either the ground or metastable state, depending upon which involves the smallest spin change. Thus, for the isomers studied in this investigation, on emission of the last γ ray all excited nuclei of spin $\frac{5}{2}$ or less would be assumed to populate the $+\frac{1}{2}$ ground state, and those of spin $\frac{7}{2}$ or greater would populate the $-\frac{11}{2}$ upper state. However, in the tellurium-119 isomers it is likely that a $+\frac{3}{2}$ state also competes. Such a state, if populated, would feed the ground-state isomer. No data are presently available on the low-lying states of tellurium-119, but a good analogy can be drawn from the levels of ^{117}Sn, which contains the same number of neutrons.[19] In ^{117}Sn the $+\frac{7}{2}$ level lies in the vicinity of 1-MeV excitation, and a $+\frac{3}{2}$-MeV level lies between a low-lying $-\frac{11}{2}$ state and the $+\frac{1}{2}$ ground state. If the same arrangement is present in tellurium-119, the $+\frac{7}{2}$ state would populate either the $-\frac{11}{2}$ isomeric state of the $+\frac{3}{2}$ state by the same spin change. The first possibility, however, would require an $M2$ transition, whereas the second would be an $E2$ transition. Since the $E2$ transition is much faster, it is assumed that the division in spins determining which isomer is produced occurs at the $\frac{7}{2}$ level. All spins of $\frac{7}{2}$ or less are assumed to populate the ground-state isomer and those above $\frac{7}{2}$ the upper-state isomer. The calculated isomer ratio is influenced rather strongly by the chosen point of division. A division at spin $\frac{5}{2}$ yields a ratio approximately twice as large as a division at spin $\frac{7}{2}$.

The calculation requires input values for the following parameters: (a) the angular momentum brought into the system by the incoming projectile and the associated transmission coefficients, (b) the angular momentum carried off by the neutrons and the associated transmission coefficients, (c) the number and multipolarity of the γ rays emitted, and (d) the spin cutoff factor σ.

The angular momentum brought into the system by the incoming projectile and the associated transmission coefficients were calculated using the parabolic approximation previously discussed.[17] The angular momentum carried off by the neutrons and the associated transmission coefficients are functions of the neutron velocities. Bishop[20] has shown that reasonable results can be obtained by assigning to the neutrons an energy of $2t$, where t is the nuclear temperature. This is one of two methods used. Calculations were also performed using the experimental neutron energy values of Simonoff and Alexander.[21] Transmission coefficients for the outgoing neutrons were taken from Feld *et al.*[22]

In calculating nuclear temperatures it is necessary to assign a value to the level-density parameter a. Recent work indicates that for a simple Fermi gas model, reasonable values lie in the range of $A/12$ to

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$A/8$ MeV^{-1}.[23–28] In the present work, calculations were performed for various values of a lying in this range in order to select a best value.

Different methods were used for assigning the number and energy of the γ rays emitted. The most successful employed Strutinsky's equation[29]

$$N_\gamma(l+1) = (aU)^{1/2},$$

where the average number of γ rays emitted is N_γ, the multipolarity of the γ ray is l, a is the level density parameter, and U is the excitation energy of the nucleus. Calculations were also performed assuming constant γ-ray energy and using the average 1.5 MeV/γ found experimentally by Mollenauer.[30] At low excitation energies this is about the same energy predicted by the theoretical equation, but at high energies, it is much less, and consequently emission of a large number of γ rays is required (as many as 17 for the ^{12}C reaction). It was always assumed that a single γ ray was emitted if the excitation energy remaining after emission of the final neutron was less than 1 MeV. The calculation is quite sensitive to the multipolarity of the γ rays emitted, especially if a large number is required.

One of the most sensitive parameters in the calculation (since a value must be assigned for each event) is the spin-cutoff or spin-density parameter σ. A number of investigators have assumed constant values for σ in calculations of this type, and have obtained reasonable results for values ranging from two through five.[6,31–36] Such a procedure is probably quite useful at low energies at which the number of neutrons and γ rays emitted is small. However, when neutron and γ-ray emission occur over a fairly wide range of nucleus energy, the variation of σ with energy must be considered.

