

NEUTRON-INDUCED α AND MULTI-PARTICLE EMISSIONS ON ^{60}Ni : COMBINING EXPERIMENTS WITH LATEST EVALUATED NUCLEAR DATA FILES AND TALYS 2.0 MODEL

OLJA DORDIC 

University of Banja Luka, Faculty of Natural Sciences and Mathematics
Mladena Stojanovica 2, Banja Luka, R. Srpska, Bosnia and Herzegovina
olja.djordjic@pmf.unibl.org

*Received 23 June 2026, accepted 13 August 2026,
published online 5 October 2026*

Neutron-induced reactions on ^{60}Ni were examined to study nuclear reaction mechanisms and provide a comparison with nuclear models. The analysis is based entirely on previously published experimental data, from charged-particle detection at Peking University to γ -ray spectroscopy at the Los Alamos Neutron Science Center/Weapons Neutron Research (LAN-SCE/WNR) facility. Charged-particle detection provides direct insight into α -particle cross sections at lower energies, while the γ -ray measurements allow for a reliable determination of total cross sections for residual even-even isotopes at higher energy ranges. Experimental cross sections for the $^{60}\text{Ni}(n, X)^{54,55,56,57}\text{Fe}$ reactions were collected from the Experimental Nuclear Reaction Data (EXFOR) database and compared with the newest Evaluated Nuclear Data Files (ENDF): JENDL-5, ENDF/B-VIII.1, TENDL-2023, and theoretical predictions from TALYS 2.0 extended to intermediate energies ~ 240 MeV. TALYS 2.0 successfully reproduces the shape of the energy dependence of the total cross section for selected α -emission channels within the theoretical uncertainty band, except for the $^{60}\text{Ni}(n, 4n2p)^{55}\text{Fe}$ channel, while the multi-nucleon emission channels at high incident-neutron energies are also in good agreement with the TALYS 2.0 predictions above ~ 180 MeV.

DOI:10.5506/APhysPolB.57.11-A1

1. Introduction

Neutron-induced reactions provide a powerful tool for studying nuclear reaction mechanisms and nuclear structure, as they impose strict constraints on nuclear models. From an applied perspective, elemental transmutation via charged-particle emission can modify material properties, as can heating caused by the Bethe–Bloch energy loss after charged-particle emission, while

the population of excited nuclear states contributes directly to γ -ray heating. Nickel is widely used in stainless steels and other corrosion resistant alloys, which are needed in the construction of nuclear reactors and accelerator facilities, where neutron fluxes may be high. Research on (n, α) reactions is of particular importance in nuclear engineering, as neutron-induced helium production can lead to helium accumulation in structural materials, causing significant radiation damage [1, 2]. Also, neutron radiation damage is a major concern for Ni-based structural materials considered for space missions. It is strongly recommended that alloys, which are needed in the construction of nuclear reactors and accelerator facilities, be pursued as a method to mitigate radiation-induced embrittlement by reducing helium generation and solute segregation [3]. Among cluster emissions, α -particle emissions are the most common due to their high binding energy and low mass. At higher neutron energies, the same residual isotope can also be produced via multi-particle emission channels with the same baryon number and charge as an α particle (*e.g.* $p + d + n$, $p + t$, $2n + 2p$ or $d + d$), although these processes occur with negligible probabilities [4]. For residual isotopes $^{54,55,56}\text{Fe}$, γ -ray production data provide reliable estimates of total production cross sections in the 5–238 MeV energy range, while for ^{57}Fe , the energy range is 5–200 MeV [4]. In addition, the $^{60}\text{Ni}(n, \alpha)^{57}\text{Fe}$ reaction has been experimentally studied in the low-energy range of 5–10.5 MeV [5, 6].

The two experimental approaches, charged-particle detection at Peking University and γ -ray spectroscopy at LANSCE/WNR, provide matching insights into (n, α) reactions. While γ -ray measurements offer reliable estimates of total cross sections through observation of characteristic transitions, charged-particle detection allows for the direct measurement of α particle total cross sections. Together, these methods establish a strong experimental basis for constraining nuclear models and validating theoretical predictions.

Experimental cross-section data can be compared with theoretical model calculations, as functions of incident-neutron energy, to enhance the understanding of the reaction mechanism and provide standards for nuclear data evaluations. The contributions from competing reaction channels can also be examined, with particular attention to α -particle and single-nucleon multi-particle productions in nickel-based structural materials. In this work, a comparison was made with the newest Evaluated Nuclear Data Files (ENDF): JENDL-5, ENDF/B-VIII.1, TENDL-2023 and with theoretical predictions from TALYS 2.0 extended to intermediate energies ~ 240 MeV.

2. Methods

Nuclear data underpin all nuclear science and technology. Nuclear data are the basic experimental data (cross sections, energy/angular distributions, multiplicities, fission yields, radioactive decay data, *etc.*) for the numerical

simulation of nuclear systems (nuclear reactors, criticality-safety, medical applications (radiotherapy), neutron sources, transport and storage of radioactive material, radioprotection, nuclear astrophysics (nucleosynthesis), design of nuclear physics experiments, *etc.*). Nuclear data evaluation is a properly weighted (*e.g.* by GLSQ fit) combination of information from measurements and theoretical models to provide recommended values and uncertainties. Nuclear data are formatted according to the ENDF format and stored in evaluated libraries containing hundreds or thousands evaluations (isotopes). Those libraries are TENDL (IAEA, PSI), ENDF/B (USA), JENDL (Japan), JEFF (Europe), and some sub-libraries are available for activation, decay data, fission yields, *etc.* The modeling of nuclear (reaction) data is energy-dependent. Different energy ranges in the evaluations correspond to different models. On the other hand, TALYS 2.0 is based on theoretical and phenomenological models and has the ability to generate nuclear data for all open reaction channels for the defined energy. In Fig. 1, we can see how TALYS 2.0 uses the input file, optical and other models to calculate nuclear properties for all possible nuclear reaction mechanisms. In this work, a combination of charged-particle experiment and γ -ray experiment is modeled within TALYS 2.0. For charged-particle cross-section modeling, all possible reaction channels can be obtained, while in the case of γ -ray cross-sections modeling, only total cross section can be modeled. Nine TALYS 2.0 runs are performed with default optical potential (the Koning–Delaroche local potential together with the Watanabe folding approach for α particles) and experimental masses, after that combination of default optical potential with the

