International Atomic Energy Agency

INDC(CCP)-357
Distr. G

INDC

INTERNATIONAL NUCLEAR DATA COMMITTEE

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1993

IAEA NUCLEAR DATA SECTION, WAGRAMERSTRASSE 5, A-1400 VIENNA

Printed by the IAEA in Austria
July 1993

93-02789

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ABSTRACT

The authors give theoretical calculation results for the cross-sections of reactions (n,n'γ) and (n,2n) with high-spin target nuclei in the excited state. It is shown that an increase in the target nucleus excitation energy shifts the cross-section curve to the left along the energy axis, while an increase in the ground state spin considerably reduces the (n,2n) reaction cross-section in the threshold region of the reaction. In the authors' opinion, this change in the excitation functions is due to a sharp rise in the role of gamma competition because of the effect of the spin conservation law on neutron emission.

INTRODUCTION

The cross-sections for the interaction of neutrons with nuclei in the ground state have been the subject of intensive experimental and theoretical studies for several decades. It is well known that the nuclear reaction theory successfully describes observed cross-sections and predicts unknown cross-sections. There are a number of problems associated with the lack of development of the theory of non-equilibrium processes and with the uncertainty of the model parameters. Nevertheless, on the whole, the situation can be regarded as satisfactory.

Neutron reactions with nuclei in excited states have been studied little, because there was no practical need for such data in the past and they are very difficult to measure. However, during the last few years, the situation has changed considerably. In connection with the design of future fusion reactors, it has become necessary to know, as a matter of urgency, the cross-sections of neutron-induced reactions with nuclei in isomeric states in order to determine the transmutations of the long-lived isomers which accumulate during operation of such reactors.

The purpose of the present work is to show how the $(n,n'\gamma)$ and (n,2n) reaction cross-sections will change in accordance with the statistical theory of nuclear reactions if the target nucleus is not in the ground state, but in an isomeric state with the corresponding excitation and total angular momentum. We also investigate sources of possible inaccuracies in the theoretical calculations.

THEORETICAL MODEL

The excitation functions of neutron-induced reactions are generally calculated with the use of the statistical model of nuclear reactions in the Hauser-Feshbach-Moldauer formalism, which takes into account the laws of conservation of total angular momentum and parity. If the incident neutron energy is high enough, the contribution of non-equilibrium processes is taken into account in the calculations in one way or another [1].

The main characteristics of the statistical model are the transmission coefficients for particles in the entrance and exit channels of the reaction and the density of excited levels of the corresponding residual nuclei. Cross-section calculations using the above model are very common and are well described in the literature. We shall therefore not go into details, but merely note that we used the SCAT 2 program to calculate the transmission coefficients and the STAPRE program [2] for the statistical calculations. The latter program has been modified by us in order to give a self-consistent description of the non-equilibrium processes within the framework of the phenomenological approach proposed in Ref. [3]. Using this approach, we were able to describe the experimental data on the neutron and proton emission spectra with a single set of parameters. The level density was calculated by the superfluid model of nuclei with parameters from the systematics in Ref. [4].

CALCULATION RESULTS

For the well-known characteristics of the models used it is very simple to calculate the cross-sections, regardless of whether the target nucleus is in an isomeric or ground state. The calculation results are given in Fig. 1 for reactions ^{178}Hf(n,n'γ) and ^{178}Hf(n,2n). Curves 2 show the results for the excitation functions of these reactions with the ^{178}Hf nucleus in the ground state. In order to demonstrate the influence of individual characteristics of the target nucleus, we first calculated the cross-sections of the above reactions with the target nucleus in the excited state, but with spin as in the ground state (curves 3). Curve 4 shows the neutron absorption cross-section for the ^{178}Hf nucleus calculated with the Wilmore-Hodgson potential. Comparison of curves 1 and curves 2 shows a perfectly natural shift of the latter to the left along the incident neutron energy scale by the value of the initial excitation of the target nucleus. Curves 3 in Fig. 1 represent the calculation results for the excitation functions of reactions ^{178}Hf^{m2}(n,n') and ^{178}Hf^{m2}(n,2n). The characteristics of the isomeric level of the ^{178}Hf nucleus are given in Table 1. The reason why curves 3 are shifted to the right in relation to curves 2 as a result of the change in spin of the target from $I_0 = 0^+$ to $I_0 = 16^+$ are not so obvious and require separate explanation. In fact, we have to answer the question why the secondary neutron emission, if it is energetically possible, becomes strongly suppressed. We should emphasize that we are talking about the near-threshold region of the (n,2n) reaction, i.e. neutron energies of 5-10 MeV (Fig. 1).

