International Symposium Commemorating the 40th Anniversary of the Halo Nuclei

10.12-10.18 Beijing, China

Predictions of (n, 2n) reaction cross section based on a Bayesian neural network approach

Weifeng Li（李伟峰）

Supervisor: Zhongming Niu（牛中明）

Contents

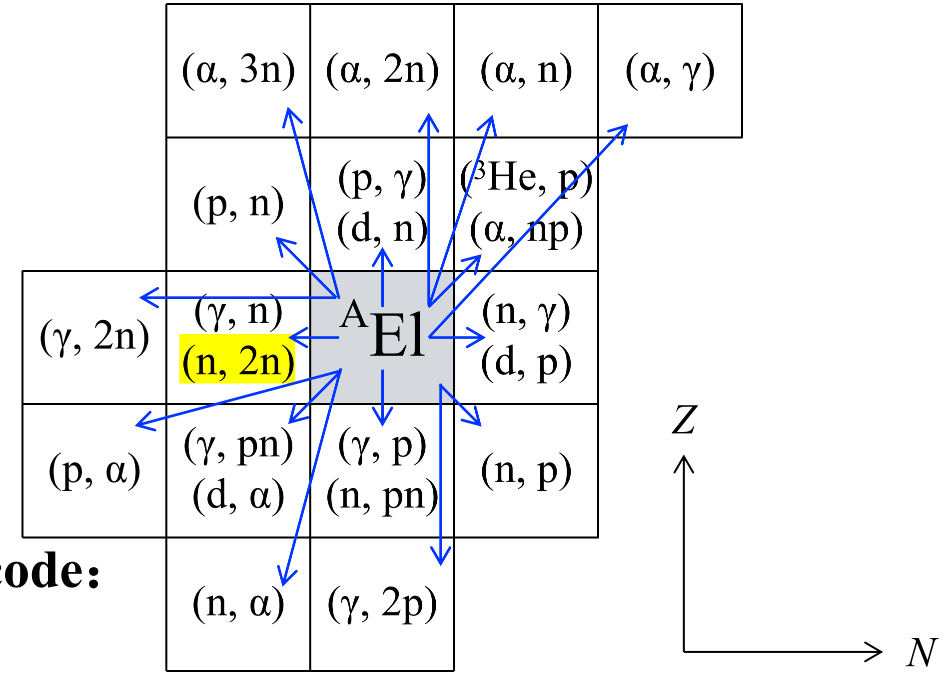
01

Introduction

Introduction

◆The (n, 2n) reaction is one of the most common reaction channels for neutron nuclear reactions. It is widely used in **neutron sources**, **neutron scattering** experiments, and **neutron irradiation** studies.

Luo2022EPJA, Kolos2022PRR

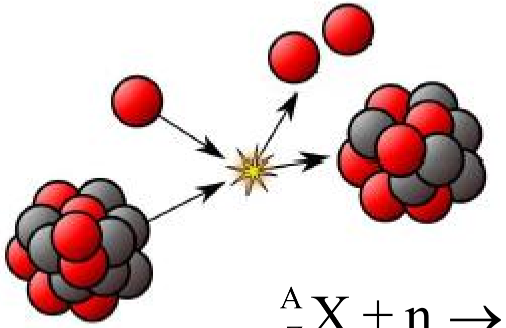


Major Nuclear Libraries:

1) ENDF/B-VIII.1 (USA, 2024)
2) JEFF-3.3 (Europe, 2017)
3) JENDL-5 (Japan, 2021)
4) CENDL-3.2 (China, 2020)
5) BROND-3.1 (Russia, 2016)

Theory-based computer code:

1) Talys (Netherlands)
2) Empire (USA)
3) CCONE (Japan)
4) UNF series (China)
5) ……



$${}^{A}_{Z}X + n \rightarrow {}^{A-1}_{Z}X + n + n$$

Introduction

Machine learning in nuclear decays and reactions

▲α-decay half-lives Saxena2021JPG, Ma2021CPC

▲β-decay half-lives Niu2019PRC, Li2024JPG

▲Fission yields Wang2019PRL, Qiao2021PRC

▲Cross-sections in proton induced spallation reactions Ma2020CPC

▲Neutron-nucleus scattering data Liang2021Thesis

▲Fusion reaction cross-sections Akkoyun2020NIMB

▲……

Machine learning in nuclear structure

▲Masses Niu2018PLB, Niu2022PRC, Wu2022PLB

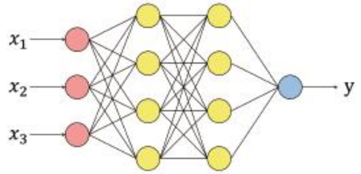
▲Nuclear spins and parities Gernoth1993PLB, Clark2006IJMPB

▲charge radii Wu2020PRC, Ma2020PRC, Dong2023PLB

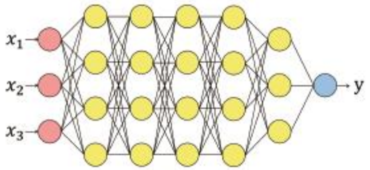
▲excited states Bai2021PLB, Wang2021PRC, Wang2022PLB