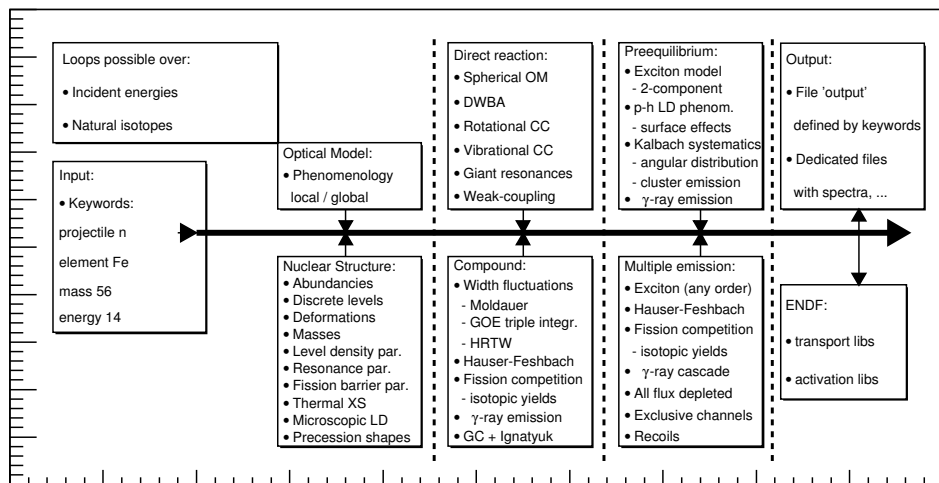


Fig. 1. Example of the TALYS 2.0 structure, from the input file to the final ENDF file, adapted from [12].

mass models (the Duflo–Zuker formula, the Möller table, the Goriely HFB-Skyrme table, and the HFB-Gogny D1M table [12]) included in TALYS 2.0 are used. Also, a set of TALYS 2.0 data is calculated using a microscopic optical potential (the Bauge–Delaroche JLM potential together with the α potential of Avrigeanu [12]) with masses from all 4 mass models. The total cross section from γ -ray transitions is calculated within the default TALYS 2.0 inputs, the default local optical potential, and experimental masses. In all runs, pre-equilibrium and multiple pre-equilibrium reaction mechanisms are enabled. For detailed explanation of all TALYS 2.0 model possibilities, see [7]. In all TALYS 2.0 runs, the local CTM level-density parameters were used.

Previous predictions from Evaluated Nuclear Data Files (ENDF): JENDL-5, ENDF/B-VIII.1, TENDL-2023, theoretical predictions from TALYS, GNASH, and CoH3 models [4–6] give accurate agreements with experimental measurements at low energies. Evaluated Nuclear Data Files (ENDF) and the TALYS 1.95 model were used for the low-energy regions up to 20 MeV [5, 6], with modification to optical potential parameters of TALYS 1.95 to obtain agreement with experimental measurements. Here, the default parameters of optical potentials were used, and variations among theoretical mass predictions were implemented without changing the default optical-potential parameters, as explained above. The GNASH and CoH3 models give good estimates of experimental datasets at lower energies as explained in [4], while at higher energies, both models tend to overestimate or underestimate measured cross sections. Since TALYS 2.0 is a newer and well-maintained model, in contrast to the older GNASH and CoH3 models, which are not maintained anymore, it is noteworthy to see its performance at higher energies, which are not well explored, and for various decay channels. The TALYS 2.0 data-driven development can benefit from extended research on various experimentally obtained observables which was a motivation for this work.

In this work, experimental cross sections for the $^{60}\text{Ni}(n, X)^{54,55,56,57}\text{Fe}$ reactions were collected from the Experimental Nuclear Reaction Data (EXFOR) database [8] and compared with newest Evaluated Nuclear Data Files (ENDF): JENDL-5 [9], ENDF/B-VIII.1 [10], TENDL-2023 [11], and with predictions from TALYS 2.0. In addition, TALYS 2.0 is extended to intermediate energy levels ~ 240 MeV and tested against experimental cross sections.

Experimental cross sections used in this work were measured for the $^{60}\text{Ni}(n, X)^{54,55,56,57}\text{Fe}$ reactions at the Los Alamos Neutron Science Center/Weapons Neutron Research (LANSCE/WNR) [4] over the incident-neutrons energy range of 5–238 MeV, while at Peking University [5, 6], cross sections for the $^{60}\text{Ni}(n, \alpha)^{57}\text{Fe}$ reactions were obtained for incident-neutron energies from 4.5 to 10.5 MeV.

γ -ray measurements were interpreted as total production cross sections because the population of higher-lying states rapidly cascades to the lowest discrete levels, see Fig. 2. For the residual isotopes $^{54-57}\text{Fe}$, the γ -ray production data gives 90% of the total production cross section for even residuals and provide a good approximation for odd ones (see Ref. [4] for more details). In this work, TALYS 2.0 calculations were done to check how the lowest transitions contribute to the total production cross section. Direct α -particle cross-section measurements from Peking University were used as a reference for charged-particles cross-sections measurements at lower energies (see Refs. [5, 6]).

