# Calculation for the excitation functions of the $^{93}$Nb($p, n$)$^{93}$Mo$^m$, $^{93}$Nb($p, \alpha n$)$^{89}$Zr, and $^{93}$Nb($p, np + pn$)$^{92}$Nb$^m$ reactions

K. Gul

*National Centre for Physics, Quaid-i-Azam University, Islamabad, Pakistan*

(Received 14 February 2009; published 28 April 2009)

Statistical model calculation has been carried out for the excitation functions of the $^{93}$Nb($p, n$)$^{93}$Mo$^m$, $^{93}$Nb($p, \alpha n$)$^{89}$Zr, and $^{93}$Nb($p, np + pn$)$^{92}$Nb$^m$ reactions up to a 20-MeV proton energy range using global reaction parameters. The results are compared and discussed with reported measurements. The calculation for the excitation function of the $^{93}$Nb($p, n$)$^{93}$Mo$^m$ reaction can only match the measured magnitudes of cross sections if we postulate the existence of two energy levels with spin-parity values of $19/2^+$ and $17/2^-$ lying immediately above the 2.425 MeV ($21/2^+$) isomeric state. The existence of the hypothetical levels has been discussed in the light of reported shell-model calculations.

DOI: 10.1103/PhysRevC.79.044608 PACS number(s): 21.60.Cs, 27.60.+j, 23.20.Lv, 24.60.Dr

## I. INTRODUCTION

The knowledge of the excitation functions of the $^{93}$Nb($p, n$)$^{93}$Mo$^m$, $^{93}$Nb($p, \alpha n$)$^{89}$Zr, and $^{93}$Nb($p, np + pn$)$^{92}$ Nb$^m$ reactions is of interest for the calculation of radioactivity induced in $^{93}$Nb used in targets for the production of medical radioisotopes and for monitoring proton beams used for this purpose. Recent measurements of these reactions show a large discrepancy among the reported data and theoretical calculations for the $^{93}$Nb($p, n$)$^{93}$Mo$^m$ and $^{93}$Nb($p, np + pn$)$^{92}$Nb$^m$ reactions [1]. Calculation for the $^{93}$Nb($p, \alpha n$)$^{89}$Zr reaction has not been reported. Present calculation has been undertaken to analyze these reactions in a consistent way using statistical model of nuclear reactions. The population of levels through $\gamma$ cascade, in general, increases with lowering of the excitation energy. Thus the population of an isomeric state is highly dependent on the nuclear structure properties of a few states lying immediately above it [2]. The calculation also investigates the dependence of the population of the 2.425 MeV ($21/2^+$) isomeric state of $^{93}$Mo on the nuclear structure properties of levels lying immediately above it.

## II. MODEL CALCULATIONS

The present nuclear model calculations were carried out using the HFMOD code [3] for Hauser-Feshbach calculation. 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 $\alpha$ 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 energy level-density calculations. The values of energy level-density parameters were taken from Refs. [2,8] and these are listed in Table I. A rigid body moment of inertia was used for nuclei. The information on the energy levels was taken from Ref. [9]. Numerical values of cross sections were taken from Ref. [10]. The $\gamma$-transition coefficients were calculated on the basis of Brink and Axel [11,12]. The giant resonance model formalism described in Refs. [8,13] was employed using a generalized Lorentzian for $E1$ transitions. Three nuclear reaction channels were included for the first stage of Hauser-Fechbach calculation, including the emission of protons, neutrons, and $\alpha$ particles. The calculation in the second stage included the emission of protons and neutrons only. A total of 34 discrete levels were included with 17 levels lying above the isomeric state for the excitation function of the $^{93}$Nb($p, n$)$^{93}$Mo$^m$ reaction.

## III. RESULTS AND DISCUSSION

The calculation for the excitation function of the $^{93}$Nb($p, np + pn$)$^{92}$Nb$^m$ reaction is shown in Fig. 1. The dominant contribution to the $^{93}$Nb($p, np + pn$)$^{92}$Nb reaction comes from the $^{93}$Nb($p, np$)$^{92}$Nb$^m$ reaction below 15 MeV, whereas above this energy the dominant contribution comes from the $^{93}$Nb($p, pn$)$^{92}$Nb$^m$ reaction. The present calculation is in better agreement with the measurement reported by Avila-Rodriguez *et al.* [1] but it is low in the 13- to 17-MeV energy range. The measurement by Levkovskij [14] is considerably higher compared with present calculation. The Brookhaven National Laboratory (BNL) data reported in Ref. [1] are rather low beyond 17 MeV and decrease with energy. The calculation for the $^{93}$Nb($p, \alpha n$)$^{89}$Zr reaction is shown in Fig. 2. It is in better agreement with the data of Avila-Rodriguez *et al.* that are available only below 18 MeV. Above this energy the calculation is in good agreement with the data of Levkovskij [14]. The BNL measurements reported in Ref. [1] are low in magnitude.