It has been shown that for nucleons moving independently in an infinite square well potential that $\sigma_r^2 = \mathcal{I}_r t/\hbar^2$, where $\mathcal{I}_r$ is the moment of inertia of the nucleus, taken as a rigid sphere, and t is the "nuclear temperature" as given by the Fermi gas model.[37–40] Calculations were performed using σ's determined in this manner. Computations were also performed using σ's derived from the pairing models of Lang,[41] Erickson,[42] and LeCouteur.[43] The superconductor model was not considered, since results obtained by others have not proved significantly better than those resulting from the simpler procedures.[1,23]

Because of the number of parameters involved in the computation, and the various available means of determining their values, many combinations are possible. Most investigators who have studied a number of reactions have considered each reaction separately, adjusting the various required parameters until a fit between experiment and computation was obtained. In this investigation trial calculations were performed with the requirement that the same method of selecting parameters fit both of the reactions ^{118}Sn(^{4}He, $3n$)^{119}Te and ^{110}Pd(^{12}C, $3n$)^{119}Te. It was not uncommon for a method of assigning parameter values to give good results for one reaction, but poor results for the other. On the basis of the trial calculations for the two reactions, a best method of assignment of the required parameters was selected. The most successful set of calculations performed for the trial pair used parameters obtained by assuming neutrons of energy $2t$, $a = 0.094\,A$ MeV^{-1}, dipole γ rays of multiplicity determined by Strutinsky's equation,[29] and a spin-cutoff parameter of $0.5\sigma_r$. These same methods of parameter determination were applied in the calculation of the isomer ratios for the other seven reactions. The results are shown as a dashed line in each of the figures.

All theoretically calculated spin-cutoff parameters yield isomer ratios that are much too large. A spin-cutoff parameter equal to $0.5\sigma_r$ produced results that agree reasonably well with experiment. The modification of the Huizenga-Vandenbosch treatment suggested by Dudey and Sugihara,[44] which takes into account charged-particle emission and assign a limiting angular momentum to the compound nucleus system would probably allow the use of σ values which are somewhat higher.

The calculations indicate that dipole radiation is more important than quadrupole radiation. The slopes of the calculated curves assuming quadrupole radiation were not satisfactory. It is very probable, how-

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ever, that a judicious mixture, with some quadrupole radiation would yield satisfactory results.

Of the methods used to predict the number and energy of the γ rays emitted, the most successful was the equation of Strutinsky.[29] The assignment of a constant γ-ray energy of 1.5 MeV was not successful. Kiefer[1] found the constant-energy γ-ray assumption was adequate in fitting his experimental data. The present work extends to considerably higher excitation energies and it is at high energies that this assumption proves inadequate. The two methods used for assignment of neutron energies predicted approximately the same total de-excitation and the calculation results were in good agreement.

The experimental and computational procedures and results are presented in much greater detail in Ref. 45.

ACKNOWLEDGMENT

We would like to express our appreciation to Dr. Robert Vandenbosch for making the isomer ratio program available to us.

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Direct Measurement of Neutron Transmission Coefficients

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Neutron transmission coefficients are determined experimentally by investigation of the neutron decay of isobaric analog resonances (IAR) in the compound nucleus. Assuming a statistical decay of the IAR, the neutron branching ratios to the different final states are determined by the transmission coefficients of the partial waves allowed by angular momentum and parity conservation. Therefore, knowing the spin and the parity of the resonance and of the final states, the transmission coefficients can be obtained from the measured decay rates. This method is applied to the ^{91}Zr$(p, n)^{91}$Nb reaction. The decay of two pronounced IAR in ^{92}Nb at $E^*=4.70$ MeV (4^+) and $E^*=5.30$ MeV (2^+) is studied by the time-of-flight method. The measured transmission coefficients are compared with calculations, using two different optical-model parameter sets. Agreement for all partial waves is obtained by modifying the parameters of Moldauer, Engelbrecht, and Fiedeldey.

NEUTRON transmission coefficients determine the neutron branching ratios in a compound-nucleus decay. They are calculated from the optical model. Its parameters are chosen to fit the elastic scattering, polarization, and neutron-strength function measurements. It is not certain, however, whether transmission coefficients calculated with these parameters are reliable. In this paper, we report on a direct measurement of the neutron transmission coefficients for different partial waves. The method uses the neutron decay of isobaric analog resonances.

In a normal compound-nucleus reaction, a Hauser-Feshbach analysis involves the sum over many spin values in the compound nucleus. Therefore, except for a very few special cases,[1] it is impossible to evaluate the different transmission coefficients. The neutron decay of isobaric analog resonances can be also be treated as a compound-nucleus decay.[2–4] However, it has the great advantage that only one spin value in the compound nucleus occurs. In this case, the Hauser-Feshbach formula reduces to the simple expression

$$\sigma_{\mathrm{res}}=\mathrm{const}\times\sum_{lj}T_{lj}.$$

By σ_{res} we describe the enhanced part of the (p, n) cross section arising from the resonance. The T_{lj} are the neutron transmission coefficients for the different partial waves. The summation goes over all l and j values which are allowed by the selection rules of the transition. Knowing the spin and the parity of the resonance and of the final states, the values of limited sums of transmission coefficients can be obtained from the measured decay rates. The transmission coefficients of each partial wave are determined from many such sums. In order to obtain the absolute value, the constant in the above formula, which is different in every resonance, must be known. In some cases, this can be achieved simply by a suitable normalization. In the given formula, the width-fluctuation corrections[5] are neglected. This is justified since the corrections are small because of the many open channels in the reaction studied.

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