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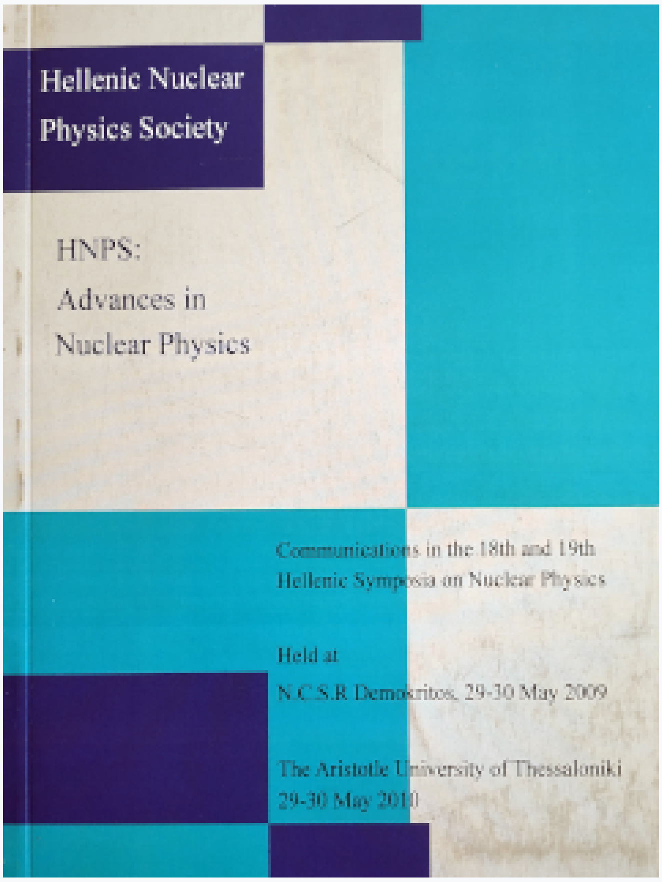

Theoretical study of the isomeric cross section of the 197Au(n,2n) reaction

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Theoretical study of the isomeric cross section of the ^{197}Au(n,2n) reaction

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Abstract

In the present work, the ^{197}Au(n,2n) reaction cross section is studied within the framework of the Generalized Superfluid Model (GSM). The cross sections for the population of the second isomeric state (12^-) of ^{196}Au and the sum of the ground (2^-) and first isomeric state (5^-) population cross sections were independently studied in the 8 to 25 MeV region with the use of the STAPRE-F, EMPIRE and TALYS codes, which were also compared in their implementation of the GSM. The theoretical results are compared with previous work in the same mass region and the strong dependence on the level scheme of the nuclei involved was revealed.

1. Introduction

The presence of a high spin isomeric state in the residual nucleus of a neutron threshold reaction provides a sensitive test for existing nuclear models. The study of such reactions is a powerful tool for getting information on the structure of nuclei. In particular, the nuclei of the transitional region from well deformed to spherical nuclei near the Z=82 shell closure (Os-Pb region) present a very complex structure (γ-softening, triaxiality, shape coexistence) and for most of them an isomer with a high spin value with respect to the spin of the corresponding ground state has been reported. For the same element the energy of this isomer increases with increasing mass number A. Its existence is attributed to the coupling of high spin intruder states, and the systematic study of the excitation function of the formation of both the ground and the high spin isomeric state on the basis of a statistical model provides information on the energy and spin distribution of the level density of the nuclei involved [1] and on the changes in the structure of the low lying excited states of the corresponding nuclei.

In this context the ^{196}Au isotope presents an interesting isomeric pair: ground and isomeric states with spin values of 2^- and 12^- respectively (Fig. ??). This 12^- isomer has been reported for other even A Au isotopes (^{198}Au, ^{200}Au) [2]. However, a survey of the literature revealed only a limited number of experimental data for the cross section of the ^{197}Au(n,2n)^{196}Au^{m2} reaction, especially near its threshold, where only one unpublished dataset [3] was found.

Thus, the purpose of this work was to perform theoretical statistical model calculations of the ^{197}Au(n,2n) ^{196}Au^{m2} and the ^{197}Au(n,2n)^{196}Au^{g+m1} reaction cross sections in the 8 to 25 MeV incident neutron energy range. The results of the theoretical calculations were compared to the experimental data obtained in the first phase of this work and to all available experimental data in the above energy range to study the contribution of the spin distribution and the details of the level scheme of the residual nucleus to the formation of the isomeric state.

