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(n,2n) and (n,3n) Neutron Induced Reaction Cross Sections above 8 MeV

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Neutron induced reaction cross sections for (n,2n) and (n,3n) have been calculated in the energy range between 8 MeV and 26 MeV. Calculations were made for the target nuclei; ^{45}Sc, ^{59}Co, ^{89}Y, ^{93}Nb, ^{103}Rh, ^{169}Tm, ^{175}Lu, ^{181}Ta, ^{197}Au, ^{209}Bi. Calculated results were compared with the available data in EXFOR. Model calculations of present data indicated clearly that some reported data from measurements failed to separate (n,2n) and (n,3n) contributions.

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1. Introduction

The (n,2n) and (n,3n) reaction cross sections are important for applied nuclear physics, reactor technology, elemental analysis, nuclear models, accelerator driven systems etc. ^{45}Sc(n,2n)^{44}Sc, ^{59}Co(n,2n)^{58}Co, ^{59}Co(n,3n)^{57}Co, ^{89}Y(n,2n)^{88}Y, ^{89}Y(n,3n)^{87}Y, ^{93}Nb(n,2n)^{92}Nb, ^{93}Nb(n,3n)^{91}Nb, ^{103}Rh(n,2n)^{102}Rh, ^{103}Rh(n,3n)^{101}Rh, ^{169}Tm(n,2n)^{168}Tm, ^{169}Tm(n,3n)^{167}Tm, ^{175}Lu(n,2n)^{174}Lu, ^{175}Lu(n,3n)^{173}Lu, ^{181}Ta(n,2n)^{180}Ta, ^{181}Ta(n,3n)^{179}Ta, ^{197}Au(n,2n)^{196}Au, ^{197}Au(n,3n)^{195}Au, ^{209}Bi(n,2n)^{208}Bi, ^{209}Bi(n,3n)^{207}Bi neutron induced reaction cross sections were measured by several scientists in the past [1–12]. In this study reaction cross-sections for several nuclei, with mass numbers ranging from 45 to 209, were calculated using TALYS 1.6 [13] code in 8–26 MeV region and were compared with the available experimental data obtained from EXFOR [14].

2. Material and methods

Calculations of (n,2n), (n,3n) were performed using TALYS 1.6 [13] code, which can address the physics of the reaction using; gamma strength functions, pre-equilibrium models, pre-equilibrium spin distributions optical model parameters, level density parameters, exciton models etc. The calculations in the present study were performed using gamma-shell correction parameters, pre-equilibrium mechanism and multiple pre-equilibrium mechanism models. The exciton numerical transition rates with optical model for collision probability pre-equilibrium model were used for ^{45}Sc(n,2n)^{44}Sc, ^{59}Co(n,2n)^{58}Co, ^{59}Co(n,3n)^{57}Co, ^{89}Y(n,2n)^{88}Y, ^{89}Y(n,3n)^{87}Y reaction cross-section calculations. On the other hand, the multistep direct/compound pre-equilibrium model were used for ^{93}Nb(n,2n)^{92}Nb, ^{93}Nb(n,3n)^{91}Nb, ^{103}Rh(n,2n)^{102}Rh, ^{103}Rh(n,3n)^{101}Rh, ^{169}Tm(n,2n)^{168}Tm, ^{169}Tm(n,3n)^{167}Tm, ^{175}Lu(n,2n)^{174}Lu, ^{175}Lu(n,3n)^{173}Lu, ^{181}Ta(n,2n)^{180}Ta, ^{181}Ta(n,3n)^{179}Ta, ^{197}Au(n,2n)^{196}Au reaction cross-section calculations. The calculated cross sections were compared with the experimental data obtained from EXFOR [14].