The calculation for the excitation function of the $^{93}$Nb($p, n$)$^{93}$Mo$^m$ reaction based on the existing nuclear structure data [9] is shown by Calc. 1 and compared with reported measurements [1,14] in Fig. 3. The calculated excitation function of the 2.425-MeV ($21/2^+$) is negligibly small in comparison with the reported measurements [1,14]. This is not unexpected using the available nuclear structure data [9] for $^{93}$Mo in the calculation. There are 16 discrete energy levels below the isomeric state with a wide spectrum of spins and

 

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

| Nuclide | a ($\mathrm{MeV}^{-1}$) | $\Delta$ (MeV) |
|---|---|---|
| $^{93}$Mo | 8.377 | −0.311 |
| $^{92}$Mo | 8.775 | 0.655 |
| $^{93}$Nb | 11.24 | −0.5 |
| $^{92}$Nb | 8.92 | −1.75 |
| $^{91}$Nb | 8.707 | 0.281 |
| $^{90}$Zr | 8.00 | 2.04 |
| $^{89}$Zr | 8.481 | 0.845 |

both positive- and negative-parity values. The isomeric state with a high spin value of 21/2 has negligible cross section for its production through emission of a neutron from the $^{94}$Mo compound nucleus. The isomeric state can be produced only through $\gamma$ cascade from levels lying above it. Due to the availability of a large number of discrete levels below the isomeric state, all the levels lying above it including the 2.429 ($17/2^+$) state lying immediately above it will decay to the levels lying below the isomeric state, thus providing little chance for its population. The 2.429-MeV ($17/2^+$) state will decay to the 2.161-MeV ($13/2^+$) state rather than to the isomeric state due to a large energy dependence in favor of the latter. The comparatively large production of the isomeric state reported through measurements can be obtained only if there exists a level with spin-parity value of $19/2^+$ immediately above the isomeric state, which cannot decay to any level below the isomeric state. To populate this hypothetical level there is need for a level with a spin-parity value of $17/2^-$ that also cannot decay to any level below the isomeric state and it serves as a source to populate the hypothetical level with spin-parity value of $19/2^+$.

The calculation for the excitation function of the $^{93}\mathrm{Nb}(p,n)^{93}\mathrm{Mo}^m$ reaction with the inclusion of the two postulated levels immediately above the isomeric state is shown by Calc. 2 in Fig. 3. The magnitude of the excitation function compares well with the reported measurements. However, the calculated position of maximum seems shifted

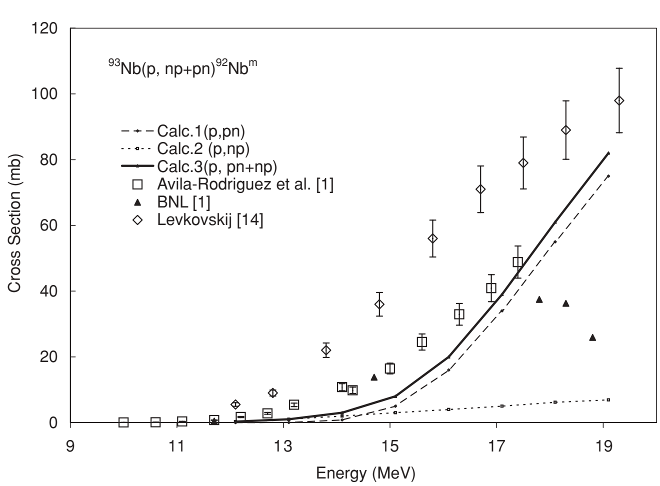


FIG. 1. Comparison of the calculated and measured excitation functions of the $^{93}\mathrm{Nb}(p,np+pn)^{92}\mathrm{Nb}$ reaction.