▲……

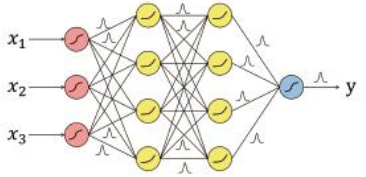
▲ANN



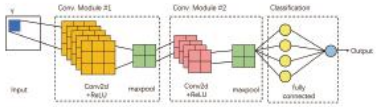
▲DNN



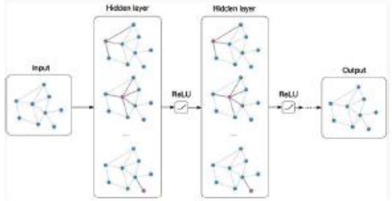
▲BNN



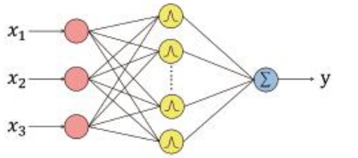
▲CNN



▲GNN



▲RBF



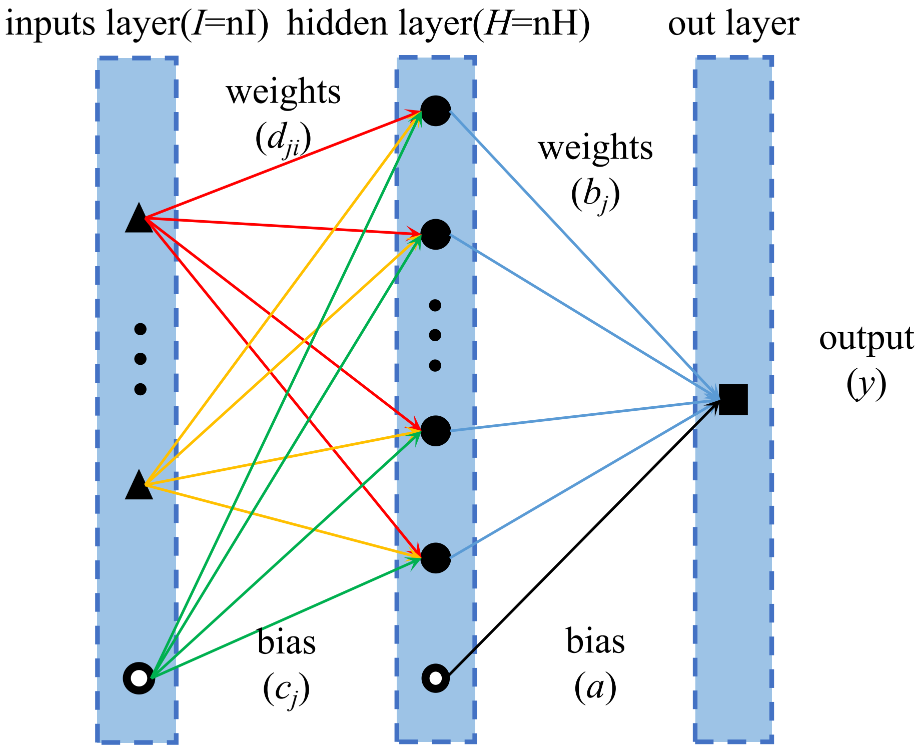
▲……

The Figure are taken from He2023SCPMA.

02 Theoretical framework

Theoretical framework

物理与光电工程学院
School of Physics and Optoelectronic Engineering



$$y(\boldsymbol{x}, \boldsymbol{\omega}) = a + \sum_{j}^{H} b_j \tanh\left(c_j + \sum_{i=1}^{I} d_{ji} x_i\right)$$

Networks	Input variables	H	Function	Output
BNN-I3	Z、N、ΔE	210	Tanh	σ
BNN-I4δ	Z、N、ΔE、δ	175	Tanh	σ
BNN-I4σ	Z、N、ΔE、σ_{th}	175	Tanh	σ
BNN-I5	Z、N、ΔE、δ、σ_{th}	150	Tanh	σ

$\boldsymbol{Z}$: Proton number;

$\boldsymbol{N}$: Neutron number;

$\boldsymbol{\Delta E}$: Incident energy – Reaction threshold;

$\boldsymbol{\delta}$: 1, 0, −1 for even-even nuclei, odd-A nuclei, and odd-odd nuclei, respectively;

$\boldsymbol{\sigma_{\mathrm{th}}}$: Theoretical value of the reaction cross-section.