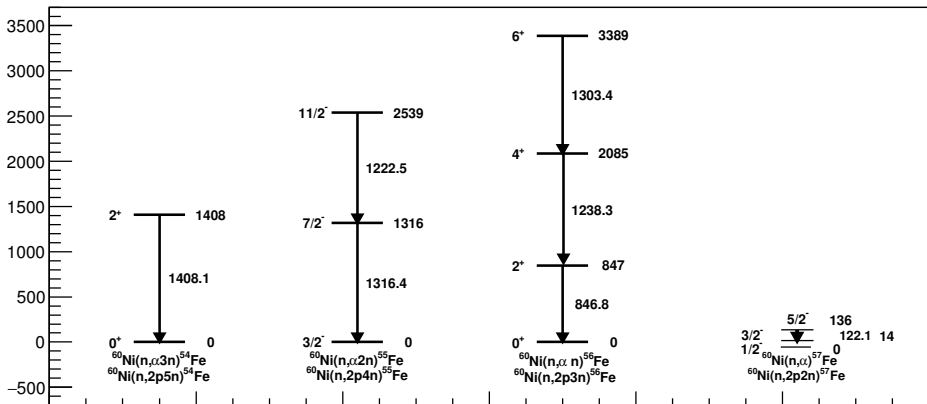


Fig. 2. Level schemes showing the transitions of Fe isotopes observed in the LAN-SCE/WNR experiment. All γ -ray and level energies are given in keV. The level schemes are adapted from [4].

3. Results and discussion

The experiments described earlier [5, 6] provide clean measurements of the $^{60}\text{Ni}(n,\alpha)^{57}\text{Fe}$ reaction channel, but only at low neutron energies of $E = 5\text{--}10.5$ MeV. The experiment described earlier [4] covers a broader energy range, $E = 5\text{--}238$ MeV, reporting only total production cross sections without channel separation. Therefore, nuclear-reaction models are essential for disentangling partial cross sections and interpreting the contribution of different channels.

The lower limits on theoretical uncertainty bands are contributed exclusively by the Duflo–Zuker formula and the Möller table. Changes in optical potentials (the Koning–Delaroche local potential and the Bauge–Delaroche JLM potential) and the other two mass models (the Goriely HFB–Skyrme and the HFB–Gogny D1M tables) or experimental masses, do not contribute to the lower theoretical uncertainty bands.

Contributions from all other decay channels are not negligible at low energies, where the α -particle cross section is equal to the total cross section, while at higher energies, contributions from all other decay channels account for up to a half of total cross section (in the energy range of 50–150 MeV), leaving the $2n2p$ channel as the most probable within the TALYS 2.0 model.

Figure 3 demonstrates the experimental cross sections, $\sigma(E)$, for the $^{60}\text{Ni}(n, \alpha)^{57}\text{Fe}$ reaction (closed black circles) as a function of neutron energy (E) [5, 6]. Evaluated data from JENDL-5 [9], ENDF/B-VIII.1 [10], and TENDL-2023 [11] are also shown (as magenta, brown, and gray lines, respectively). The ENDF evaluations were parsed for MT = 107, corresponding to the (n, α) channel. TALYS 2.0 modeling of population of the ^{57}Fe $3/2^-$ Mössbauer level is automatically counted as ground-state production, therefore, the experimental $5/2^- \rightarrow 3/2^-$ transition can be compared to the TALYS 2.0 ground-state cross section. Evaluated Nuclear Data Files (ENDF/B-VIII.1, JENDL-5, TENDL-2023) tend to overestimate measured cross section for the $^{60}\text{Ni}(n, \alpha)$ channel, while TALYS 2.0 gives good agreement within the theoretical uncertainty bands for the $^{60}\text{Ni}(n, \alpha)^{57}\text{Fe}$ reaction [4–6] (the blue line for the TALYS 2.0 prediction and the dashed blue line for the theoretical uncertainty bands). Good agreement is also obtained for the $^{60}\text{Ni}(n, 2n2p)^{57}\text{Fe}$ channel, above 40 MeV within the theoretical uncertainty bands (the yellow line for the TALYS 2.0 prediction and the dashed yellow line for the theoretical uncertainty bands) [4].

Overestimated values of the total cross section predicted by TALYS 2.0, both from γ transition (green line) and from charged-particle measurement (red line), may result from the experimental inability of γ -ray measurements to capture 100% of total cross section [4] and from the lack of experimental points from charged-particle measurements which cover the energy interval only up to 10.5 MeV [5, 6].

Figure 4 shows experimental cross sections, $\sigma(E)$, for the $^{60}\text{Ni}(n, n\alpha)^{56}\text{Fe}$ reaction at three different final-state excited residual energies, as measured in [4] (full circles, squares, and triangles), along with the evaluated data from JENDL-5 [9], ENDF/B-VIII.1 [10], TENDL-2023 [11] parsed for MT = 22 and presented with colored lines (magenta, brown, and gray, respectively), and TALYS 2.0 [7] predictions for the (n, X) , $(n, n\alpha)$, and $(n, 3n2p)$ channels, presented with colored lines together with theoretical uncertainty bands given as dashed lines in the same colors (red, blue, and yellow). The transition cross section $^{60}\text{Ni}(n, X)^{56}\text{Fe}$ from $2^+ \rightarrow 0^+$ within TALYS 2.0 is plotted as the green line and compared with the same results for the total $^{60}\text{Ni}(n, X)^{56}\text{Fe}$ channel from experiment (full black circles) [4]. The data show that lower-level excited residuals are produced more frequently, yielding higher cross sections, whereas cross sections decrease for higher-level excited residuals.

