Calculation of excitation functions and isomeric cross section ratio of the ^{58}Ni$(n,p)^{58}$Co^{m,g} reactions in the 1–20 MeV energy range

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Calculation of the excitation functions and isomeric cross section ratio of ^{58}Ni$(n,p)^{58}$Co^{m,g} reactions has been carried out using Hauser-Feshbach and preequilibrium nuclear reaction model codes in the 1–20 MeV energy range, and compared with measurements and previous calculations. The structure in the isomeric cross section ratio curve in the low-energy region has been investigated. The anomaly of the branching ratio of the 53 keV (4^+) state to the isomeric states has been resolved by using more precise formalism of the γ-ray transition probabilities available in the literature for the continuum and discrete levels.

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Precise knowledge of the excitation function of the ^{58}Ni$(n,p)^{58}$Co reaction is desirable for application in fission and fusion technology as well as in fast neutron dosimetry. The study of excitation functions of isomeric states is useful for fusion reactor technology and for radionuclidic purity of medically important radioisotopes [1]. The calculation of excitation functions of isomeric states and, therefore, of the isomeric cross-section ratio is sensitive to the γ transition probabilities [2,3]. This is particularly true of the low-lying states which are, in general, highly populated due to the decay of all higher states to these states. A large number of measurements of the isomeric cross section ratio and the excitation function of the ^{58}Ni$(n,p)^{58}$Co^m reaction [4–16], and their calculations [2,6,17] have been reported. Most of the previous calculations of the excitation functions and isomeric cross-section ratio of the ^{58}Ni$(n,p)^{58}$Co^{m,g} reactions were carried out using various versions of the STAPRE code [18]. In the present work these calculations are done using different codes and the structure of the isomeric cross-section ratio in the low-energy region has also been investigated. The outstanding anomaly of the branching ratio of the 53 keV (4^+) level to the isomeric states has been successfully resolved by using a more precise formalism of γ transition probabilities for the continuum and discrete levels.

The present nuclear model calculations were carried out using the HFMOD code [19] for Hauser-Feshbach and the PREMOD code [20] for preequilibrium calculations. Wilmore-Hodgson [21] potentials were used for neutrons and Perey [22] potentials were used for protons. Potentials for α particles were taken from Avrigeanu *et al.* [23]. The back-shifted Fermi-gas model based on the formalism of Dilg *et al.* [24] was used for energy-level density calculations. The values of energy-level density parameters were taken from the published literature [24,25]. A rigid body moment of inertia was used for nuclei. The γ transition probabilities were calculated using the formalism of Kopecky and Uhl [26] which is based on Lorentzian expressions for $M1$ and $E2$. The information on the discrete energy levels was ob-