taken from TENDL-2021

Theoretical framework

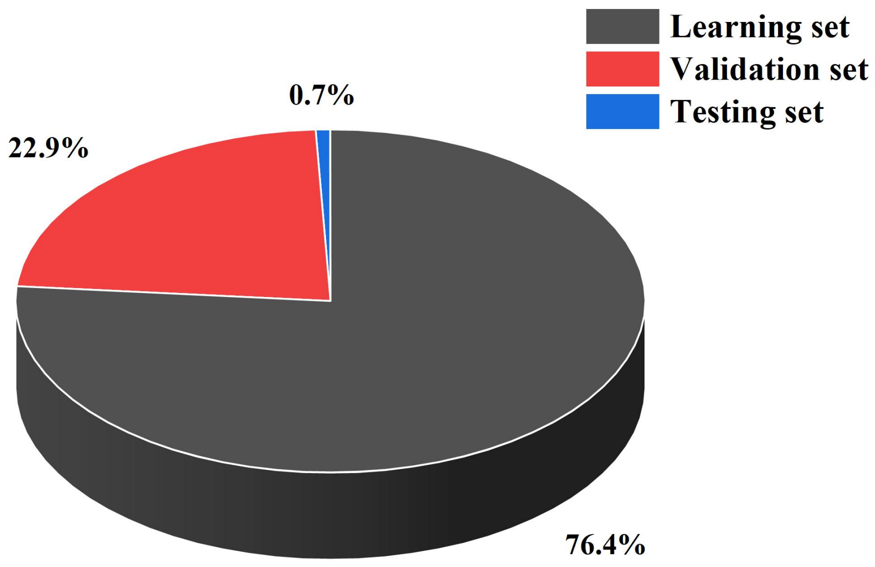
★**Total set:** $Z = 8 - 100$ nuclei region in the energy range from threshold to the region for which data are available or up to 20 MeV. (**519** nuclei, **11349** cross-section data)

All data taken from ENDF/B-VIII.0

★**Testing set:** **85** cross-section data of ^{115}Ag, ^{139}Ba, ^{178}Hf and ^{248}Cm;

★**Learning set:** No more than 20 cross-section data were randomly selected for each nucleus. (**8666** cross-section data)

★**Validation set:** The remaining **2598** cross-section data.



03

Results and discussion

Results and discussion

物理与光电工程学院
School of Physics and Optoelectronic Engineering

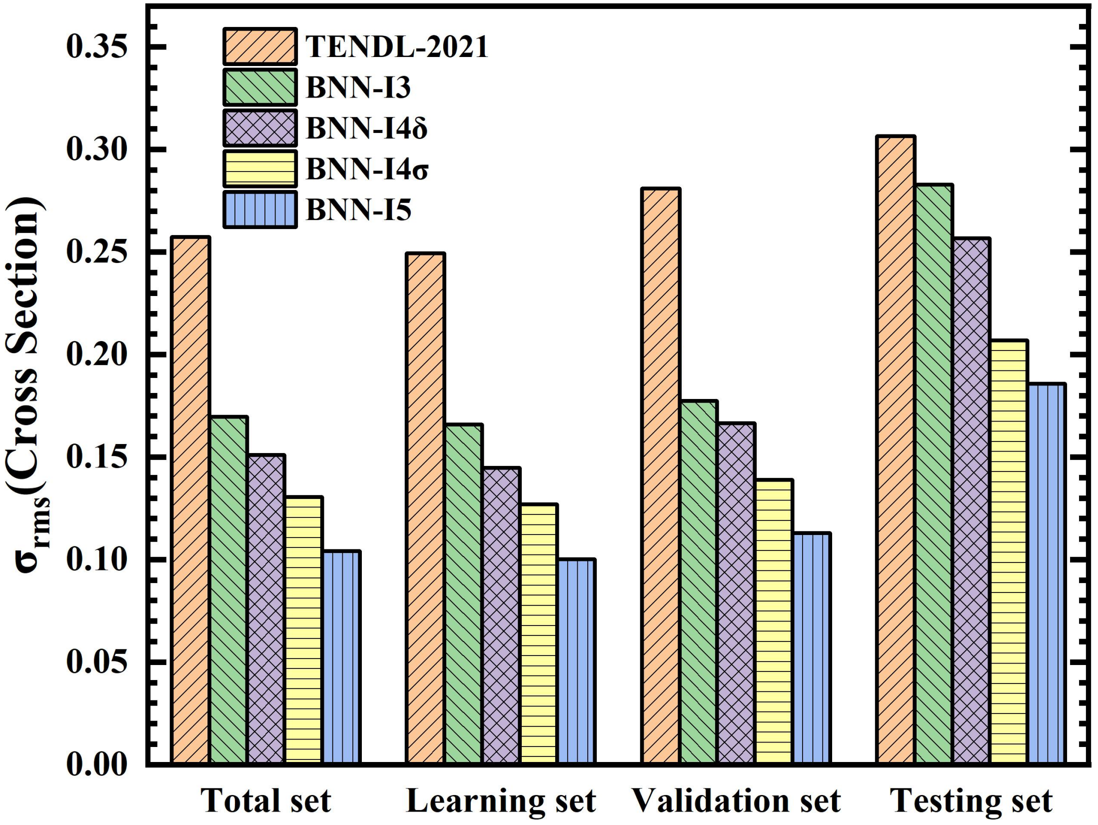


Fig. 1 The rms deviations σ_{rms}(Cross Section) of different BNN predictions with respect to the evaluation data of (n, 2n) reaction cross sections for the total set, learning set, validation set, and testing set.