We now turn to the discrete level scheme for the ^{177}Hf nucleus - the residual nucleus after emission of the secondary neutron. Analysis of the scheme of Ref. [5] shows that the spins of the discrete levels lie within J_{min} = 1/2 to J_{max} = 13/2. For excitation energies in the continuum for the ^{177}Hf nucleus the level density model predicts total angular momenta of the same order. On the other hand, when the spin of the target is I_0 = 16, the total angular momentum of the compound nucleus attains high values, the most probable value being about J = 16. Thus, for the low-spin levels of ^{177}Hf to be populated by successive emission of two neutrons, it is necessary that these neutrons should be emitted with a high angular momentum. The probability of emission of a neutron with a high l sharply decreases as l increases and the neutron energy decreases. The latter factor is decisive because the secondary neutron emission probability is determined strongly by the spin conservation law, the accessible energy being lower than the excitation energy of the compound nucleus by a magnitude equal to the primary neutron binding energy. For this reason, in the second cascade of the (n,2n) reaction, the photons compete noticeably with the neutrons and this leads to an increase in the (n,n'γ) reaction cross-section. As the energy of the incident neutrons increases, the effect of the spin conservation law on secondary neutron emission becomes weaker for two reasons: the increase in the energy available for the secondary neutron and the increase in the effective energy of the residual ^{177}Hf nucleus and, consequently, its total angular momentum.

Figure 2 shows the calculation results for the spectra of neutrons from the (n,n'γ) reaction, i.e. the spectra of those neutrons after whose emission the residual nucleus will be de-excited by the emission of photons. Of course, the part of the spectrum which is of interest is that of neutrons whose emission is energetically possible after the emission of the primary neutron. The dotted curve (Fig. 2(a)) shows the neutron spectra from the (n,n'γ) and (n,2n) reactions with a target nucleus having a spin of $I_0 = 0^+$, and the dashed curve those for a target nucleus with $I_0 = 16^+$. It can be seen that in the latter case where, as described above, the secondary neutron emission probability is strongly determined by the spin conservation law, the primary neutron spectrum is represented by a steeply ascending curve in the E = 0-4 MeV region. Figure 2(b) shows similar spectra for the incident neutron energy of E_n = 11 MeV. The difference between the two spectra is not as pronounced as in the first case, and finally for E_n = 14 MeV (Fig. 2(c)), they differ very little, so that the cross-sections naturally coincide. The (n,2n) reaction cross-sections exhibit some difference at the maximum of the excitation function, owing to the decrease in the neutron absorption cross-section with the increase in energy.

INFLUENCE OF COMPETITION OF CHARGED PARTICLES

We selected the second isomer $^{178}Hf^{m2}$ as the target nucleus in the neutron reactions for two reasons: because of its uniquely high energy and spin and because of its importance in the accumulation of long-lived activity in a fusion reactor. In addition, there are isomeric states of other nuclei with long half-lives, whose "burning" by neutrons needs to be determined with a sufficient degree of accuracy. As an example, we consider the neutron reactions (n,n'γ) and (n,2n) with the ^{108}Ag and ^{166}Ho nuclei in isomeric states. The characteristics of these isomeric states are given in Table 1. Since the energy of both isomers is fairly small, the differences between the excitation functions for reactions with nuclei in the ground and excited states are determined mainly by the spin differences. A comparison of the cross-sections, similar to Fig. 1, is shown in Figs 3 and 4. It can be seen that the shift of the curves is similar in nature to that in the case of ^{178}Hf, with the one difference that it is smaller in magnitude owing to the smaller spin differences (see Table 1). In order to demonstrate the influence of the increase in spin of the isomeric state, we present in Fig. 3 the calculation results for cross-sections when the spin of the isomeric state of the target is assigned the value of 10^+ (curves 3). We note that it is possible to have a situation where the ground state of the target nucleus has a smaller spin than the isomeric state. Such nuclei are known. It is obvious that in this case the situation will be the reverse, but the presence of the excitation energy will reduce the difference in the cross-section curves.