2. Theoretical Calculations

Theoretical cross section calculations in the energy region between 8 and 25 MeV were performed taking into account the compound and pre-compound nuclear processes, in the framework of the Hauser-Feshbach theory [4] and the exciton model [6] respectively. The level densities of the nuclei involved in the calculations were treated within the Generalized Superfluid Model (GSM) in its phenomenological version developed by

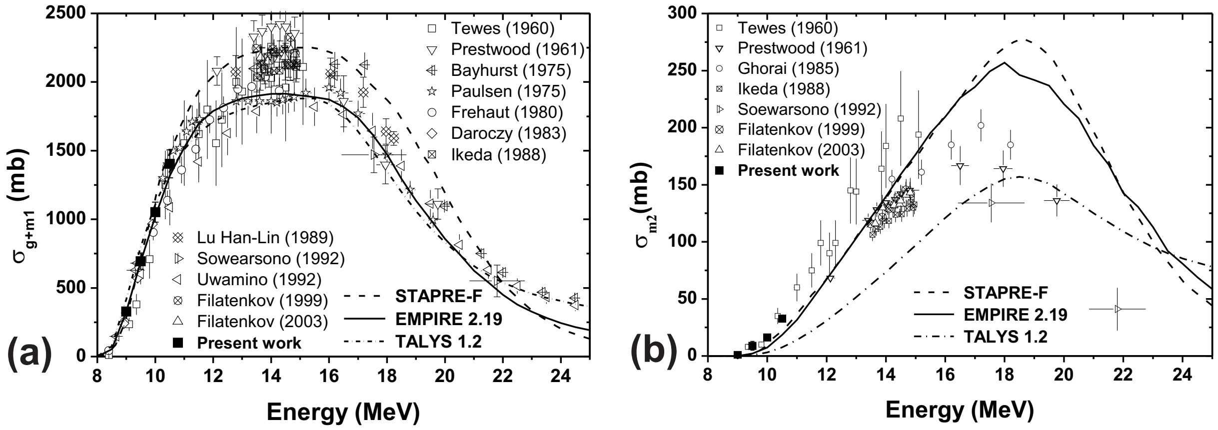

Figure 1: Experimental values and theoretical calculations for the population of the ground and first isomeric state of ^{196}Au (g+m1) (a) the second isomeric state of ^{196}Au (m2) (b). Several single-point datasets around 14 MeV omitted for clarity.

Ignatyuk et al [7, 8], which takes into account superconductive pairing correlations, shell effects and collective enhancement of the level density of the nucleus in a consistent way. It has already been successfully used in the past for theoretical cross section calculations in ^{191}Ir [9], which also lies in the transitional Os-Pb region. The calculations were carried out using three codes, STAPRE-F [10], EMPIRE 2.19 [11] and TALYS-1.2 [12].

The choices for the transmission coefficients, the preequilibrium and the level densities used for the calculations of the three codes were made in order to compare how the three codes implement the generalized superfluid model. The STAPRE-F code provides a local approach in which a consistent calculation is made using local model parameters established on the basis of various independent data, while EMPIRE and TALYS provide global approaches of the nuclear models included [15, 16].

The theoretical calculations obtained from the three codes for σ_{g+m1} and σ_{m2}, along with the data from this work and the previous measurements are presented in figure 1.

As can be seen, the results from all three codes fairly reproduce the trend of the experimental data for σ_{g+m1}. The theoretical curves appear to span the whole range of the experimental values in the 12-16 MeV region where large discrepancies in the data exist. This precludes a conclusion on the accuracy of the results in this region.

Concerning the cross section of the second isomeric state (Fig. 1b) the STAPRE-F and EMPIRE theoretical calculations seem to underestimate the near-threshold data up to about 13 MeV, while in the high-energy region they overestimate the cross sections by about 100 mb, despite the large discrepancies among the experimental data. The TALYS calculation underestimates the data in the whole energy range, a behavior also encountered in [15]. Furthermore, in all cases the cross section attains its maximum value at around 18 MeV, about 2 MeV higher than the experimental data suggests. This result will be discussed later. Nevertheless, all three codes reproduce the general trend of the experimental data.

Based on these observations, several tests were made, using the STAPRE-F code, to better reproduce the isomeric cross section results by changing the input parameters of the theoretical calculations. Particular attention was given to the value of $\tilde{\alpha}$ which is the level density parameter at high excitation energies and plays an important role in the calculations. These values were changed in a consistent way within their experimental uncertainties (i.e. $\pm$ 6 %) for $^{195-198}$Au isotopes and, subsequently, the systematics proposed in [13, p.103] were tested. Nevertheless, none of these attempts seemed to simultaneously improve the fit to the experimental data of σ_{m2}, σ_{g+m1} and the cross section values of the (n,3n) reaction. Changing the average experimental total radiation width and the moment of inertia of the ground state within their experimental uncertainties, the percentage of preequilibrium emission and the assumptions on the shape and symmetry of the Au isotopes also had limited effect.