- ◆ BNN method describes the (n, 2n) reaction cross section with significantly **higher accuracy** than the traditional TALYS approach.

- ◆ Adding relevant physical quantities to the input of the neural network can improve the prediction accuracy of the network to some extent.

Results and discussion

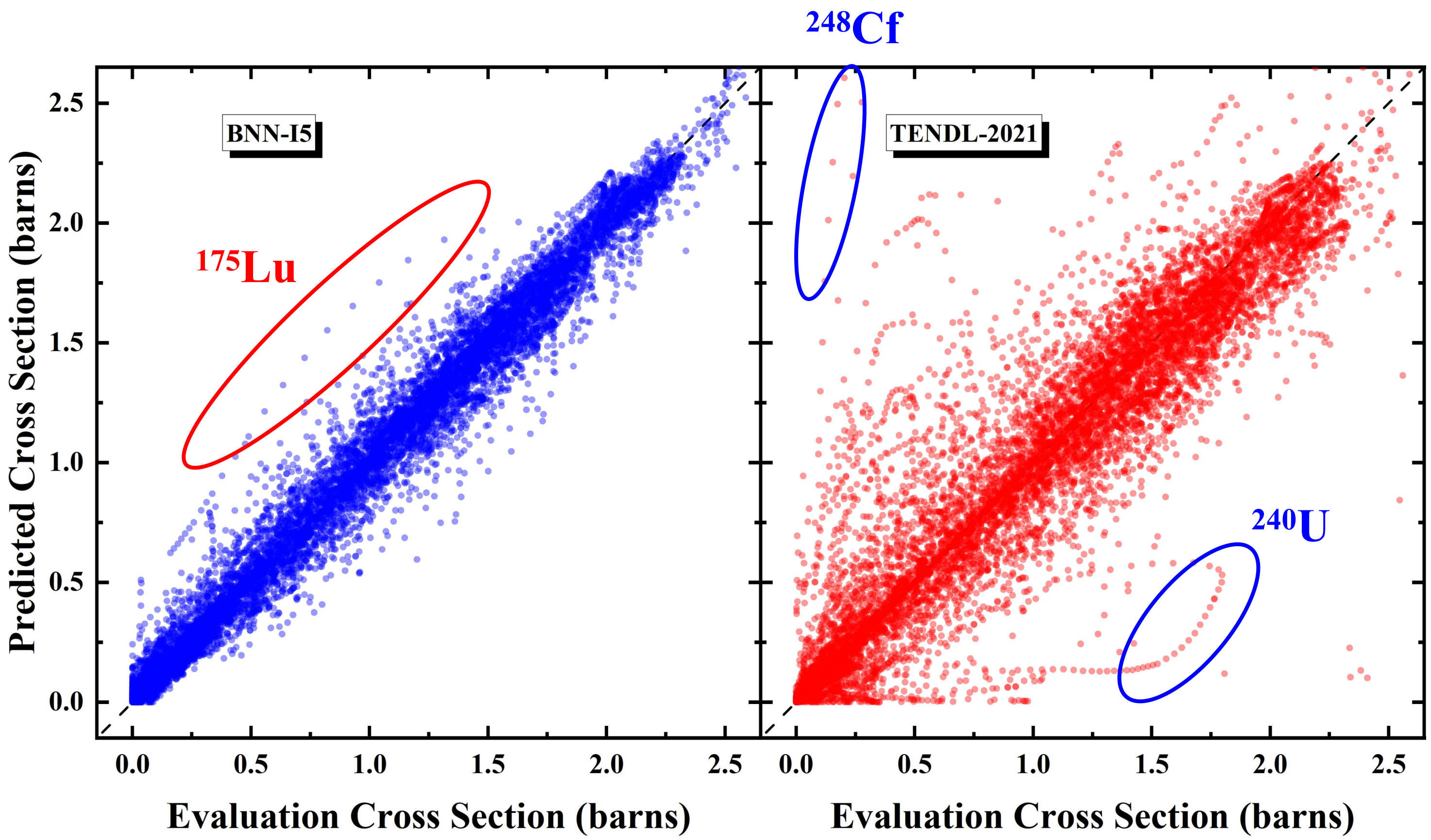


Fig.2 Scatter distribution of the (n, 2n) reaction cross sections predicted by BNN-I5 approach and TENDL-2021 as a function of the evaluation data.

◆ The BNN-I5 predictions are in general agreement with the evaluation data for the (n, 2n) cross section and provide better correlation and stability than TENDL-2021.