3. Results and discussion

The calculated ^{45}Sc(n,2n)^{44}Sc, ^{59}Co(n,2n)^{58}Co, ^{59}Co(n,3n)^{57}Co, ^{89}Y(n,2n)^{88}Y, ^{89}Y(n,3n)^{87}Y, ^{93}Nb(n,2n)^{92}Nb, ^{93}Nb(n,3n)^{91}Nb, ^{103}Rh(n,2n)^{102}Rh, ^{103}Rh(n,3n)^{101}Rh, ^{169}Tm(n,2n)^{168}Tm, ^{169}Tm(n,3n)^{167}Tm, ^{175}Lu(n,2n)^{174}Lu, ^{175}Lu(n,3n)^{173}Lu, ^{181}Ta(n,2n)^{180}Ta, ^{181}Ta(n,3n)^{179}Ta, ^{197}Au(n,2n)^{196}Au, ^{197}Au(n,3n)^{195}Au, ^{209}Bi(n,2n)^{208}Bi, ^{209}Bi(n,3n)^{207}Bi reaction cross sections were compared with the experimental data measured by R.J. Prestwood et al. [1], L.R. Veeser et al. [2], C.G. Hundson et al. [3], V. Semkova et al. [4], A.J.M. Plompen et al. [5], A.A. Filatenkov et al. [6], Huang Jianzhou et al. [7], Y. Uno et al. [9], S. Iwasaki et al. [9], J. Frehaut et al. [10], Lu Hanlin et al. [11] and B.P. Bayhurst et al. [14]. The calculated cross sections are generally in agreement with the literature (See Figs. 1–20). However for some reactions TALYS 1.6 [13] calculations were above or under the experimental measurements reported in literature.

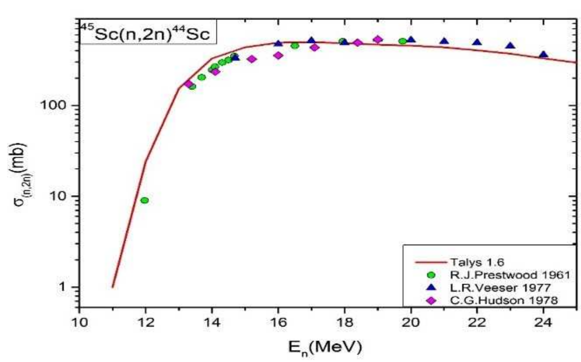

Fig. 1. Comparison of the calculated Talys 1.6 45Sc(n,2n)44Sc reaction cross section data with Refs. [1–3].

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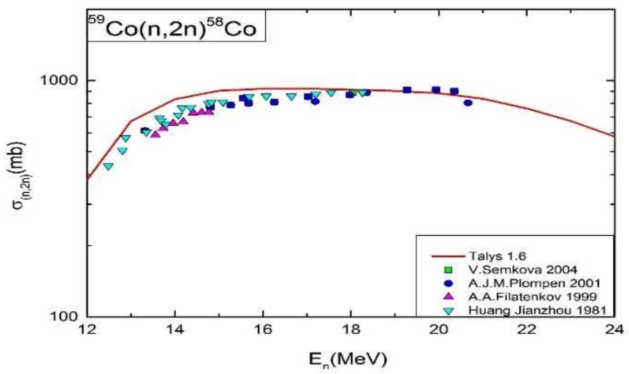

Fig. 2. Comparison of the calculated Talys 1.6 59Co(n,2n)58Co reaction cross section data with Refs. [4–7].

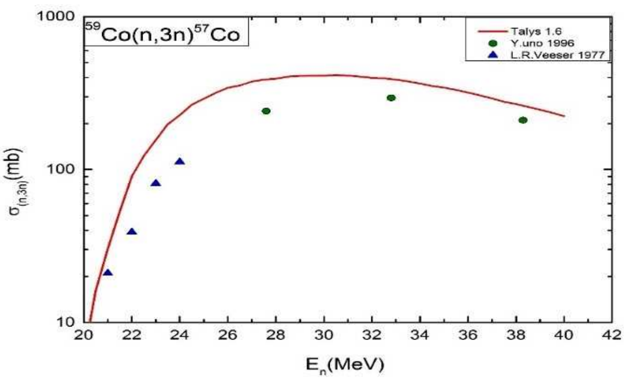

Fig. 3. Comparison of the calculated Talys 1.6 59Co(n,3n)57Co reaction cross section data with Refs. [2, 8].

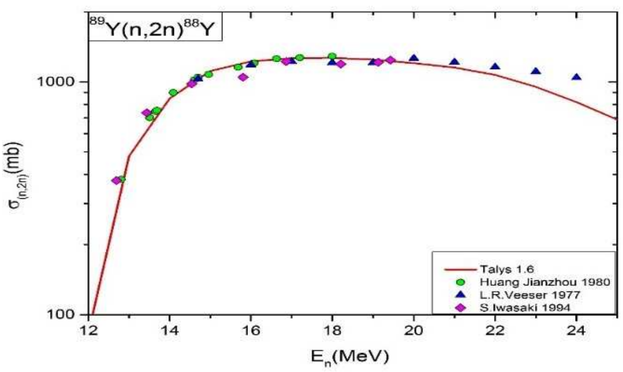

Fig. 4. Comparison of the calculated Talys 1.6 89Y(n,2n)88Y reaction cross section data with Refs. [2, 7, 9].

