Evidence of shell effects in the excitation function of 0.136-MeV isomeric state populated in the ^{93}Nb$(n,2n)^{92}$Nb^m reaction

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Calculation for the excitation function of 0.136-MeV (2^+) isomeric state in ^{92}Nb has been carried out using Hauser-Feshbach and pre-equilibrium nuclear reaction models in 10–20 MeV energy range. A satisfactory agreement between the calculation and measurements requires the suppression of contribution from the negative-parity doublet consisting of the 0.226-MeV (2^-) and 0.390-MeV (3^-) states in ^{92}Nb. This can be explained on the basis of highly retarded gamma transitions of higher energy states to the negative-parity doublet on account of its different shell model configuration compared to the shell model configuration of positive-parity states.

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I. INTRODUCTION

Hauser-Feshbach formalism of nuclear reaction calculation takes into account the conservation of spin and parity but ignores the effect of the difference in the shell model configurations of states involved in a transition by emission of a particle or a photon [1]. It is virtually based on the single particle shell model with one nucleon outside an inert core. For more than one nucleon outside a closed shell, energy levels can arise from different types of configurations including excitation from the closed shell and transitions between them may be considerably retarded. Such an effect of retardation of transitions between levels arising from different types of configurations has been observed in the process of calculation of the excitation function of the 0.136-MeV isomeric state in ^{92}Nb populated through the ^{93}Nb$(n,2n)^{92}$Nb reaction. It has been discovered that the calculation agrees with measurements only if one ignores the contribution from the negative-parity doublet consisting of 0.226-MeV (2^-) and 0.390-MeV (3^-) states to the production of isomeric state. The agreement gets further improved if we neglect the participation of all negative-parity states below 2 MeV in the reaction. This has been explained on the basis of retardation of transitions between different types of configurations giving rise to the positive-parity and negative-parity states in ^{92}Nb. The details of the calculation, results, discussion and conclusions are provided in the following sections.

II. MODEL CALCULATION

The present nuclear model calculation was carried out using the HFMOD code [2] for Hauser-Feshbach and PREMOD code [3] for pre-equilibrium calculations. The HFMOD code takes into account the conservation of angular momentum and parity in all the reaction stages. It also provides information on the population of all the energy levels included for the calculation in these reaction stages. Wilmore-Hodgson potentials [4] were used for neutrons and Perey potentials [5] were used for protons. Potentials for α particles were taken from Avrigeanu *et al.* [6]. The back-shifted Fermi gas model based on the formalism of Dilg *et al.* [7] was used for the energy level density calculations. The values of the energy density parameters were taken from the published literature [7–9] and are listed in Table I. A rigid body moment of inertia was used for nuclei. The information on the energy levels was taken from Refs. [10–13]. The number of discrete levels below 2 MeV in ^{92}Nb, considered for the calculation, was equal to 27, which contained 9 negative-parity states. The γ transition probabilities were calculated on the basis of shell model [14,15]. However a correction factor consistent with the effective charge arising from a neutron outside the core, $(Z/A)^2$, was taken into consideration for E1 transitions [16]. In the present calculation an energy bin of width equal to 1 MeV was used in the continuum energy region.

III. RESULTS AND DISCUSSION

The results of the calculation for the production of the 0.136-MeV isomeric-state in ^{92}Nb are compared with the reported measurements [17–19] in Fig. 1. Only measurements covering an extended range of neutron energy have been included for the comparison. The Cal.1 includes 27 discrete energy levels containing 9 negative-parity states below 2 MeV. As seen the calculation predicts very high cross section values compared with measurements giving a discrepancy as high as 70%. The production cross section of an isomeric state strongly depends on the properties of energy

TABLE I. The energy level density parameters used in the calculation.

Nuclide	a(MeV^{-1})	Δ(MeV)
^{93}Nb	11.24	−0.5
^{93}Zr	12.31	0.81
^{92}Nb	8.92	−1.75
^{92}Zr	10.43	0.77
^{91}Nb	8.73	0.3
^{91}Zr	10.26	0.57
^{90}Y	8.91	−0.74