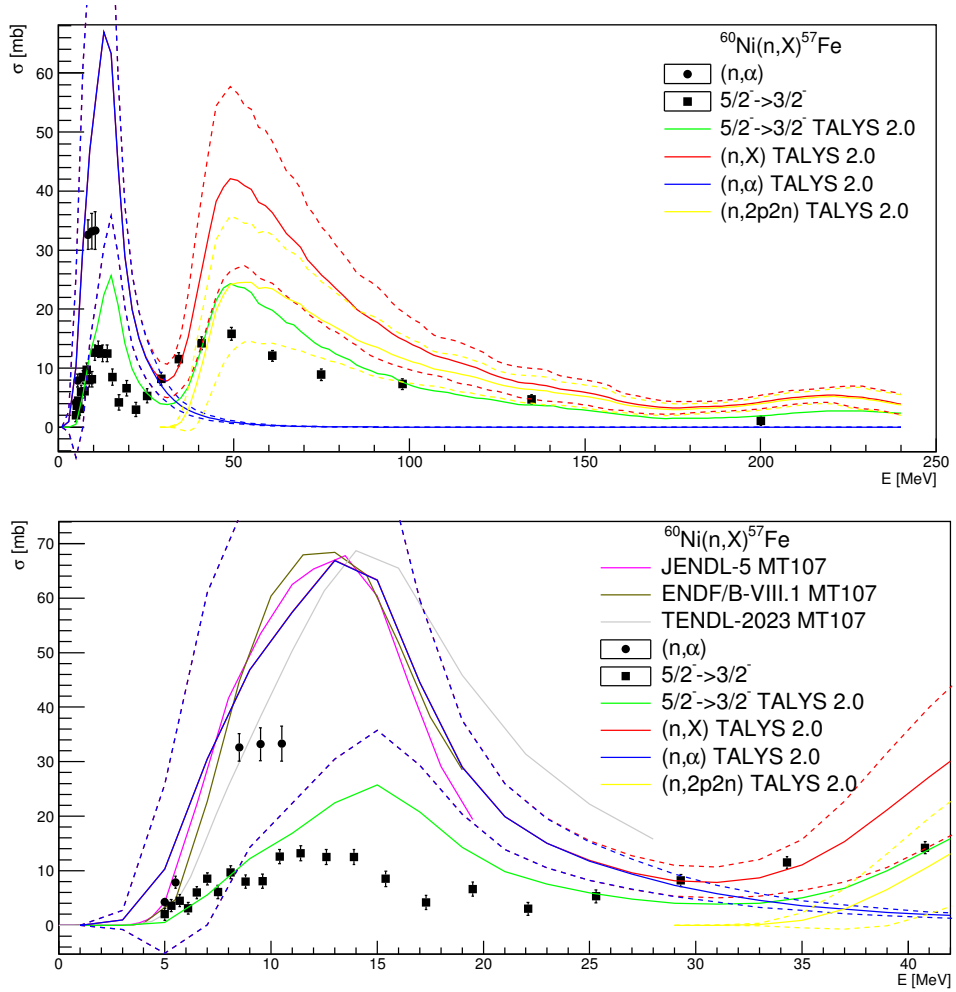


Fig. 3. Upper panel: Experimental cross sections, $\sigma(E)$, for the $^{60}\text{Ni}(n,\alpha)^{57}\text{Fe}$ reaction (full black circles) [5, 6], together with JENDL-5 [9], ENDF/B-VIII.1 [10], TENDL-2023 [11] (MT = 107) evaluated data presented with colored lines (magenta, brown, and gray, respectively), and TALYS 2.0 [7] predictions for the (n,X) , (n,α) , and $(n,2n2p)$ channels, presented with colored lines together with theoretical uncertainty bands shown as dashed lines in the same colors (red, blue, and yellow), as well as results for the total $^{60}\text{Ni}(n,X)^{57}\text{Fe}$ channel from the experiment (full black squares) [4]. A comparison with the experimental $^{60}\text{Ni}(n,X)^{57}\text{Fe}$ cross section [4] from the $5/2^- \rightarrow 3/2^-$ transition modeled with TALYS 2.0 is plotted as the green line. Bottom panel: Same as the upper panel, extended to higher energies and without the ENDF predictions.