The above calculation results were obtained without taking into account the competition of charged particles, and there naturally arises the question as to whether the influence of the neglected competition will not increase for a target nucleus in the isomeric state, as in the case of photon competition.

The excitation functions for the ^{108}Ag(n,2n) reaction calculated with and without allowance for proton competition are compared in Fig. 5. The solid curves show three variants of cross-section calculation, as in Fig. 3, and the dashed curves show similar results, but with allowance for proton competition. It will be seen that the magnitude and nature of the changes in cross-sections resulting from the consideration of proton competition are, in all three cases, identical and perfectly normal and do not depend on the state of the target nucleus. Calculations to study the influence of α-particle competition show that this influence is negligible.

Thus, the change in excitation functions for the (n,n'γ) and (n,2n) reactions during the change of state of the target nucleus is caused only by the increased photon competition, while the influence of the other reaction channels remains unchanged.

CONCLUSION

The study of neutron reactions with target nuclei in excited states is of theoretical interest, since with the appearance of experimental data it will improve our understanding of the mechanism of nuclear reactions, and is of practical significance because it enables us to answer the question whether long-lived isomers accumulated during the operation of a fusion reactor can be burnt. In the present work, we attempted to ascertain what differences might exist between the excitation functions for the (n,n'γ) and (n,2n) reactions with target nuclei in the ground and isomeric states. We have shown that cross-sections differ because of excitation in the isomeric state, which shifts the curve to the left along the energy scale, and that the high spin of the isomer leads to the opposite effect. In our study we did not consider the possible differences in the neutron absorption cross-sections for nuclei in the ground and excited states, since this effect was expected to be negligible.

As the target nucleus, we selected the very interesting isomeric level of the $^{178}Hf^{m2}$ nucleus, which has an anomalously high spin and energy, and the isomeric states of the ^{108}Ag and ^{166}Ho nuclei, which are important from the standpoint of build-up of long-lived activity in fusion reactors. The calculations demonstrate that in all the three cases considered the difference in the neutron reaction cross-sections by comparison with the ground state of the targets will not be appreciable, particularly if the shape of the neutron spectrum in fusion reactors is taken into account.

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Table 1.
Some characteristics of target nuclei

Notation: I_0 is the spin of the ground state, B_n the neutron binding energy $< \Gamma_\gamma >$ the averaged radiation width, and E, J^π are the energy, spin and parity of the isomeric state.

Nucleus	I^π_0	B_n, MeV	$< \Gamma\gamma >$, MeV	E, MeV	J^π
^{178}Hf	0^+	7.63	66	2.446	16^+
^{108}Ag	1^+	7.27	140	0.109	6^+
^{166}Ho	1^-	6.24	-	0.006	7^-