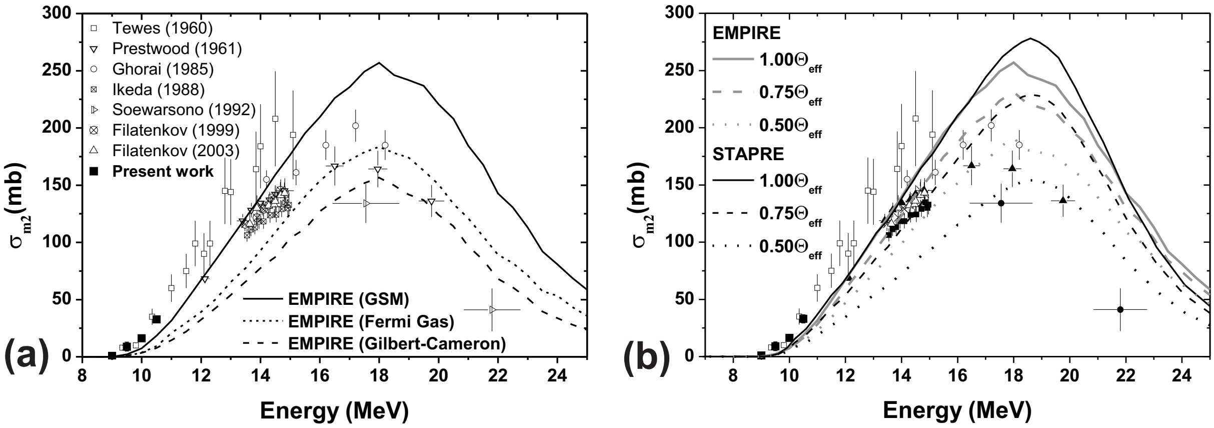

Figure 2: Theoretical calculations for σ_{m2} using the Fermi gas and Gilbert-Cameron level density models, compared to the result using the GSM (a) and theoretical calculations for σ_{m2} using values of the effective moment of inertia reduced by 25 and 50%. (b).

In order to understand and correct the shift of the σ_{m2} theoretical curve, the calculations were repeated using the Back Shifted Fermi Gas [17] and the Gilbert-Cameron level density models [18] with the EMPIRE code, leaving the rest of the input parameters as mentioned above. The results (Fig. 2) show that the shift of the isomeric cross section curve is independent on the model of the level density of the nuclei involved and also on the implementation of the GSM in the three codes used.

Generally, the population of the high spin isomers is highly dependent on the spin distribution of the continuum. The effect of this factor on the feeding of the 12^- isomer was examined in order to improve the theoretical predictions.

In previous cross section measurements of high spin isomers in nuclei belonging to the transitional region from the well deformed Os to the spherical Pb isotopes [9, 19–21] the need of the reduction of the effective moment of inertia was pointed out, in order to better reproduce the data of σ_{m2} and the isomeric ratio. Such systematics have been evaluated in the framework of the Back-Shifted Fermi Gas Model (BSFGM) for the mass dependence of the reduction of the effective moment of inertia with respect to the rigid body value [22] which have been proved quite satisfactory in an extended mass region, even in the heavy Hg and Au isotopes [19]. The same result has occurred in the framework of the GSM for the Ir isotopes as reported in [9]. The BSFGM and GSM have the same spin distribution shape and a similar systematic behavior of the spin cutoff parameter within the GSM would be expected. Calculations were carried out using Θ_{eff} values lowered by 25 and 50% using the STAPRE-F and EMPIRE codes, and the results are presented in Fig. 2. The reduction of the effective moment of inertia causes a significant decrease of the isomeric cross section but does not seem to improve the theoretical results with reference to the experimental data, since the theoretical calculations are already lower than the experimental data below 14 MeV. In the high energy region the theoretical predictions move closer to the experimental data but retain the maximum cross section value around 18 MeV.

After these results, the hypothesis of possible discrepancies in the level scheme was examined. In particular, the level schemes of ^{196}Au and ^{195}Au are expected to play a crucial role in the cross section value of the 12^- isomer and are discussed below.