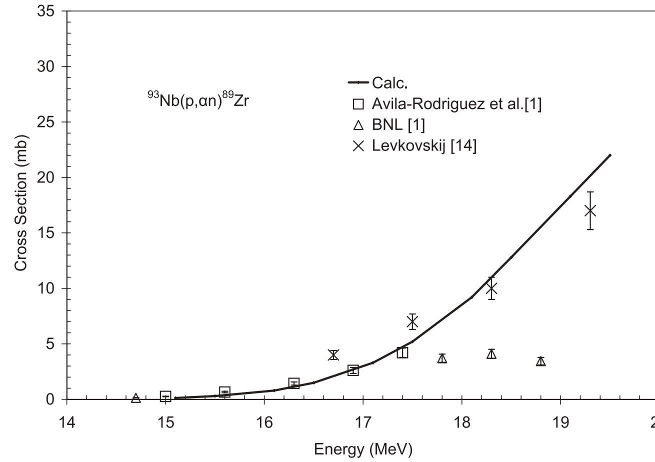


FIG. 2. Comparison of the calculated and measured excitation functions of the $^{93}\mathrm{Nb}(p,\alpha n)^{89}\mathrm{Zr}$ reaction.

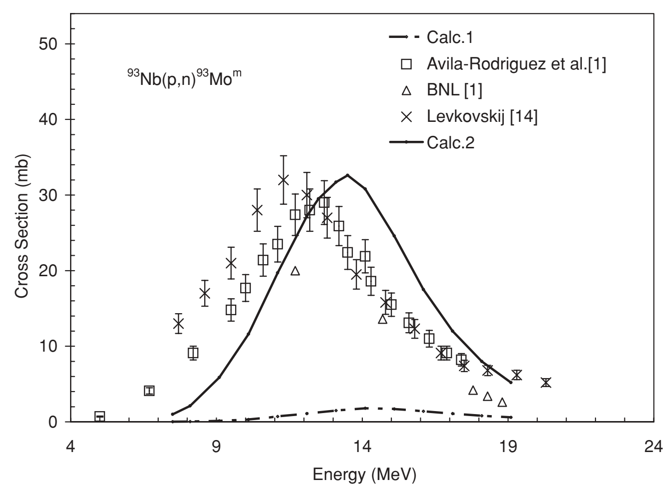


FIG. 3. Comparison of the calculated excitation function shown by Calc. 1 on the basis of existing nuclear structure and measured excitation functions of the $^{93}\mathrm{Nb}(p,n)^{93}\mathrm{Mo}^m$ reaction. The calculation after inclusion of the postulated levels is shown by Calc. 2.

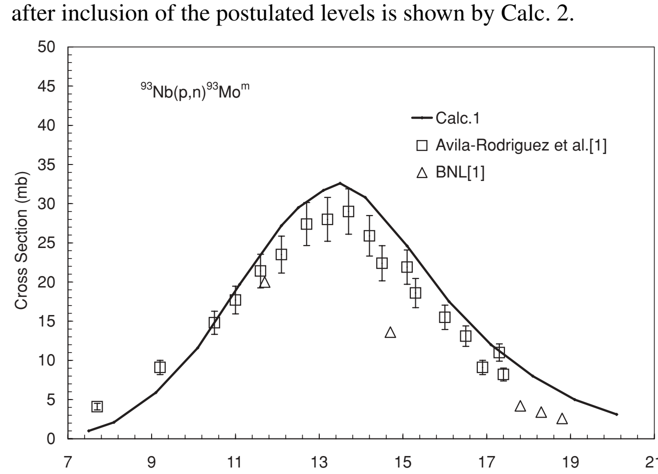


FIG. 4. Comparison of the calculation with reported data for the excitation function of the $^{93}\mathrm{Nb}(p,n)^{93}\mathrm{Mo}^m$ reaction after shifting the data of Avila-Rotriguez *et al.* [1] by 1 MeV toward the higher-energy side.

toward higher energy compared with the measurements of Levkoskvij [14] and Avila-Rodriguez *et al.* [1] by about 1.5 and 1 MeV, respectively. Such shifts of excitation functions in energy are not unexpected in the measurements based on the stacked foil techniques [1,15–17]. The position of maximum of the calculation, reported in Ref. [1], supports the present work. The present calculation of the excitation function is compared in Fig. 4 with the measurement of Avila-Rodrigues *et al.* [1] shifted by 1 MeV toward higher energy side and the agreement is very good between the measurement and the calculation. The BNL measurements shown in the figure have not been shifted and show lower values.