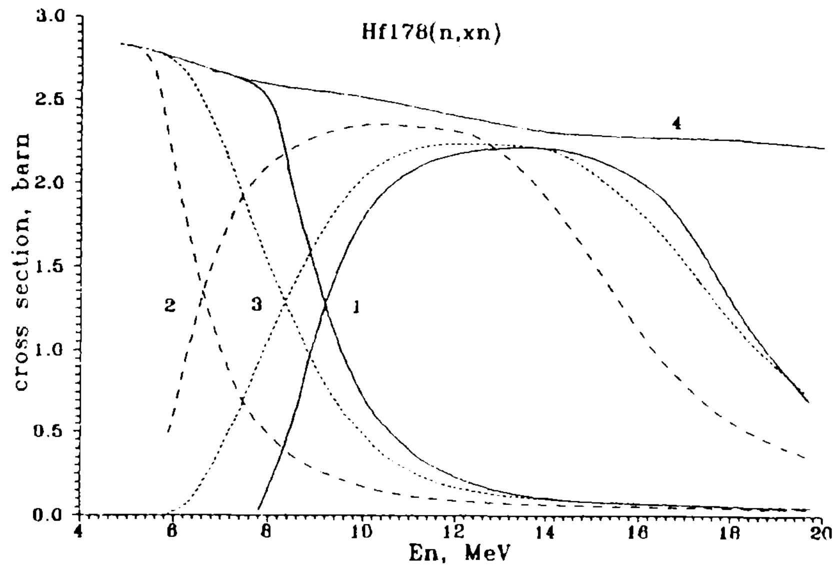

Fig. 1. Comparison of model calculations of the excitation functions for the reactions (n,n'γ) and (n,2n) with the ^{178}Hf target nucleus in different states. Curve 4 - neutron absorption cross-section; curves 1 - reaction cross-sections for ground state; curves 2 - target nucleus with the isomeric excitation energy of 2.446 MeV and spin $I_0 = 0^+$; curves 3 - target nucleus in the isomeric state: $E = 2.446$ MeV, $I_0 = 16^+$.

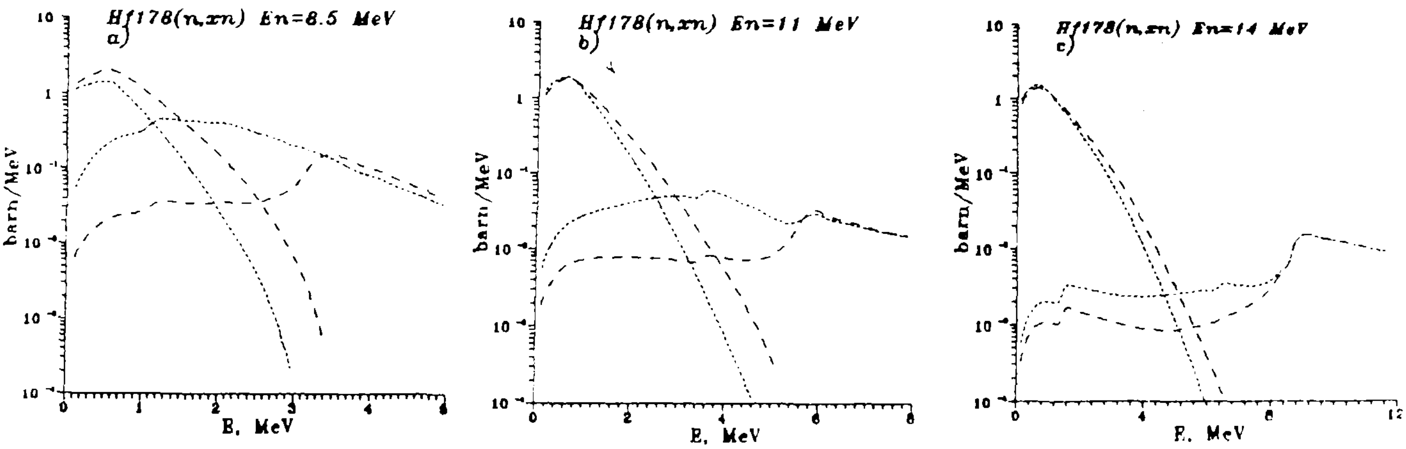

Fig. 2(a). Neutron spectra for reactions (n,n'γ) and (n,2n) with the ^{178}Hf target nucleus in different states at an incident neutron energy of E_n = 8.5 MeV. The dotted curves show the neutron spectra for reactions (n,n'γ) and (n,2n) when the target nucleus has an excitation energy of 2.446 MeV and a spin of $I_0 = 0^+$; the dashed curves show the spectra for the target nucleus in the isomeric state (E = 2.446 MeV and $I_0 = 16^+$).

Fig. 2(b). The same as in Fig. 2(a), but for E_n = 11 MeV.

Fig. 2(c). The same as in Fig. 2(a), but for E_n = 14 MeV.