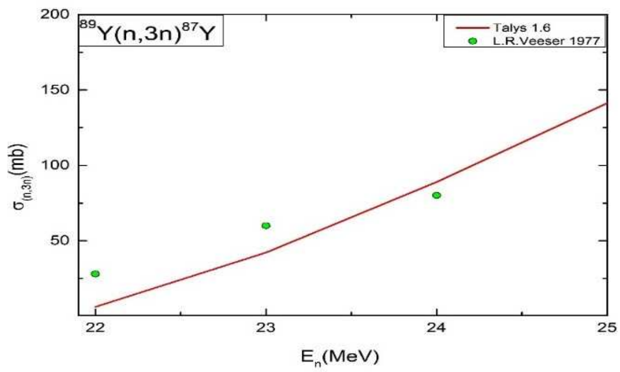

Fig. 5. Comparison of the calculated Talys 1.6 89Y(n,3n)87Y reaction cross section data with Ref. [2].

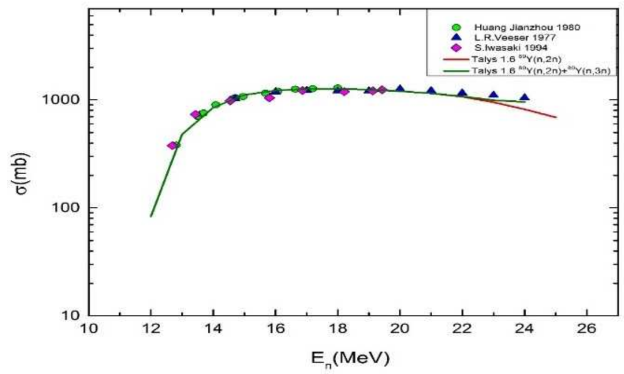

Fig. 6. Comparison of the calculated Talys 1.6 89Y(n,2n)88Y reaction cross section data combined with 89Y(n,2n)+ 89Y(n,3n) and Refs. [2, 7, 9].

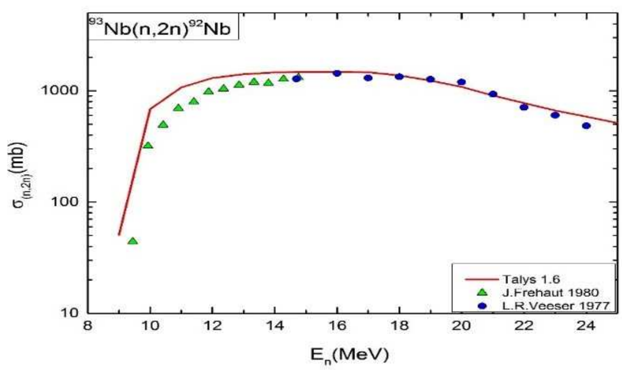

Fig. 7. Comparison of the calculated Talys 1.6 93Nb(n,2n)92Nb reaction cross section data with Refs. [2, 10].

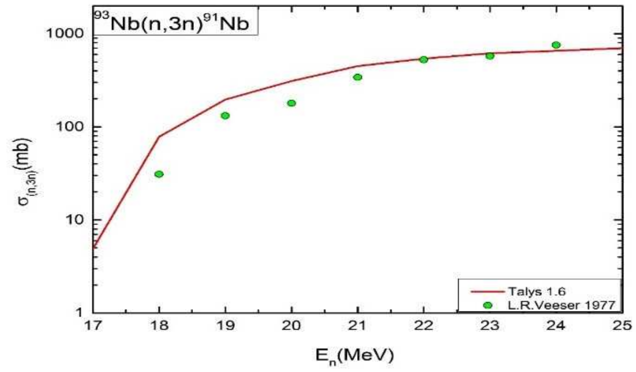

Fig. 8. Comparison of the calculated Talys 1.6 93Nb(n,3n)91Nb reaction cross section data with Ref. [2].