Results and discussion

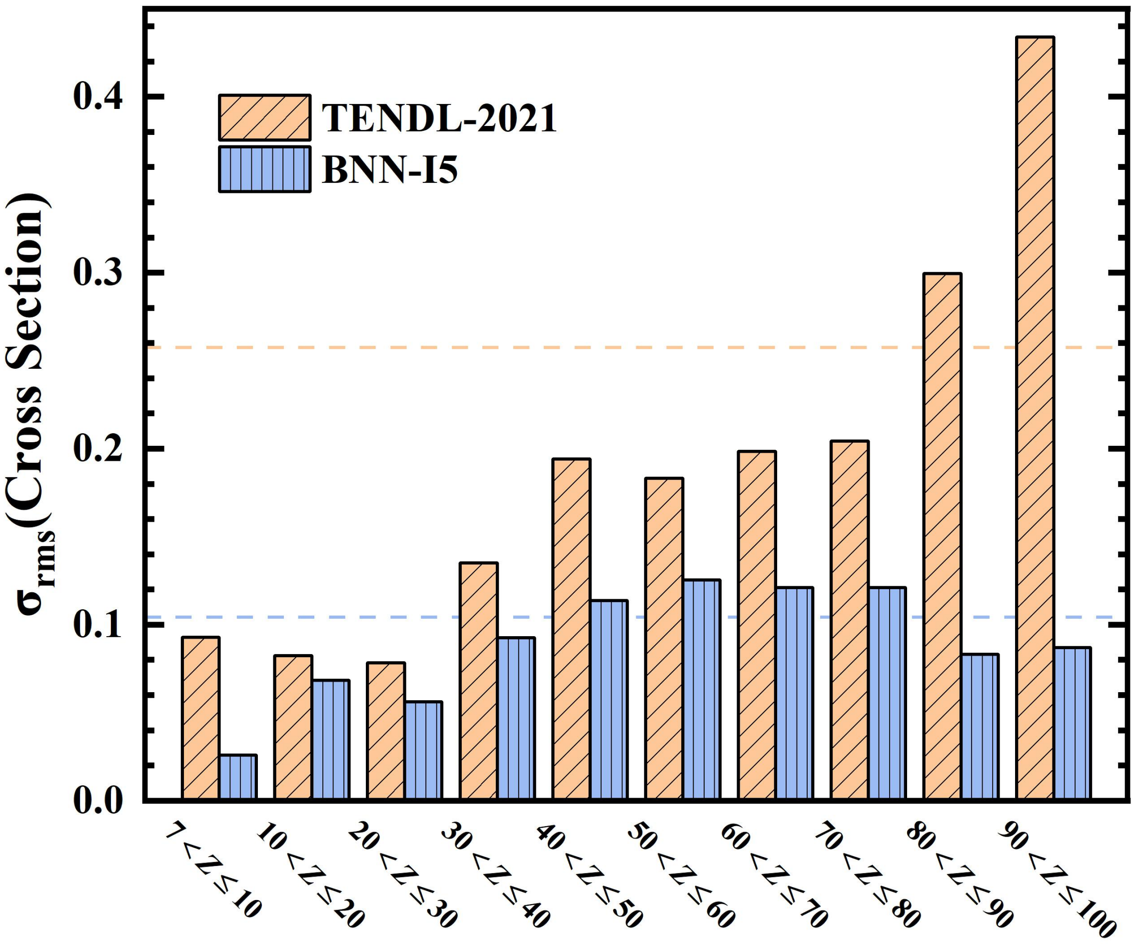


Fig. 3 The rms deviations σ_{rms}(Cross Section) of cross section predictions by BNN-I5 and TENDL-2021 with respect to the evaluation data in different nuclear regions.

- The description of the (n, 2n) reaction cross section by TENDL-2021 gets progressively worse with increasing protron number.

- The ability of the neural network to predict the (n, 2n) reaction cross section for **$30 < Z \leq 80$** nuclei is relatively weak, but it is still a large improvement compared to the results of TENDL-2021.