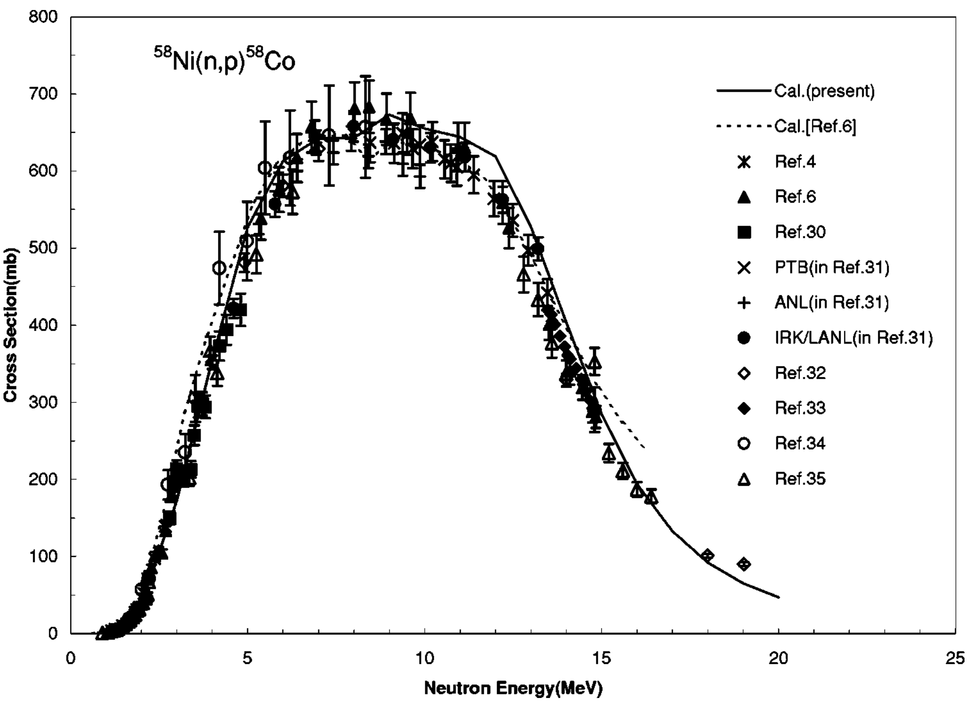

FIG. 1. Comparison of the calculations of the excitation function of the ^{58}Ni$(n,p)^{58}$Co reaction with measurements.

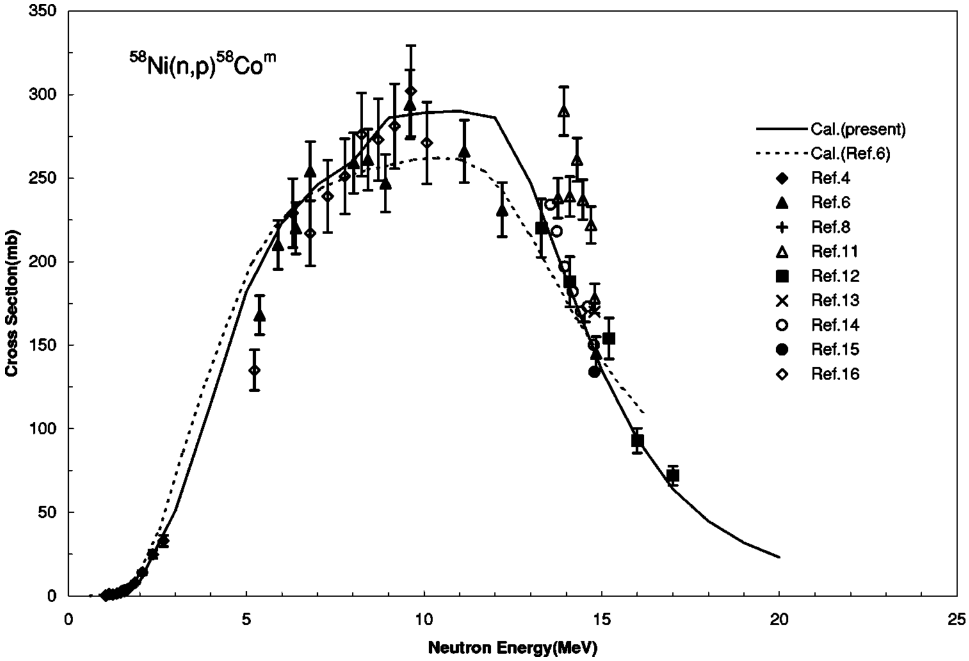

FIG. 2. Comparison of the calculations of the excitation function of the ^{58}Ni$(n,p)^{58}$Co^m reaction with measurements.

tained from Refs. [27–29]. 32 discrete levels were used for ^{58}Co up to 2 MeV.

The calculation of the excitation function of the ^{58}Ni$(n,p)^{58}$Co reaction is compared with reported measurements [4,6,30–35] and the calculation of Buczko *et al.* [6] in Fig. 1. The present calculation is in acceptable agreement with the measurements. The calculation of the excitation function of the ^{58}Ni$(n,p)^{58}$Co^m reaction is compared with reported measurements [4,6,8,11–16] and the calculation of Buczko *et al.* [6] in Fig. 2. The measurements of Meadows and Whalen [4] were deduced from their data of the ^{58}Ni$(n,p)^{58}$Co reaction and isomeric cross-section ratio. Except for the data of Venniot *et al.* [11], the agreement of the calculation with the measurements is satisfactory. The calculation of the isomeric cross-section ratio is compared with reported measurements [2,4–7,9–12] and the calculation of Buczko *et al.* [6] in Fig. 3. Where direct measurements of the isomeric cross-section ratio were not available these values were deduced from the available data on the cross sections of the two isomeric states. The data in 13–15 MeV energy region are highly discrepant and except for this energy region the agreement of the calculation with the measurements is acceptable. The measurements in the lower energy region are shown on an expanded scale in Fig. 4 and are compared with the calculation labeled as Ratio-1. The calculation shown as Ratio-2 is the ratio of the inelastic scattering cross section of the 25 keV (5^+) isomeric state to the compound elastic-scattering cross section. We observe that there is one to one