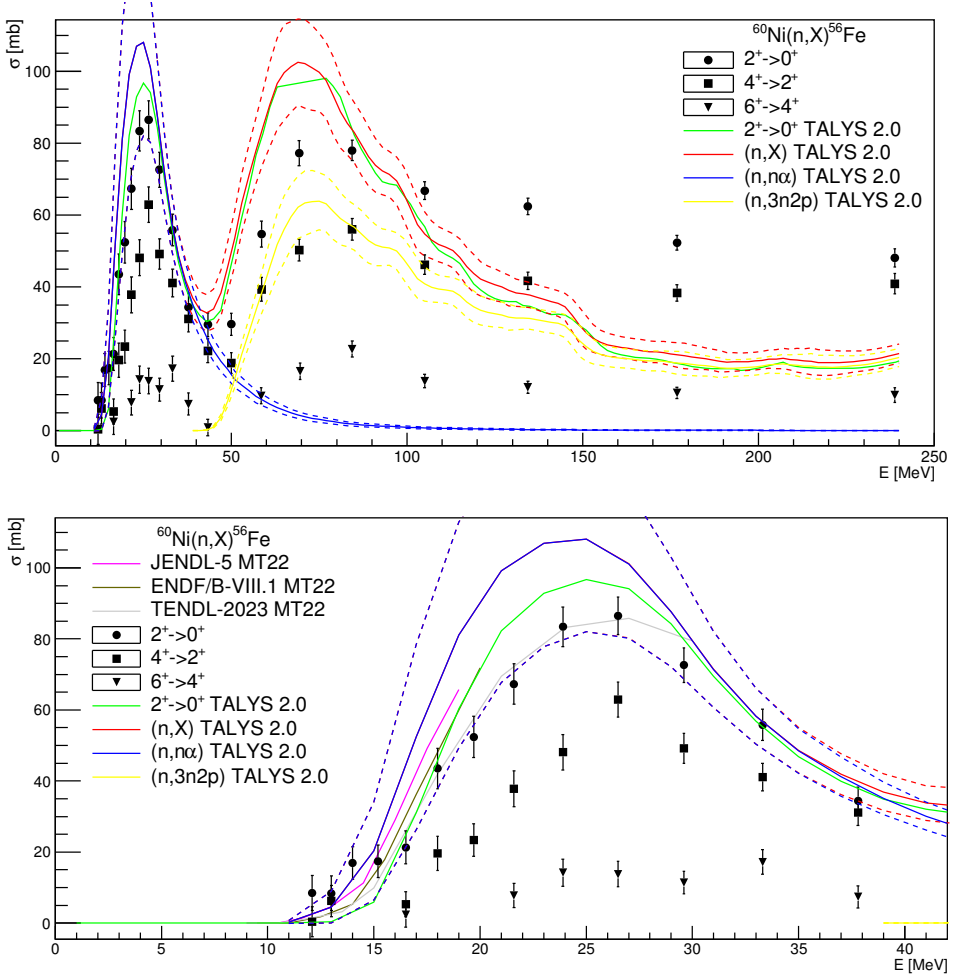


Fig. 4. Upper panel: JENDL-5 [9], ENDF/B-VIII.1 [10], TENDL-2023 [11] (MT = 22) evaluated data presented with colored lines (magenta, brown, and gray, respectively) and TALYS 2.0 [7] predictions for the (n, X) , $(n, n\alpha)$, and $(n, 3n2p)$ channels, presented with colored lines together with theoretical uncertainty bands shown as dashed lines in the same colors (red, blue, and yellow), as well as results for the total $^{60}\text{Ni}(n, X)^{56}\text{Fe}$ channel from the experiment for various transitions given in legend (full black circles, full black squares, and full black triangles) [4]. A comparison with the experimental $^{60}\text{Ni}(n, X)^{56}\text{Fe}$ cross section [4] from the $2^+ \rightarrow 0^+$ transition modeled with TALYS 2.0 is plotted as the green line. Bottom panel: Same as the upper panel extended to higher energies and without the ENDF predictions.

Evaluated data from JENDL-5, ENDF/B-VIII.1, TENDL-2023, and TALYS 2.0 reproduce the experimental results well up to 40 MeV for the $^{60}\text{Ni}(n, n\alpha)^{56}\text{Fe}$ reaction populating the ground state through the $2^+ \rightarrow 0^+$ transition. Above 40 MeV up to 80 MeV, TALYS 2.0, within theoretical uncertainty bands, favor the $^{60}\text{Ni}(n, 3n2p)^{56}\text{Fe}$ channel. The TALYS 2.0 predictions show severe discrepancies with the shape of the experimental excitation functions [4], significantly underpredicting the experimental data above ~ 100 MeV.

Figure 5 shows experimental cross sections, $\sigma(E)$, for the $^{60}\text{Ni}(n, X)^{55}\text{Fe}$ reaction for the $7/2^- \rightarrow 3/2^-$ final-state excited residual energies [4] (full black squares), together with the TALYS 2.0 [7] predictions for the total (n, X) , $(n, 2n\alpha)$, and $(n, 4n2p)$ channels presented with colored lines together with theoretical uncertainty bands shown as dashed lines in the same colors (red, blue, and yellow). No evaluated data from JENDL-5 [9], ENDF/B-VIII.1 [10] or TENDL-2023 [11] are available for this channel. TALYS 2.0 reproduces the experiment well up to 60 MeV, favoring $^{60}\text{Ni}(n, 2n\alpha)^{55}\text{Fe}$ production at lower energies for the $11/2^- \rightarrow 3/2^-$ transition (green line). Experiment [4] states that total cross section is measured for the $7/2^- \rightarrow 3/2^-$ transition. TALYS 2.0 underpredicts the total cross section for this transition (lilac line). This behavior is unexpected, since all other TALYS 2.0 predictions are in good agreement with experiments at lower energies,

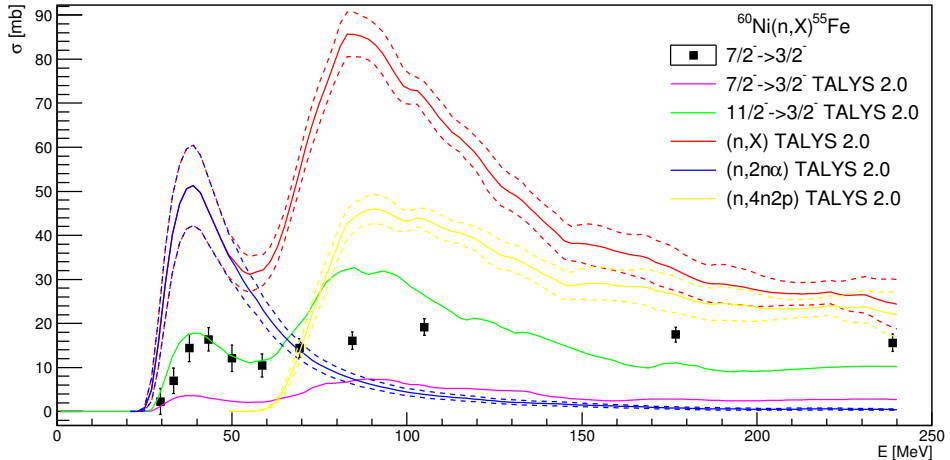


Fig. 5. TALYS 2.0 [7] predictions for the (n, X) , $(n, 2n\alpha)$, and $(n, 4n2p)$ channels, presented with colored lines together with theoretical uncertainty bands given as dashed lines in the same colors (red, blue, and yellow), as well as results for the total $^{60}\text{Ni}(n, X)^{55}\text{Fe}$ channel from the experiment (full black squares) [4]. A comparison with the experimental $^{60}\text{Ni}(n, X)^{55}\text{Fe}$ cross section from the $7/2^- \rightarrow 3/2^-$ and $11/2^- \rightarrow 3/2^-$ transitions within TALYS 2.0 is plotted as lilac and green lines, respectively.

or overpredict (see Figs. 3 and 4) measured cross sections from the γ -ray experiment. Above 60 MeV up to 160 MeV, TALYS 2.0 does not provide a good description of the experiment. However, above 160 MeV and up to 240 MeV, we can see that within theoretical uncertainty bands, TALYS 2.0 favors the $^{60}\text{Ni}(n, 4n2p)^{55}\text{Fe}$ channel.