Results and discussion

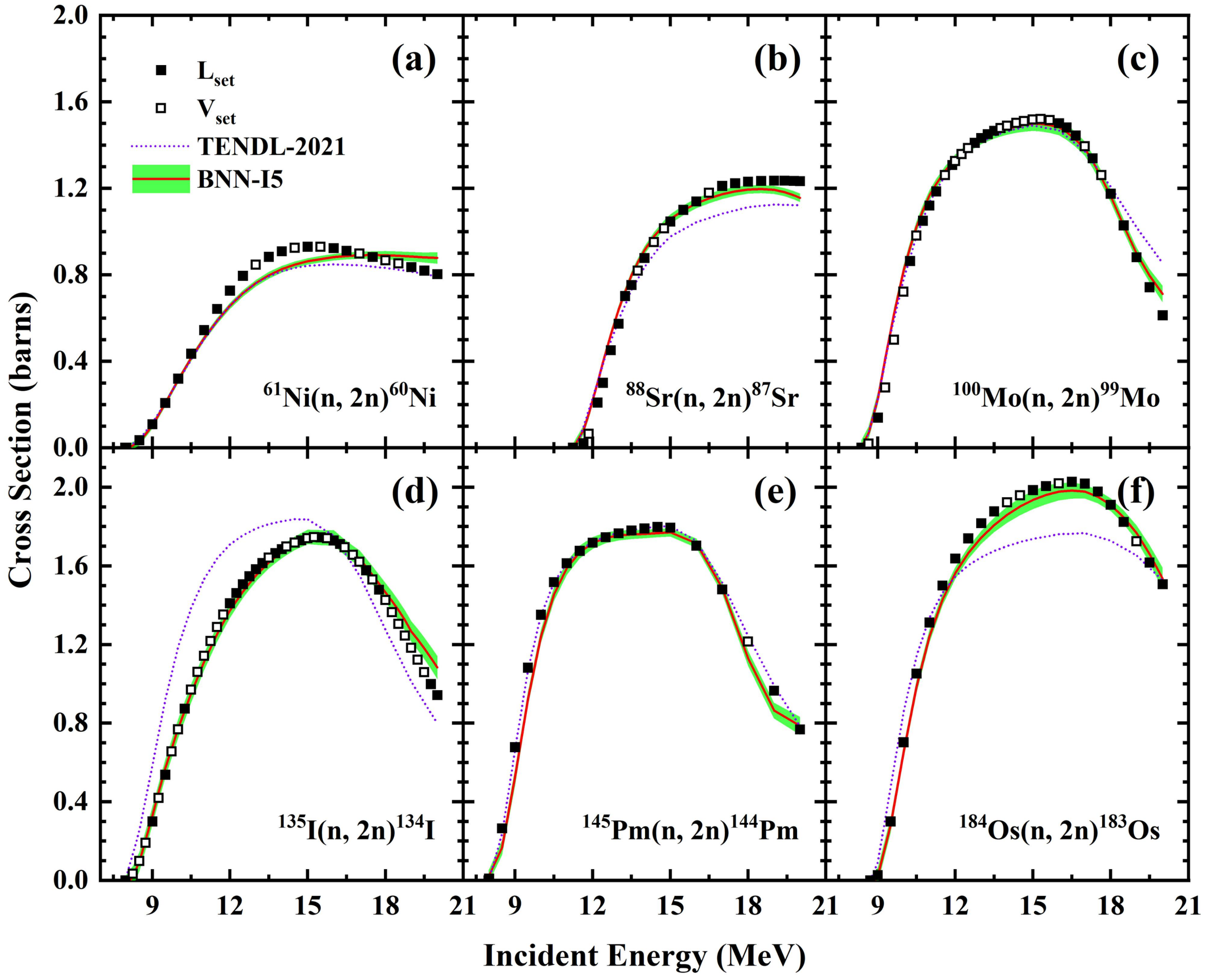


Fig. 4 The (n, 2n) reaction cross sections predicted by the BNN-I5 approach for ^{61}Ni, ^{88}Sr, ^{100}Mo, ^{135}I, ^{145}Pm, and ^{184}Os.

- The BNN-I5 approach has a better ability to describe the (n, 2n) reaction excitation function than TENDL-2021.
- The BNN-I5 approach reproduces the (n, 2n) reaction cross section well for both the **learning and validation sets**.