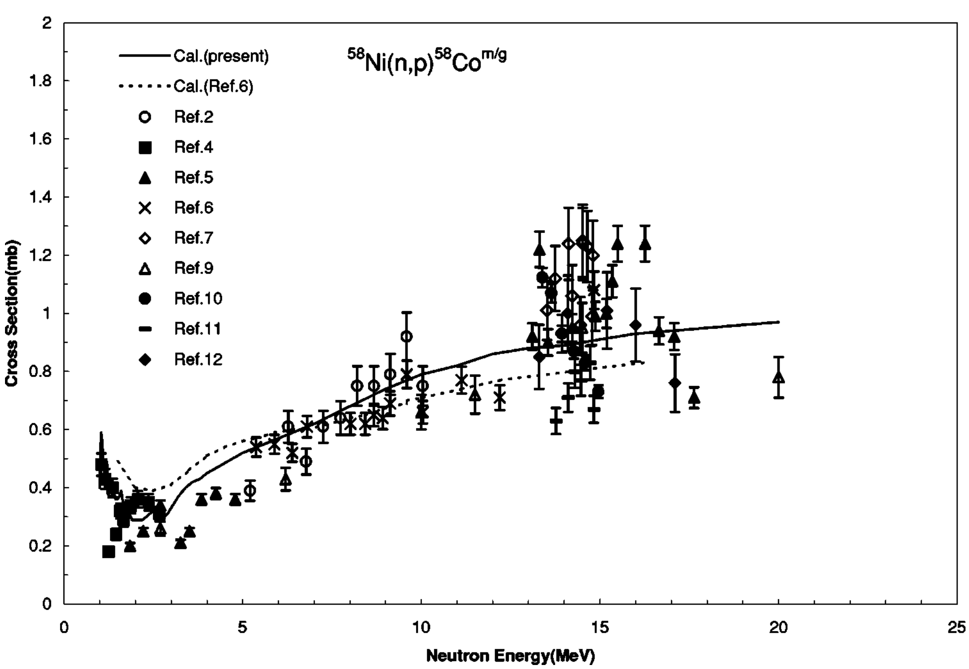

FIG. 3. Comparison of the calculations of the isomeric cross-section ratio of the ^{58}Ni$(n,p)^{58}$Co^{m,g} reactions with measurements.