Figure 6 shows experimental cross sections, $\sigma(E)$, for the $^{60}\text{Ni}(n, X)^{54}\text{Fe}$ reaction for the $2^+ \rightarrow 0^+$ transition [4] (full black squares), together with TALYS 2.0 [7] predictions for the total (n, X) , $(n, 3n\alpha)$, and $(n, 5n2p)$ channels presented with colored lines together with theoretical uncertainty bands shown as dashed lines in the same colors (red, blue, and yellow). No evaluated data are available for this channel from JENDL-5 [9], ENDF/B-VIII.1 [10] or TENDL-2023 [11]. In the case of ^{54}Fe residual channel, TALYS 2.0 gives a good description of the experiment, favoring α production at lower energies and single-nucleon production at higher energies.

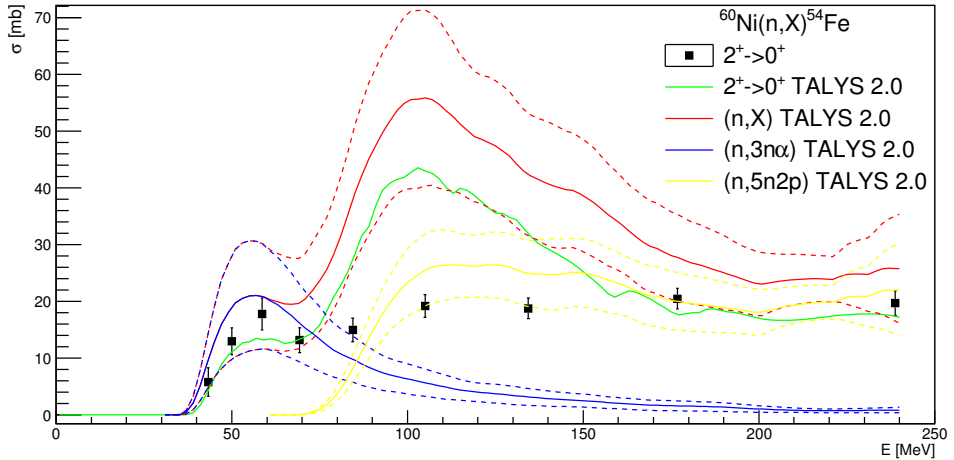


Fig. 6. TALYS 2.0 [7] predictions for the (n, X) , $(n, 3n\alpha)$, and $(n, 5n2p)$ channels, presented with colored lines together with theoretical uncertainty bands shown as dashed lines in the same colors (red, blue, and yellow), as well as results for the total $^{60}\text{Ni}(n, X)^{54}\text{Fe}$ channel from the experiment (full black squares) [4]. A comparison with the experimental $^{60}\text{Ni}(n, X)^{54}\text{Fe}$ cross section from the $2^+ \rightarrow 0^+$ transition within the TALYS 2.0 model prediction is plotted as the green line.

TALYS 2.0 reproduces the experiment well, favoring the $^{60}\text{Ni}(n, 3n\alpha)^{54}\text{Fe}$ channel within theoretical uncertainty bands (brown and yellow dashed lines) and for the $2^+ \rightarrow 0^+$ transition, favoring the $^{60}\text{Ni}(n, 3n\alpha)^{54}\text{Fe}$ channel. TALYS 2.0 predictions for the (n, X) channel above 80 MeV up to 140 MeV do not agree with the experiment, while above 140 MeV, we can see good agreement and the total cross section becomes equal to that of the $(n, 5n2p)$ channel.

To summarize the overall performance of TALYS 2.0 across the considered channels and energies, Fig. 7 presents the ratios of TALYS 2.0 predictions to experimental cross sections for the total production of ^{57}Fe . The figure includes results from the default run as well as the spread arising from variations in optical potentials (the Koning–Delaroche local *versus* the microscopic Bauge–Delaroche JLM) and mass models (experimental, Duflo–Zuker, Möller, Goriely HFB-Skyrme, HFB-Gogny D1M). The ratios generally remain close to 1 (± 20 –30% due to theoretical uncertainty bands) for even residuals at lower energies, while for odd residuals, the ratios are around 10, confirming a reasonable reproduction of the data shapes and magnitudes, though over-prediction persists. At intermediate energies, the ratios are well above 1 for the total cross sections and for all residuals (except ^{56}Fe), but the multi-particle channels remain around 1 in this energy region. Above 100 MeV, the total cross sections ratios are close to 1 again, except for the ^{56}Fe residual, which shows underprediction above 100 MeV.