Results and discussion

物理与光电工程学院
School of Physics and Optoelectronic Engineering

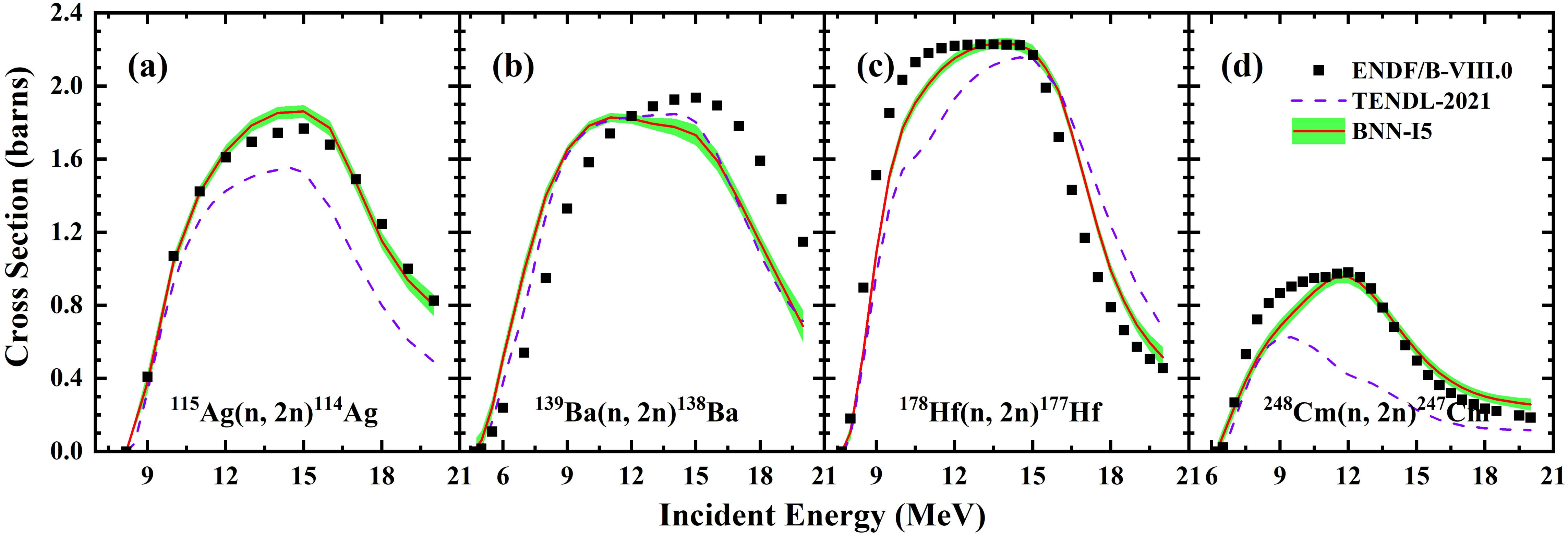


Fig. 5 Same as Fig. 4 but for ^{115}Ag, ^{139}Ba, ^{178}Hf and ^{248}Cm.

◆ The predictive ability of the BNN-I5 approach is also better than that of TENDL-2021 in the **testing set**.

Results and discussion

物理与光电工程学院
School of Physics and Optoelectronic Engineering

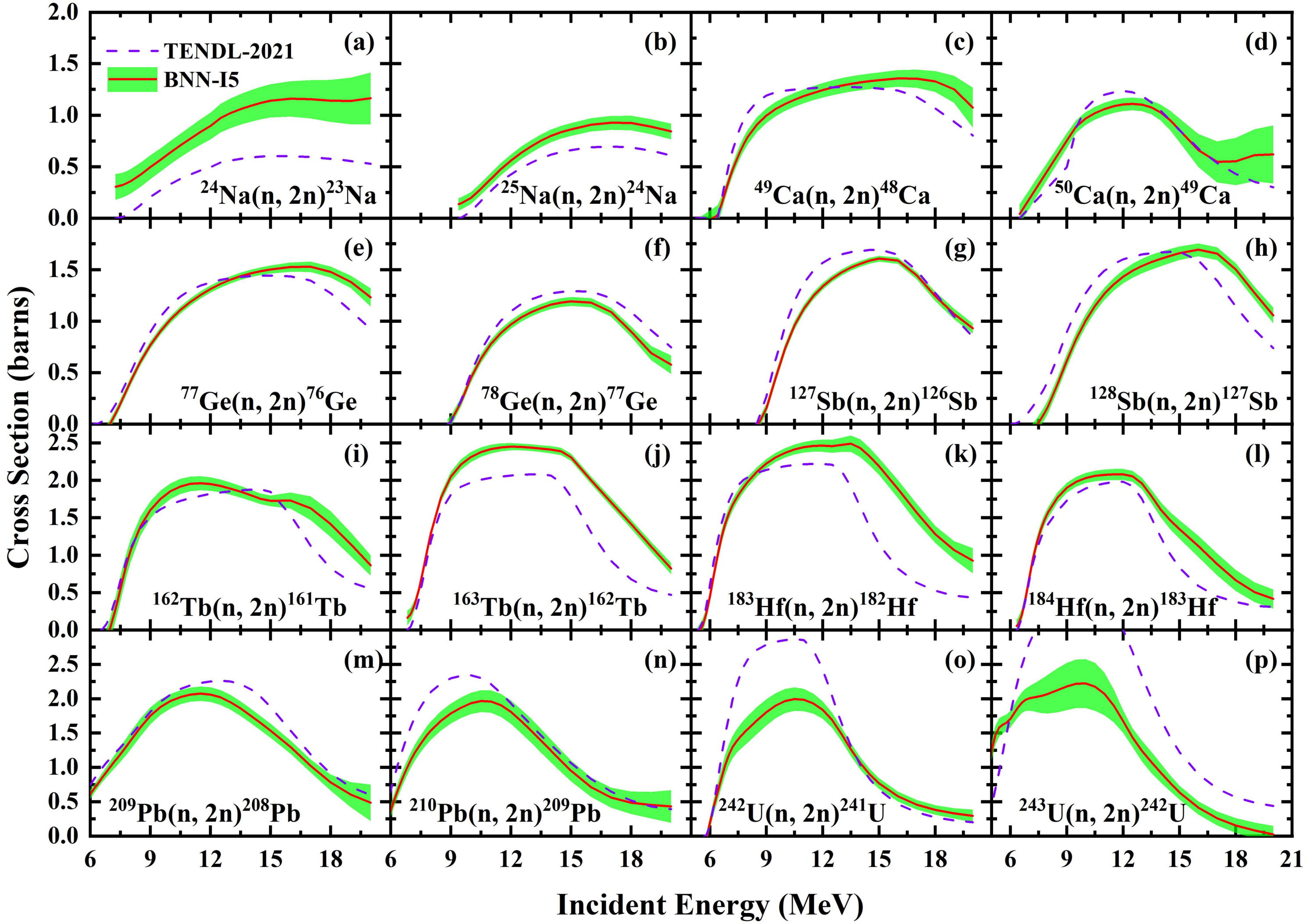


Fig.6 Comparison of the (n, 2n) reaction cross sections from BNN-I5 predictions and TENDL-2021 for various nuclei.