The level scheme of ^{196}Au, especially the spins of levels lying above the 12^- isomer are very important for the feeding of this level [23, 24] in the whole neutron energy range. The possible existence of a rotational band built on the 12^- isomer and feeding it through gamma cascade would increase the calculated cross section, and lead to a better reproduction of σ_{m2} at incident neutron energies below 16 MeV. In a similar case, the existence of a rotational band built on the configuration of the 16^+ isomer of ^{178} Hf has been proposed in [24] in order to successfully reproduce, within the Hauser Feshbach theory, the cross section values of the

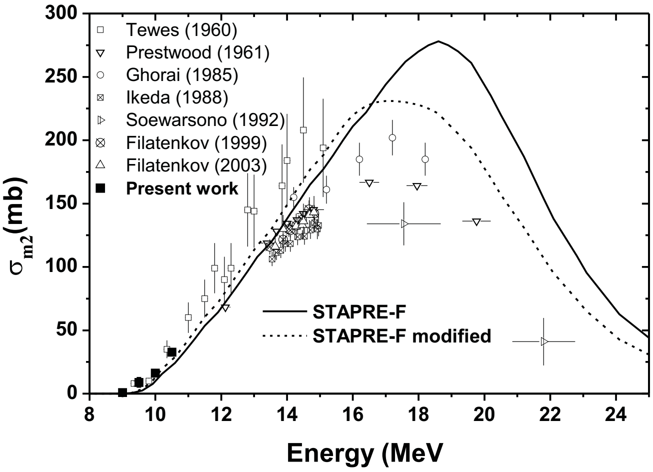

Figure 3: Theoretical calculations for σ_{m2} using a modified level scheme for ^{196}Au and ^{195}Au including hypothetical high-spin levels.

^{179} Hf(n,2n) reaction that leads to its formation and was experimentally observed some years later via the incomplete fusion ^{176}Yb(^{9}Be,α 3n) ^{178}Hf reaction [31]. The possible existence of a rotational band built on this intrinsic structure for doubly odd nuclei in this region is proposed in [25] and [26], and rotational bands based on high-j unique parity quasiparticle states (πh9/2, πh11/2, νi13/2) have been reported for Tl isotopes in [25] and other isotopes in the transitional region Os-Pb (references in [26]), as well as dipole bands in Pb and Hg isotopes [27–30].

The level scheme of ^{195}Au is also expected to play an important role in the neutron energy region above 16 MeV, where the (n,3n) channel becomes important and where the largest deviation from the experimental data occurs. An examination of the level scheme of ^{195}Au in comparison with the level schemes of neighboring odd Au isotopes ([32–34]) indicates a possible absence of high spin rotational band members from the documented levels. The introduction of such high spin states in the level scheme of ^{195}Au would lead to an increase of the de-excitation of the continuum of ^{196}Au towards these states, and thus a reduction of the theoretical σ_{m2} values above an incident neutron energy of 16 MeV.

Although the above assumptions on the level schemes of ^{196}Au and ^{195}Au seem physically likely, there is no possibility of embedding discrete levels in the continuum of the nuclei of interest via any of the three codes in order to further investigate this hypothesis and extract safe results.

The only test that could be performed was the addition of a few high spin levels in the discrete via the STAPRE-F code implementation. The result was an enhancement of σ_{m2} without altering the g+m1 and (n,3n) cross section values, simultaneously reducing the σ_{m2} by 10 % in the energy region above 16 MeV, as expected, and moved the maximum of the curve towards lower energies. The results of these two tests are shown in Fig. 3. Higher spins than those used in the tests, attributed to rotational bands, are expected to lie in the higher energy part of the continuum.

3. Conclusions

A theoretical study of the (n,2n) reaction cross section on ^{197}Au has been perofrmed in the energy range 8-25 MeV with the use of three different codes (STAPRE-F, EMPIRE 2.19 and TALYS-1.2) taking into account all available experimental data. The exciton model and Hauser-Feshbach theory were employed for the pre-compound and compound processes respectively. The Generalized Superfluid Model was chosen for the description of the level density of the nuclei involved. The σ_{g+m1} cross section was easily reproduced by the calculations, while for σ_{m2}, the theoretical results could only reproduce the general trend of the experimental data, with the distribution being shifted to higher energies. Several tests were performed to improve the theoretical predictions. The results of these tests reveal the importance of the level scheme of the residual nuclei and indicate the possibility of incomplete documentation of high-spin levels in the level schemes of ^{196}Au and ^{195}Au. Furthemore, they highlight certain limitations of the nuclear codes used, particularly regarding the embedding of discrete states in the continuum, which is not currently possible and affects the reproduction of high-spin isomeric cross sections.

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