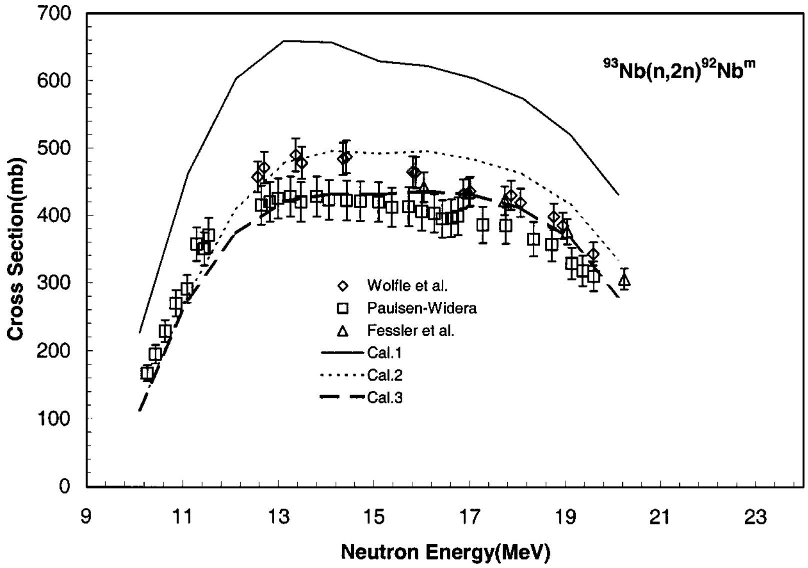

FIG. 1. Comparison of the measured and calculated cross sections of the 0.136 MeV (2^{+}) state produced in the ^{93}Nb$(n,2n)^{92}$Nb reaction. Cal.1: 27 discrete states below 2 MeV are included in the calculation. Cal.2: The two lowest negative-parity states are excluded from the calculation. Cal.3: All the negative-parity states below 2 MeV are excluded from the calculation.

levels right above it [20–22]. The 0.390-MeV (3^{-}) state decays by 3% to the 0.136-MeV (2^{+}) isomeric state and by 97% to the 0.226-MeV (2^{-}) state, which in turn decays by 91% to the 0.136-MeV (2^{+}) isomeric state. Therefore the suppression of the negative-parity doublet was a natural way to reduce this discrepancy. The second calculation, Cal.2, contains all the discrete energy states except that the two negative-parity 0.226-MeV (2^{-}) and 0.390-MeV (3^{-}) states were excluded from the calculation. It results in a closer agreement with the measurements. In Cal.3 all the nine negative-parity sates were dropped from the calculation and it agrees reasonably well with the experimental data. In order to demonstrate that 70% deviation is not due to optical model parameters and energy level density parameters the results of calculation for the excitation function of the ^{93}Nb$(n,2n)^{92}$Nb reaction are shown and compared with reported measurements [17,23–26] in Fig. 2. Calc.1 includes both positive and negative parity states and it is in acceptable agreement with the measurements though the agreement further improves on dropping the negative-parity doublet (Cal.2) and all negative-parity levels below 2 MeV (Cal.3). This also points to the passive role of the negative-parity states in the reaction.

In order to understand the suppression of negative-parity states from the calculation, it is necessary to understand the configurations of the low lying states in ^{92}Nb shown in Fig. 3. The nuclei of ^{92}Nb and ^{93}Nb have simple shell model ground-state configurations with one proton in the $1g9/2$ state in both of them, and one neutron and two neutrons in the $2d5/2$ state, respectively. A sextuplet of positive-parity states in ^{92}Nb was predicted on the basis of the shell model by de-Shalit [27] and Kim [28]. These six low-lying positive-parity states, which include the ground state of ^{92}Nb, were investigated by Sweet, Bhatt and Ball [29] through the ^{93}Nb$(p,d)^{92}$Nb reaction and by Sheline, Watson and Hamburger [30] using the ^{93}Nb$(d,t)^{92}$Nb reaction. The negative-parity doublet consisting of 0.226-MeV (2^{-}) and 0.390-MeV (3^{-}) states was predicted by Auerbach and Talmi [31] and studied by Cates, Ball and Newman [32] through the ^{91}Zr$(^{3}$He$,d)^{92}$Nb reaction. The negative-parity doublet is

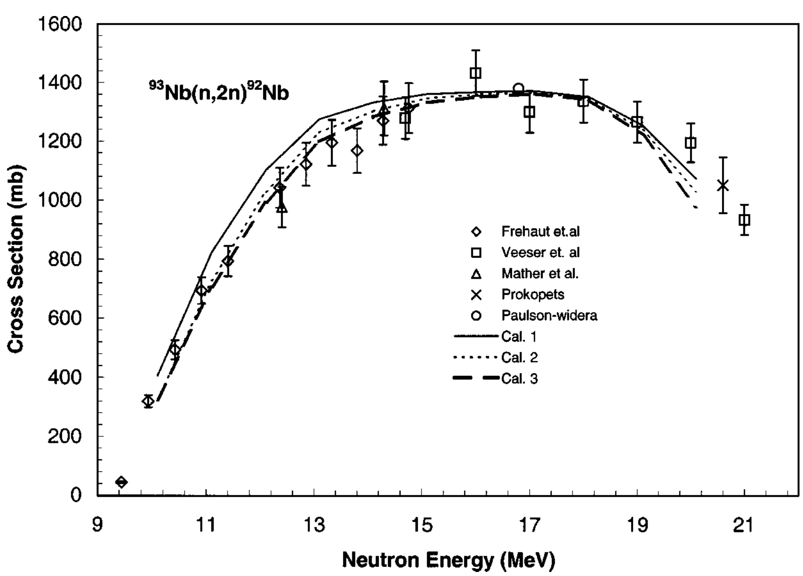

FIG. 2. Comparison of the calculated and measured cross sections for the ^{93}Nb$(n,2n)^{92}$Nb reaction.