- ◆ The BNN-I5 approach can well reflect the variation trend of these unknown nuclei (n, 2n) reaction cross section with the incident energy.
- ◆ The BNN-I5 approach has good extrapolation ability.

Results and discussion

物理与光电工程学院
School of Physics and Optoelectronic Engineering

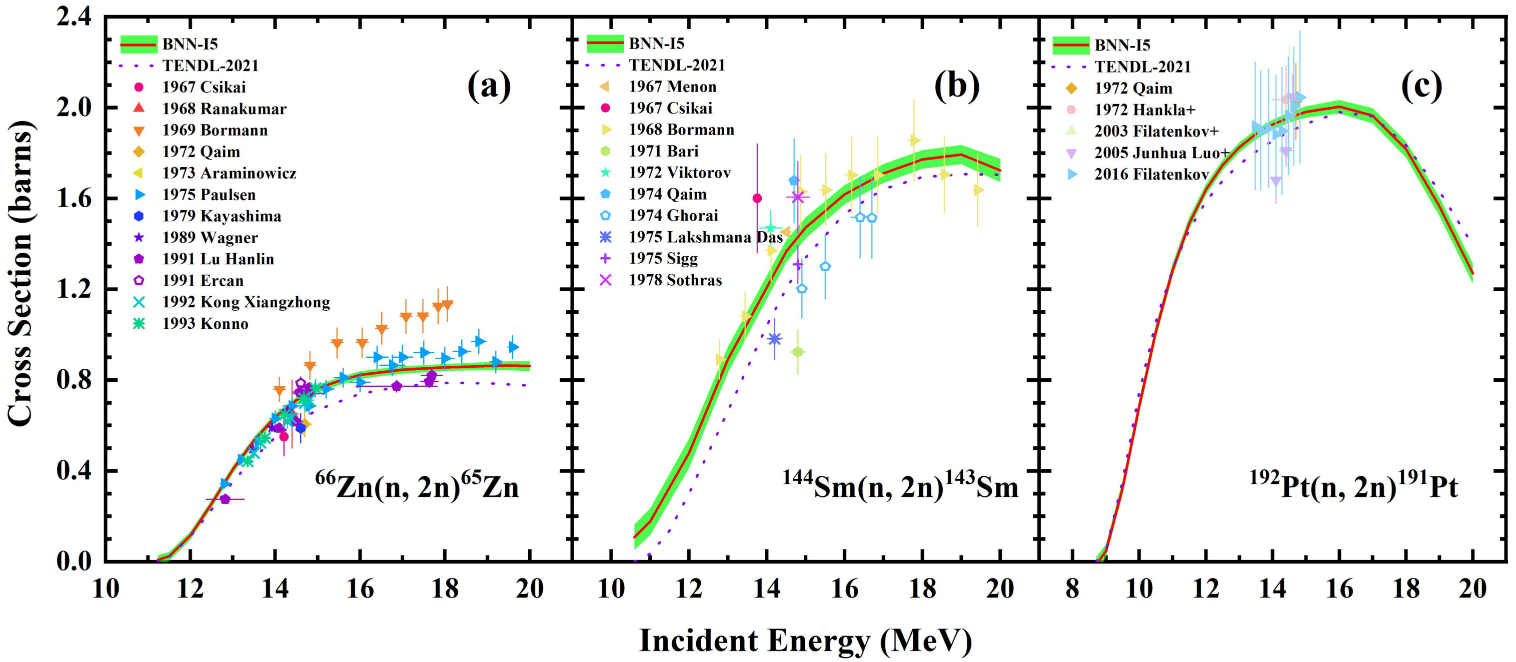


Fig. 7 Comparison of the (n, 2n) reaction cross sections from BNN-I5 predictions with the original experimental data for ^{66}Zn, ^{144}Sm, and ^{192}Pt.

◆ The experimental data from different groups can have significant deviations and may even not agree within the uncertainties.

◆ Near the incident energy of **14.6 MeV**, the BNN-I5 results are in high agreement within the margin of experiment error.

04 Summary and perspectives

Summy

The nuclear (n, 2n) reaction cross section are investigated and give reasonable uncertainty evaluations with the BNN approach.

★Five physical quantities, including $\boldsymbol{Z}$, $\boldsymbol{N}$, $\boldsymbol{\Delta E}$, $\boldsymbol{\delta}$, and $\boldsymbol{\sigma_{th}}$, were identified as the best neural network inputs to describe the (n, 2n) reaction excitation function.

★The BNN-I5 approach reproduces the (n, 2n) reaction cross section well for both the learning, validation and **testing sets**.

★When extrapolated to the unknown region, the BNN approach can still well describe the **trend of first increasing and then decreasing** for the (n, 2n) reaction excitation functions with the incident neutron energy predicted by TENDL-2021.

Futrue perspectives

In the future, the approach will be extended to more reaction channels and more nuclear regions to provide more data for nuclear reaction studies.

Thank You!