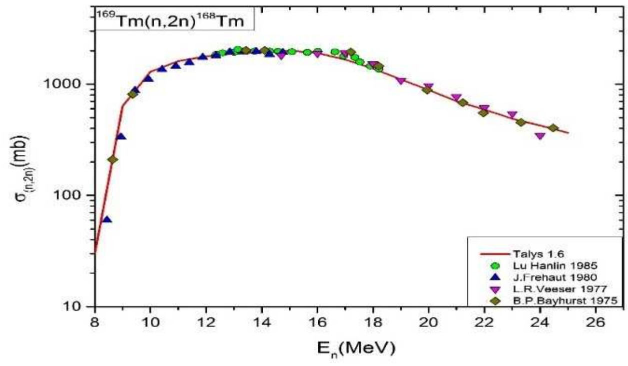

Fig. 11. Comparison of the calculated Talys 1.6 169Tm(n,2n)168Tm reaction cross section data with Refs. [2, 10–12].

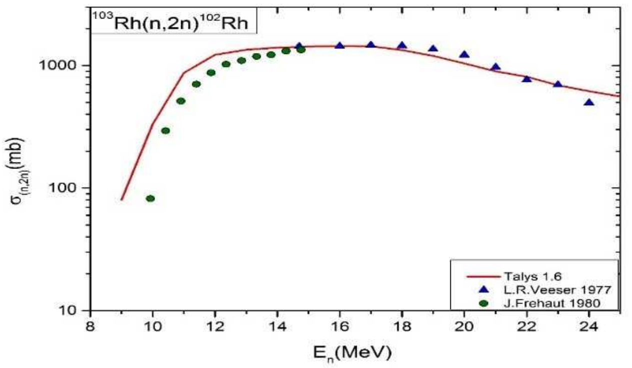

Fig. 9. Comparison of the calculated Talys 1.6 103Rh(n,2n)102Rh reaction cross section data with Refs. [2, 10].

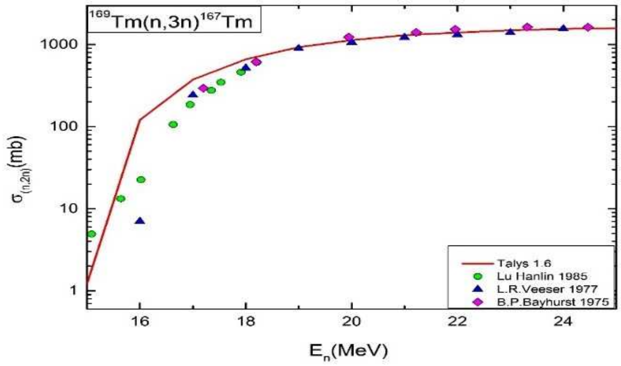

Fig. 12. Comparison of the calculated Talys 1.6 169Tm(n,3n)168Tm reaction cross section data with Refs. [2, 11, 12].

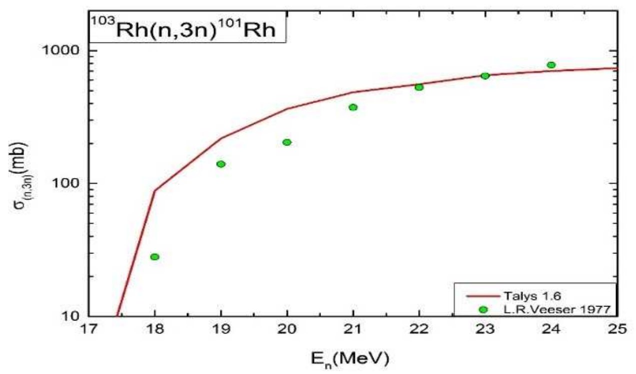

Fig. 10. Comparison of the calculated Talys 1.6 103Rh(n,3n)101Rh reaction cross section data with Refs. [2].

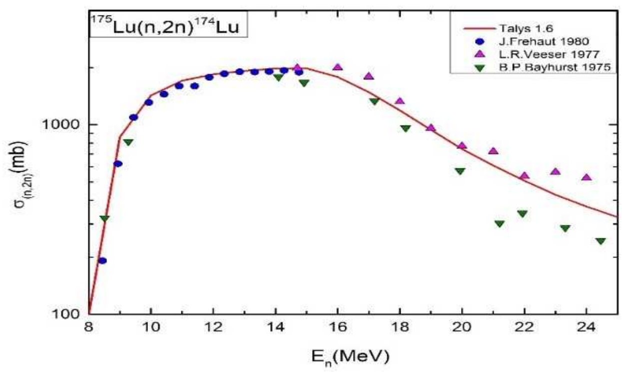

Fig. 13. Comparison of the calculated Talys 1.6 175Lu(n,2n)174Lu reaction cross section data with Refs. [2, 11, 12].