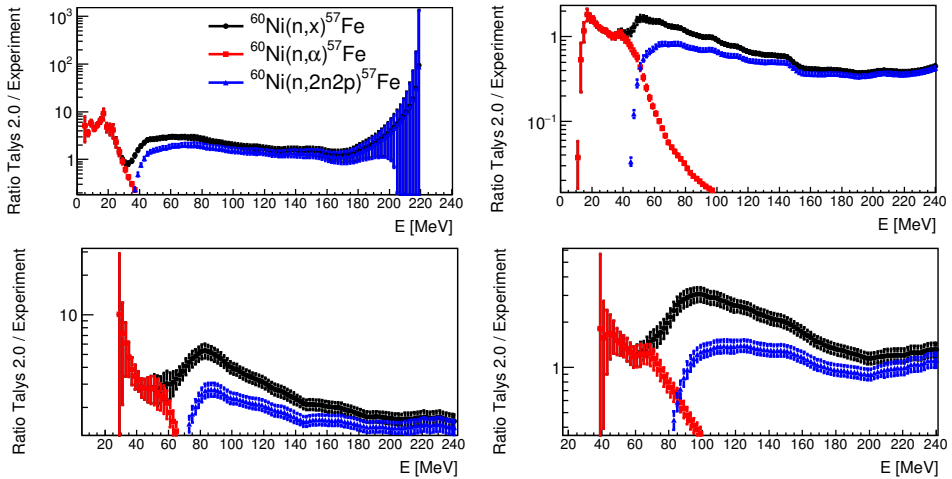


Fig. 7. The ratios of TALYS 2.0 predictions to total experimental cross sections [4] for the residual production of ^{57}Fe . The black line represents the total cross section ratios, the red line shows the (n, α) channel ratios, while the blue line stands for the multi-particle emission channel ratios. Theoretical uncertainty bands are shown as vertical lines.

Furthermore, the energy evolution of the dominant reaction mechanisms is shown in Figs. 8–10. These plots display the relative or absolute contributions to the total cross section. Compound, pre-equilibrium and direct cross-section components are shown as a function of incident-neutron energy E_n . The dominance of α -particle emission below ~ 50 –80 MeV, followed by the

increasing importance of channels such as $(n, 2n2p)$, $(n, 3n2p)$, *etc.*, above ~ 150 – 180 MeV, is consistent with the partial cross-section breakdowns shown in Figs. 3–6.

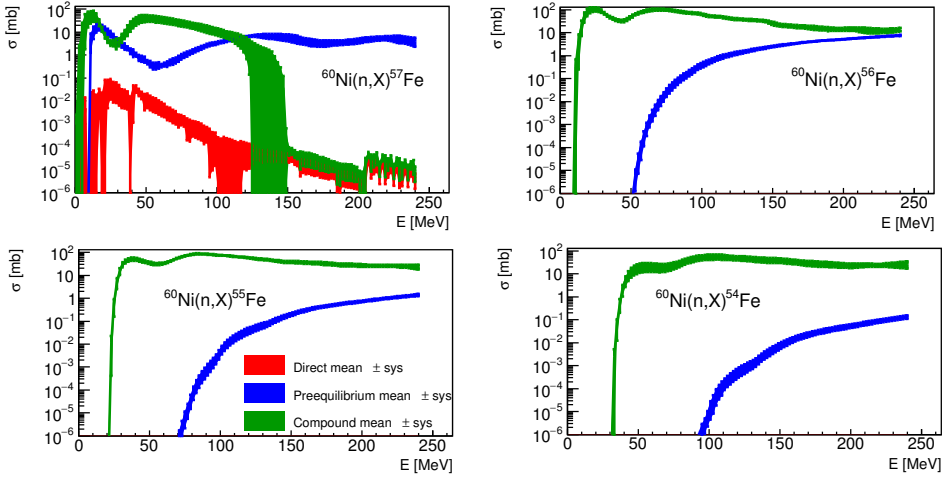


Fig. 8. TALYS 2.0 predictions of reaction mechanism contributions *versus* incident-neutron energy E_n for neutron-induced reactions on ^{60}Ni leading to the production of ^{57}Fe , ^{56}Fe , ^{55}Fe , and ^{54}Fe residual nuclei. The curves illustrate the compound, pre-equilibrium, and direct cross-section components (green, blue, and red, respectively) for the total cross section.

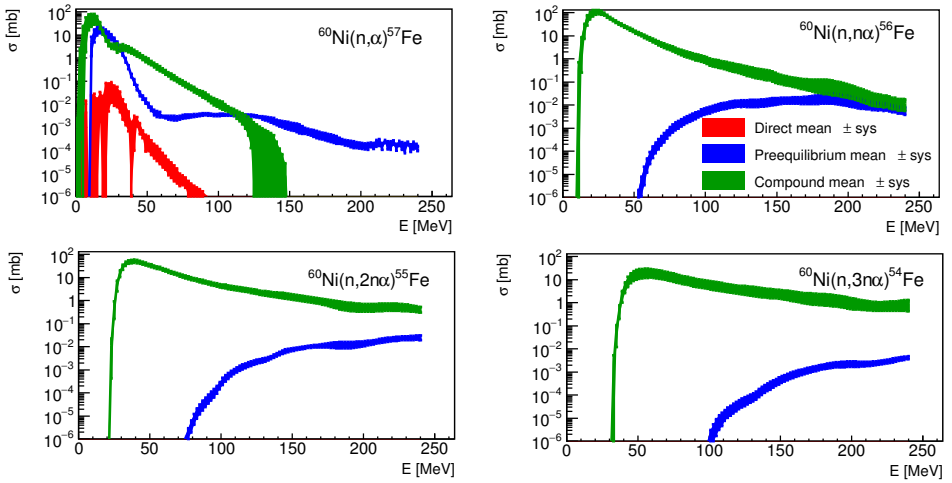


Fig. 9. Same as Fig. 8, but for the α -particle cross-section components.