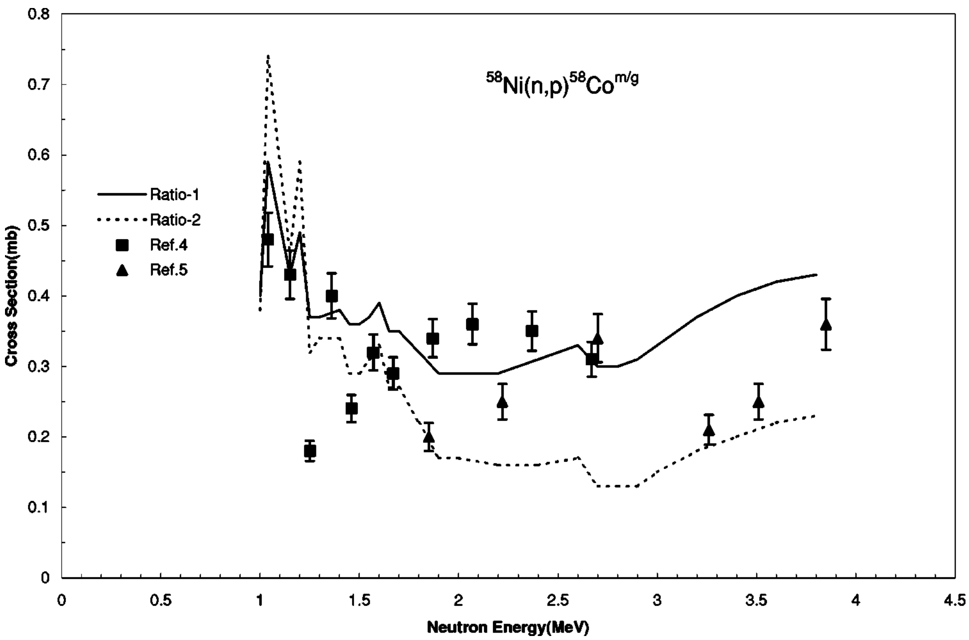

FIG. 4. Comparison of the calculation of the isomeric cross-section ratio with measurements and with the ratio of the inelastic scattering cross section of 25 keV (5^+) state to the compound elastic cross section.

correspondence in the structure of the two curves. In this energy region the n-α cross section is very small and the reaction cross section is shared between the ^{58}Ni$(n,n)^{58}$Ni and ^{58}Ni$(n,p)^{58}$Co reactions. When the incident neutron energy just crosses the threshold of the excitation of the first level of ^{58}Ni at 1.45 MeV, a new channel opens up resulting in the decrease of the cross section of the ^{58}Ni$(n,p)^{58}$Co reaction. This decrease in the cross section predominantly comes from the excitation of the ground state of ^{58}Co resulting in the raising of the isomeric cross-section ratio value as observed at about 1.6 MeV. Similarly the structure at about 2.6 MeV arises from the onset of the excitation of the 2.459 MeV level of ^{58}Ni. There is some indications of structure in the measurements at these energies.

An important point of discussion in the calculation concerns the branching ratios of the 53 keV (4^+) state to the 25 keV (5^+) and the ground (2^+) states. In the previous calculations [4,17] it was shown that the measured branching ratios gave lower cross sections for the 25 keV (5^+) isomeric state and correspondingly lower values for the isomeric cross section ratio. A very large branching ratio of the 53 keV (4^+) state to the 25 keV (5^+) was required to fit the data which was grossly inconsistent with the reported branching ratio [36,37]. In the present calculation no assumption of the branching ratio was required to get a good fit to the experimental data. This was due to the use of the improved formalism of Kopecky and Uhl [26] for the calculation of γ transition probabilities for the continuum and discrete levels. This formalism gives the branching ratio of the 53 keV (4^+) state to the 25 keV (5^+) state as 31% $(E2+M1)$ and that to the ground state as 69% $(E2)$ which are in good agreement with measured values of 29% and 71%, respectively [36].

In conclusion, a satisfactory agreement between the calculation and the measurements of the excitation functions and the isomeric cross-section ratio of the ^{58}Ni$(n,p)^{58}$Co reaction has been obtained by using the improved formalism for the calculation of γ transition probabilities and the outstanding issue of the branching ratios of the 53 keV (4^+) state to the two isomeric states has been resolved.

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[1] S. M. Qaim, in *Proceedings of the International Conference on Nuclear Data for Science and Technology*, Gatlinburg, 1994, edited by J. K. Dickens (American Nuclear Society, LaGrange Park, 1994), p. 186.
[2] S. Sudár and S. M. Qaim, Phys. Rev. C **53**, 2885 (1996).
[3] S. Sudár, A. Hohn, and S. M. Qaim, Appl. Radiat. Isot. **52**, 937 (2000).
[4] J. W. Meadows and J. F. Whalen, Phys. Rev. **130**, 2022 (1963).
[5] P. Decowski, W. Grochulski, A. Marcinkowsky, K. Siwek, I. Sledzinska, and Z. Wilhelmi, Nucl. Phys. **A112**, 513 (1968).
[6] Cs. Buczkó, J. Csikai, S. Sudar, A. Grallert, S. A. Jonah, B. W. Jimba, T. Chimoye, and M. Wagner, Phys. Rev. C **52**, 1940 (1995).
[7] P. Raics, F. Paszti, S. Daroczy, and S. Nagy, Atomki Kozli. **23**, 45 (1981).
[8] W. G. Cross, R. L. Claree, K. Morin, G. Slinn, N. M. Ahmed, and K. Beg, Report No. EANDC(CAN)-16, European-American Nuclear Data Committee Documents, 1963, p. 1.
[9] W. G. Cross, Bull. Am. Phys. Soc. **8**, 368 (1963).