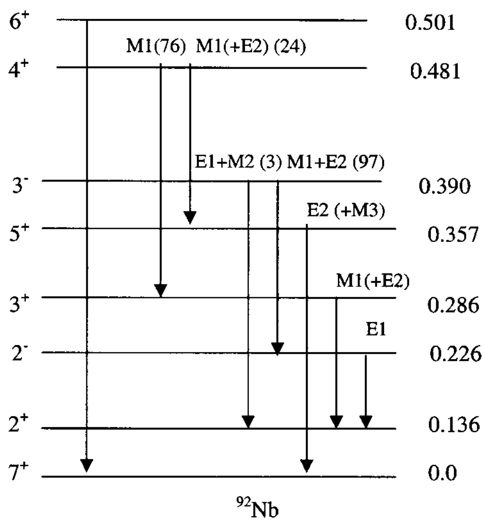

FIG. 3. Low lying energy levels (MeV) of ^{92}Nb and their main decay scheme. The percentage gamma decay branching ratio is given in parentheses.

generated from the ground-state configuration of ^{92}Nb by raising one proton from the $2p1/2$ state to the $1g9/2$ state and coupling the one proton left in the $2p1/2$ state to the neutron in the $2d5/2$ state. These two negative-parity states were not seen in the above two neutron-pickup reactions, which resulted in the observation of the six positive-parity states. This implies that there is almost no overlap between the configurations of the negative-parity doublet and the ground state of ^{93}Nb as well as the six positive-parity states in ^{92}Nb. The γ decay of the 0.226-MeV (2^-) state to the 0.136-MeV (2^+) state has been reported to be hindered by a factor of 10^7 compared to the shell model prediction for the expected E1 transition [33,34]. This is so as it involves a j-forbidden transition of transferring one proton from the $1g9/2$ state to the $2p1/2$ state assuming pure shell model configurations. Thus gamma transitions among the negative-parity states and positive-parity states are highly retarded.

A calculation using measured gamma transition probabilities for 14 discrete levels above the meta-stable state was also done which agreed with Cal. 1 within 1%. It shows that the measured gamma transition probabilities agree in general with the shell model estimates of gamma transition probabilities for these states. In the process of neutron emission from ^{93}Nb the higher energy states in ^{92}Nb are more intensely populated than the lower discrete energy states. The pattern of population of the lower discrete energy states strongly depends on the way the higher energy states decay to the lower energy states. The gamma transition probabilities for this energy region are not known. Therefore it is not necessary that the inclusion of the measured transition probabilities of the lower energy states should always result in agreement with the calculation. However it does take care of the shell effects for these states and it is always preferable to use measured gamma transition probabilities over the values obtained through a model.

The 0.226-MeV (2^-) state decays by 100% to 0.136-MeV (2^+) state in spite of its high retardation because there is no other faster channel available for its gamma decay. The retardation effect can be explained with reference to the decay of the 0.39-MeV (3^-) state, which decays to the 0.136-MeV (2^+) state through E1+M2 mode by 3% only whereas it decays to the 0.226-MeV (2^-) state by 97% through M1+E2 mode. On the basis of the statistical model using the conventional shell model estimates of gamma decay transition probabilities one would expect a higher gamma transition probability for E1+M2 mode rather than M1+E2 mode. This situation applies to higher energy positive-parity states decaying to the negative-parity states where there are several open channels for their gamma decay mode. Therefore the population of negative-parity states will be adversely affected from the retarded decay of the positive-parity energy states to the negative-parity energy states. Thus the lower negative-parity energy states will be negligibly populated in this reaction. There is no provision in the statistical model to take care of this retardation phenomenon in the absence of the knowledge of gamma transition probabilities. Thus the removal of these inert energy states, which are treated as active by the statistical model, improves the agreement of the statistical model calculation with measurements.

IV. CONCLUSIONS

The present work highlights the role of shell effects in the statistical model calculations. It also shows that the production cross section of an isomeric state depends not only on the energies, spins and parities of the levels right above it but also on their shell model configurations.

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