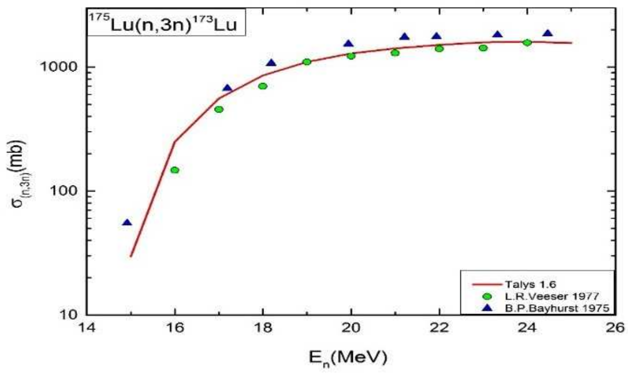

Fig. 14. Comparison of the calculated Talys 1.6 175Lu(n,3n)173Lu reaction cross section data with Refs. [2, 10].

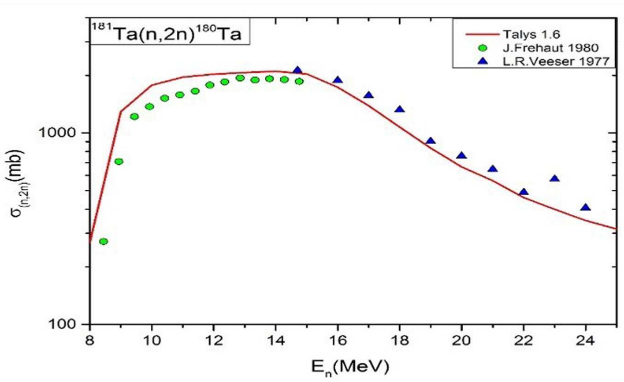

Fig. 15. Comparison of the calculated Talys 1.6 181Ta(n,2n)180Ta reaction cross section data with Refs. [2, 10].

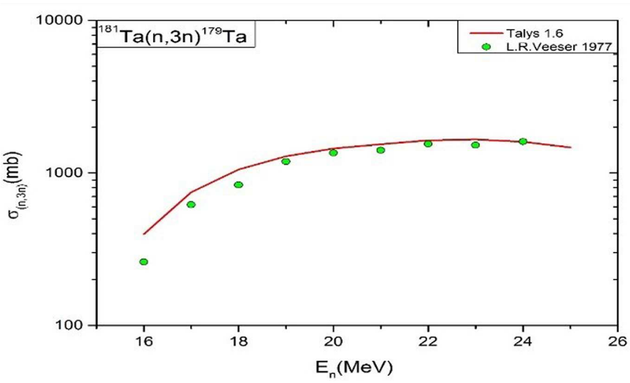

Fig. 16. Comparison of the calculated Talys 1.6 181Ta(n,3n)179Ta reaction cross section data with Ref. [2].

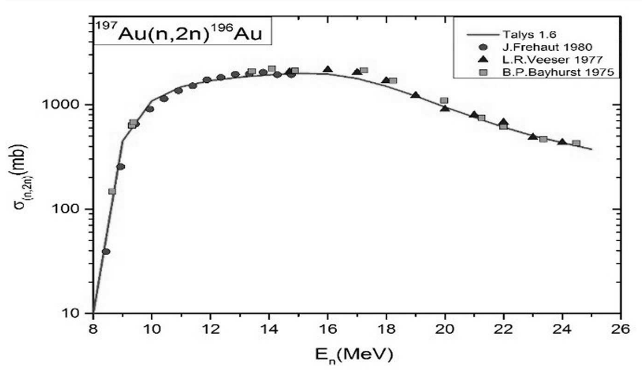

Fig. 17. Comparison of the calculated Talys 1.6 197Au(n,2n)196Au reaction cross section data with Refs. [2, 11, 12].