[10] S. Okumura, Nucl. Phys. **A93**, 74 (1967).
[11] M. Viennot, A. Haddou, A. Chiadli, and G. Paic, in *Proceedings of the International Conference on Nuclear Data for Science and Technology*, Antwerp, 1982, edited by K. H. Bockhoff (Reidal, Dordrecht, 1983), p. 406.
[12] C. G. Hudson, W. L. Alford, and S. K. Ghorai, Ann. Nucl. Energy **5**, 589 (1978).
[13] V. N. Levkosky, G. P. Vinitskaya, G. E. Kovel Skaya, and V. M. Stepanov, Yad. Fiz. **10**, 44 (1969) [Sov. J. Nucl. Phys. **10**, 25 (1970)].
[14] A. A. Filatenkov *et al.*, International Nuclear Data Committee Report No. INDC (CCP)-402, 1997, IAEA, Vienna.
[15] I. Ribansky, J. Kristiak, L. Stoeva, and C. Paneleev, Report No. INDC (CSR)-7, 1985, IAEA, Vienna.
[16] S. Sudar, J. Csikai, and G. Stöklin, in *Proceedings of the International Conference on Nuclear Data for Science and Technology*, Julich, 1991, edited by S.M. Qaim (Springer-Verlag, Berlin, 1992) p. 291.
[17] V. Avrigeanu *et al.*, in *Proceedings of the International Conference on Nuclear Data for Science and Technology,* Trieste, 1997, edited by G. Reffo, A. Ventura, and G. Grandi (Italian Physical Society, Bologna, Italy, 1997), p. 1274.
[18] M. Uhl and B. Strohmaier, IRK Report No. 76/01, 1976.
[19] K. Gul, Report No. INDC (PAK) 011, 1995, IAEA, Vienna.
[20] K. Gul, Report No. SID-7, PINSTECH, 1996, Nilore.
[21] D. Wilmore and P. E. Hodgson, Nucl. Phys. **55**, 673 (1964).
[22] F. G. Perey, Phys. Rev. **131**, 745 (1963).
[23] V. Avrigeanu, P. E. Hodgson, and M. Avrigeanu, Phys. Rev. C **49**, 2136 (1994).
[24] W. Dilg, W. Schantl, H. Vonach, and M. Uhl, Nucl. Phys. **A217**, 269 (1973).
[25] M. Avrigeanu, M. Ivascu, and V. Avrigeanu, Z. Phys. A **335**, 299 (1990).
[26] J. Kopecky and M. Uhl, Phys. Rev. C **41**, 1941 (1990).
[27] M. R. Bhat, Nucl. Data Sheets **80**, 789 (1997).
[28] M. R. Bhat, Nucl. Data Sheets **85**, 415 (1998).
[29] Huo Junde, Nucl. Data Sheets **64**, 723 (1991).
[30] M. W. Wu and J. C. Chou, Nucl. Sci. Eng. **63**, 268 (1977).
[31] D. L. Smith, J. W. Meadows, H. Vonach, M. Wagner, R. C. Haight, and W. Mannhart, in *Proceedings of the International Conference on the Nuclear Data for Science and Technology*, Julich, 1991 (Ref. [16]), p. 282.
[32] X. Haung, W. Yu, X. Han, W. Zhao, H. Lu, J. Chen, Z. Shi, G. Tang, and G. Zhang, Nucl. Sci. Eng. **131**, 267 (1999).
[33] A. Pavlik, G. Winkler, M. Uhl, A. Paulsen, and H. Liskien, Nucl. Sci. Eng. **90**, 186 (1985).
[34] J. F. Barry, J. Nucl. Energy **16**, 467 (1962).
[35] A. A. Paulsen and R. Widera, in Proceedings of the International Conference on Chemical Nuclear Data, Canterbury, 1971, p. 129.
[36] R. G. H. Robertson and R. G. Summers-Gill, Can. J. Phys. **49**, 1186 (1971).
[37] B. Haas, C. Gehringer, J. Chevallier, J. C. Merdinger, and E. Bozek, Nucl. Phys. **A194**, 249 (1972).