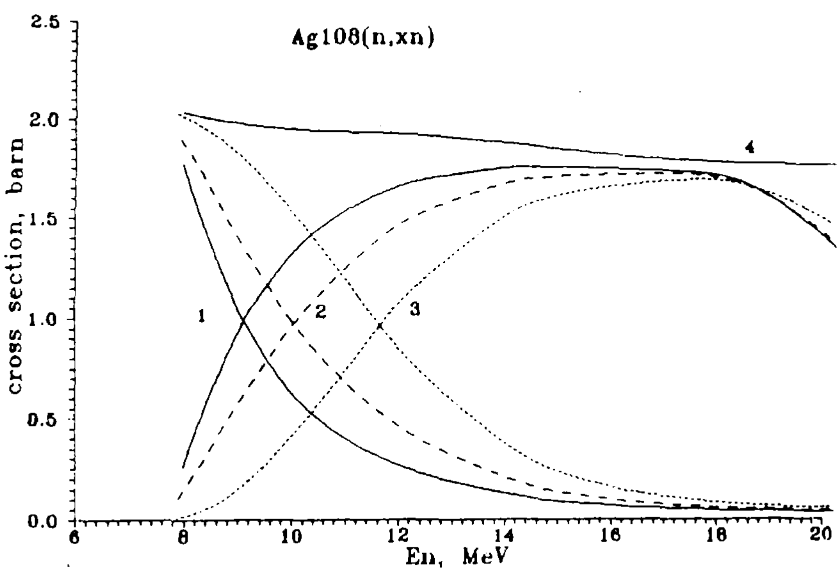

Fig. 3. Comparison of model calculations of the excitation functions for reactions (n,n'γ) and (n,2n) with the ^{108}Ag target nucleus in different states. Curve 4 shows the neutron absorption cross-section and curves 1 show the reaction cross-sections for the ground state; in curves 2 the target nucleus is in the isomeric state: E = 0.109 MeV, $I_0 = 6^+$ and in curves 3 the target nucleus spin is assigned the value of 10^+.

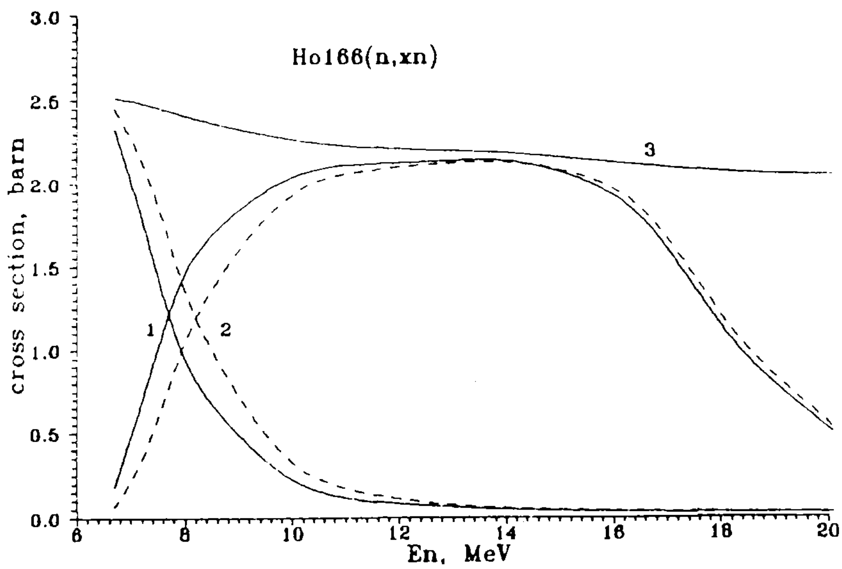

Fig. 4. The same as in Fig. 3, but for the ^{166}Ho nucleus. Curve 3 shows the neutron absorption cross-section.

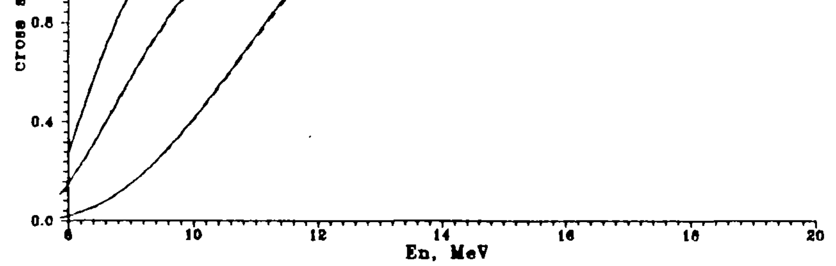

Fig. 5. Influence of proton competition on the excitation function calculation results for reaction ^{108}Ag(n,2n). The solid curves show the three calculation variants similar to those in Fig. 3 and the dashed curves the results of calculation with allowance for proton competition.