The probability of existence of the two postulated levels needs be discussed at this stage. Auerbach and Talmi [18] reported calculation for the positive-parity states of $^{93}$Mo on the basis of shell model. These states up to 3 MeV are considered to arise from the configurations $(\pi p_{1/2})^2(\pi g_{9/2})^2(\nu d_{5/2})^1$. The coupling of two protons in $g_{9/2}$ shell can give rise to angular-momentum values of $J = 0, 2, 4, 6, 8$ that on coupling with one neutron in $2d_{5/2}$ shell gives rise to 24 states in the spin range from 0 to 21/2 spread over the energy dispersion of 3 MeV. Similar calculations have also been reported by Bhatt and Ball [19] and Vervier [20]. These calculations have correctly predicted the isomeric state having energy of about 2.43 MeV. Auerbach and Talmi [18] predicted the level with spin-parity value of 17/2 to lie above the isomeric state while calculation by Bhatt and Ball [19] placed it below the isomeric state. It has been located through $^{93}$Nb$(p, n\gamma)^{93}$Mo reactions [21,22] to lie above the isomeric state. The observed levels in some cases have been found to be shifted by as much energy as 600 keV due to configuration mixing. Auerbach and Talmi predicted the level with a spin-parity value of $19/2^+$ at 2.81-MeV energy. The present postulated level could as well be identified with this predicted level shifted below by about 400 keV. The existence of negative-parity states in this energy region has been discussed by Mitarai and Minehara [21]. The negative-parity states can arise from the $[p^1_{1/2}, g^3_{9/2}]$ configuration of protons coupled to a neutron in $2d_{5/2}$. The hypothetical level having spin-parity value of $17/2^-$ could arise from this type of configuration.

## IV. SUMMARY

The calculation for the excitation functions of the $^{93}$Nb$(p, n)^{93}$Mo$^m$, $^{93}$Nb$(p, \alpha n)^{89}$Zr, and $^{93}$Nb$(p, np + pn)^{92}$Nb reactions have been calculated using available data of reaction parameters and agrees in general with the recent reported data. The agreement of calculation with reported data of the $^{93}$Nb$(p, n)^{93}$Mo$^m$ reaction requires the existence of two levels with spin-parity values of $19/2^+$ and $17/2^-$ lying immediately above the isomeric state. The existence of these two levels seems feasible on the basis of available shell-model calculations.

[1] M. A. Avila-Rodriguez, J. S. Wilson, M. J. Schueller, and S. A. McQuarrie, Nucl. Instrum. Methods Phys. Res. B **266**, 3353 (2008).
[2] K. Gul, Phys. Rev. C **70**, 034602 (2004).
[3] K. Gul, IAEA Report No. INDC (PAK) 011, 1995.
[4] D. Wilmore and P. E. Hodgson, Nucl. Phys. **55**, 673 (1964).
[5] F. G. Perey, Phys. Rev. **131**, 745 (1963).
[6] V. Avrigeanu, P. E. Hodgson, and M. Avrigeanu, Phys. Rev. C **49**, 2136 (1994).
[7] W. Dilg, W. Schantl, H. Vonach, and M. Uhl, Nucl. Phys. **A217**, 269 (1973).
[8] T. Belgya *et al.*, Handbook for calculations of nuclear reaction data, RIPL-2, IAEA-TECDOC-1506, IAEA, Vienna, 2006.
[9] Evaluated Nuclear Structure Data File, 2008, ENDSF NNDC, Brookhaven National Laboratory, USA. Available online http://www.nndc.bnl.gov/endf/.
[10] Experimental Nuclear Reaction Data EXFOR/CSCSRS, NNDC, Brookhaven National Laboratory, USA. Available online http://www.nndc.bnl.gov/exfor/exfor00.htm.
[11] D. M. Brink, Ph.D. thesis, Oxford University, 1955.
[12] P. Axel, Phys. Rev. **126**, 671 (1962).
[13] J. Kopecky and M. Uhl, Phys. Rev. C **41**, 1941 (1990).
[14] V. N. Levkovskij, *Cross Sections of Medium Mass Nuclide Activation (A=40–100)* (Inter-Vesi, Moscow, 1991).
[15] K. Gul, Appl. Radiat. Isot. **67**, 30 (2009).
[16] K. F. Hassan, S. M. Qaim, Z. A. Saleh, and H. H. Coenen, Appl. Radiat. Isot. **64**, 101 (2006).
[17] K. Gul, Appl. Radiat. Isot. **54**, 147 (2001).
[18] N. Auerbach and I. Talmi, Phys. Lett. **9**, 153 (1964).
[19] K. H. Bhatt and J. B. Ball, Nucl. Phys. **63**, 286 (1965).
[20] J. Vervier, Nucl. Phys. **75**, 17 (1966).
[21] S. Mitarai and E. Minehara, Nucl. Phys. **A406**, 55 (1983).
[22] L. L. Rutlidge, Jr., E. S. Macias, and D. G. Sarantites, Phys. Rev. C **13**, 2166 (1976).