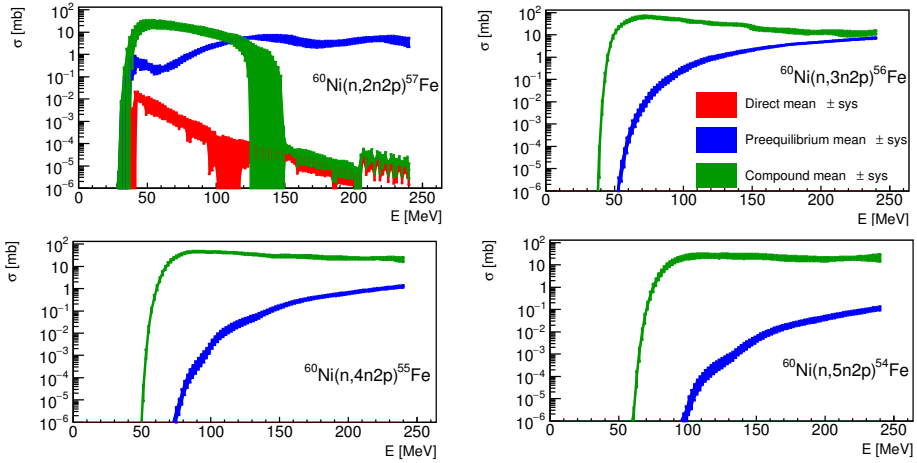


Fig. 10. Same as Fig. 8, but for the multi-nucleon emission channels.

4. Conclusion

Neutron-induced reactions on ^{60}Ni have been studied using complementary experimental approaches: charged-particle detection at Peking University [5, 6] and γ -ray spectroscopy at LANSCE/WNR [4], providing a comprehensive view of the reaction mechanisms from low to high neutron energies. The experimental data, combined with Evaluated Nuclear Data Files (JENDL-5 [9], ENDF/B-VIII.1 [10], TENDL-2023 [11]) and TALYS 2.0 [7] theoretical predictions, allow for a detailed analysis of partial and total cross sections for α -particle emission and multi-particle emission channels.

The (n, α) reaction channel is dominant at low neutron energies (~ 5 – 40 MeV), depending on the reaction, as confirmed by both γ -ray and charged-particle measurements. At higher energies, multi-nucleon emission channels, such as $(n, 2n2p)$, $(n, 3n2p)$, $(n, 4n2p)$, and $(n, 5n2p)$, become increasingly important. JENDL-5, ENDF/B-VIII.1, and TENDL-2023 successfully reproduce total shape of the (n, α) , $(n, n\alpha)$, $(n, 2n\alpha)$, and $(n, 3n\alpha)$ contributions in the energy ranges where predictions are available but does not provide good agreement with experimental cross-sections magnitudes. TALYS 2.0 gives undoubtable α -particle production channels at lower energies, except in the specific case of $^{60}\text{Ni}(n, 5n2p)^{55}\text{Fe}$ channel. Since TALYS 2.0 can be extended to higher incident-neutron energies to access multi-nucleon channels (*e.g.* $(n, 2n2p)$, $(n, 3n2p)$, $(n, 4n2p)$, and $(n, 5n2p)$), we evaluated its predictions and confirmed that they provide good agreement above 180 MeV.

The mechanism contribution plots (Figs. 8–10) further clarify that the low-energy behavior is governed by (n, α) processes, while high-energy interactions shift toward multi-nucleon emission channels, showing good TALYS 2.0 agreement above ~ 180 MeV. Ratios of TALYS 2.0 predictions to experimental data from LANSCE/WNR are presented in Fig. 7. These results confirm that model variations (optical potentials and masses) produce spreads comparable to, or smaller than, the typical theoretical uncertainty bands in such comparisons.

REFERENCES

- [1] M.A. Stopher, «The effects of neutron radiation on nickel-based alloys», *Mater. Sci. Technol.* **33**, 5 (2017).
- [2] M. Griffiths, «Structural Alloys for Nuclear Energy Applications», *Elsevier Inc.*, 2019.
- [3] T.M. Angeli, J.T. Ward, J.K. Witter, «Assessing the effects of radiation damage on Ni-base alloys for the prometheus space reactor system», *J. Nucl. Mater.* **366**, 223 (2007).
- [4] N. Fotiades *et al.*, « α and $2p2n$ emission in fast neutron-induced reactions on ^{60}Ni », *Phys. Rev. C* **91**, 064614 (2015).
- [5] Haoyu Jiang *et al.*, «Cross-section measurements for $^{58,60,61}\text{Ni}(n, \alpha)^{55,57,58}\text{Fe}$ reactions in the 4.50–5.50 MeV neutron energy region», *Chinese Phys. C* **44**, 114102 (2020).
- [6] Haoyu Jiang *et al.*, «Cross-section measurements for the $^{58,60,61}\text{Ni}(n, \alpha)^{55,57,58}\text{Fe}$ reactions at 8.50, 9.50 and 10.50 MeV neutron energies», *Chinese Phys. C* **46**, 024001 (2022).
- [7] A. Koning, S. Hilaire, S. Goriely, «TALYS: modeling of nuclear reactions», *Eur. Phys. J. A* **59**, 131 (2023).
- [8] V.V. Zerkin, B. Pritychenko, «The experimental nuclear reaction data (EXFOR): Extended computer database and Web retrieval system», *Nucl. Instrum. Methods Phys. Res. A* **888**, 31 (2018).
- [9] O. Iwamoto *et al.*, «Japanese evaluated nuclear data library version 5: JENDL-5», *J. Nucl. Sci. Technol.* **60**, 1 (2023).
- [10] G.P.A. Nobre *et al.*, «ENDF/B-VIII.1: Updated Nuclear Reaction Data Library for Science and Applications», *Nucl. Data Sheets* **210**, 1 (2026).
- [11] A.J. Koning *et al.*, «TENDL: Complete Nuclear Data Library for Innovative Nuclear Science and Technology», *Nucl. Data Sheets* **155**, 1 (2019).
- [12] A. Koning, S. Hilaire, S. Goriely, «TALYS-2.2: Simulation of nuclear reactions», <https://nds.iaea.org/talys/tutorials/talys.pdf>