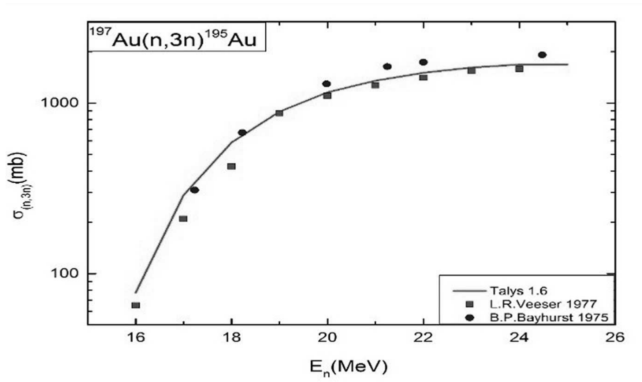

Fig. 18. Comparison of the calculated Talys 1.6 197Au(n,3n)195Au reaction cross section data with Refs. [2, 12].

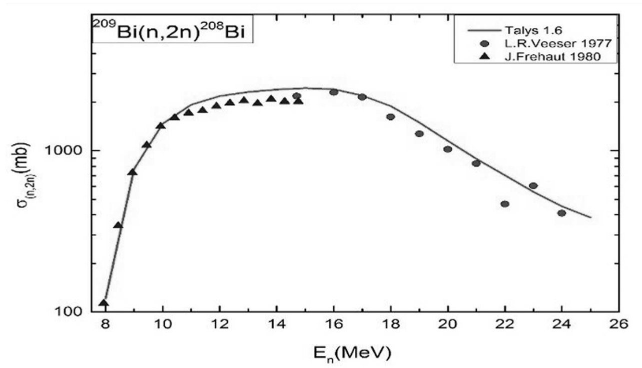

Fig. 19. Comparison of the calculated Talys 1.6 209Bi(n,2n)208Bi reaction cross section data with Refs. [2, 10].

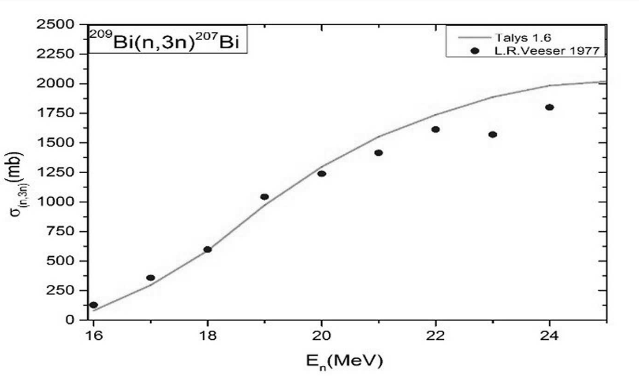

Fig. 20. Comparison of the calculated Talys 1.6 209Bi(n,3n)207Bi reaction cross section data with Ref. [2].

In Fig. 4, the calculated results and the experimental data strongly deviates above the incident energy of 19 MeV. A closer look to Figs. 4–6 indicates the (n,2n) and (n,3n) reaction cross sections overlapping. It seems that experimental results reported by L.R. Veeser et. al. [2] failed to separate (n,3n) contribution in (n,2n) measurements as shown in Fig. 6.

4. Conclusion

Present results reported in this study are generally in good agreement with the experimental data throughout all reactions especially around the giant dipole resonance (GDR) region. Moreover, our TALYS 1.6 calculations were generally above the reported experimental data in literature between 8–16 MeV as the incident neutron energy approaches the GDR region. It is sound to say that TALYS 1.6 calculation results for ^{169}Tm(n,2n)^{168}Tm, ^{169}Tm(n,3n)^{167}Tm ^{197}Au(n,2n)^{196}Au, ^{197}Au(n,2n)^{195}Au reactions are in excellent agreement with the experimental data reported by Lu Hanlin et al. [11], J. Frehaut et al. [10], L.R. Veeser et al. [4], B.P. Bayhurst et al. [14] (see Figs. 11, 12, 17, 18). Other reaction cross sections measured by L.R. Veeser et al. [2] were analyzed for the same (n,3n) contributions to (n,2n) reactions (see Figs. 1, 9, 13, 15). However, the (n,3n) contribution could not be exactly determined for ^{45}Sc(n,2n)^{44}Sc, ^{103}Rh(n,2n)^{102}Rh, ^{175}Lu(n,2n)^{174}Lu and ^{181}Ta(n,2n)^{180}Ta reactions due to the fluctuations in the experimental data after 19 MeV that makes the (n,3n) contribution an unresolved question.

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