Neural Network-Based Prediction of Particle-Induced Fission Cross Sections for r-Process Nucleosynthesis Trained with Experimental Data and Dynamical Reaction Models

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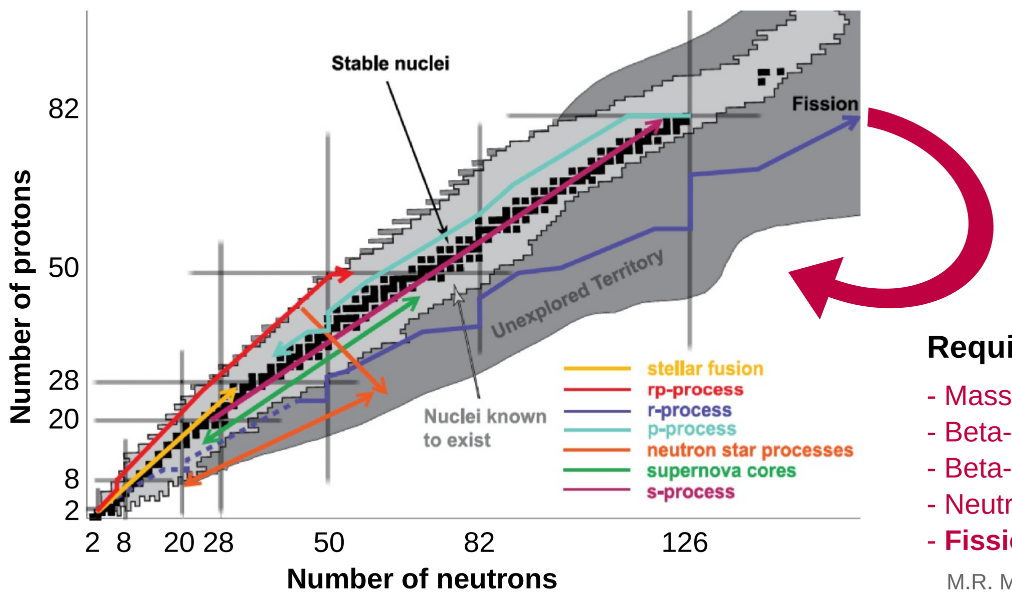
Motivation

Nearly half of the elements beyond the iron are expected to be formed by the rapid neutron capture process (r-process). However, the astrophysical sites of the r-process are not well known. The proposed sites include neutrino driven winds in Type-II supernovae, neutron star (NS) or NS-Black hole mergers, collapsars, etc. Detection of lanthanides from the red kilonova spectra of GW170817 has shown clear evidence of r-process production during NS merger events. In such scenario, decreasing nuclear stability terminates the r-process when its heaviest nuclei become unstable to spontaneous fission, but if the fission barrier height is low enough, neutron capture might induce fission instead of continuing up the neutron drip line



Fission recycling

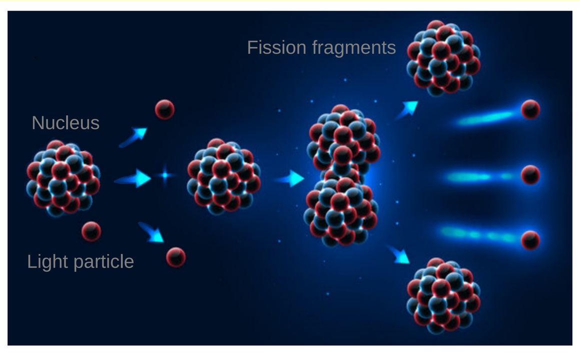
Fission sets the end point of the r-process and strongly influences the r-process abundances and light curves

Required nuclear data

- Masses
- Beta-decay rates
- Beta-delayed neutron emission probabilities
- Neutron capture and **fission rates**
- **Fission yields** in terms of charge (Z) and mass (A)

M.R. Mumpower et al., Prog. Part. and Nucl. Phys. **86**, 86 (2016)

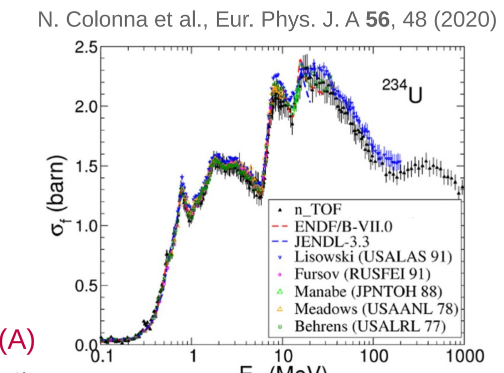
Nuclear fission is the process by which a heavy atomic nucleus divides into two lighter fragments and represents the clearest example of a large-scale collective excitation in nuclei. The fission process is a unique tool to investigate the nuclear potential-energy landscape and its evolution as a complex function of excitation energy, elongation, mass asymmetry and spin, passing over the fission barrier and culminating at the scission point in the formation of fission fragments

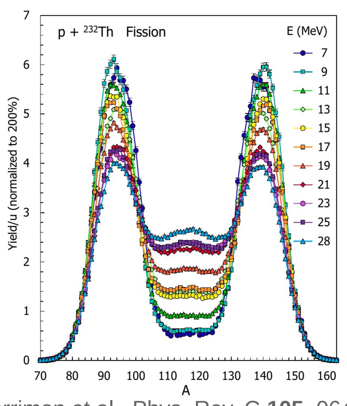


Key observables such as the fission probabilities or fission barrier heights and fission yields have a clear impact in the particle-induced fission flows calculated for NS merger simulations and depending on the model (TF, FRLDM, ETFSI or HFB) the populated isotopic range changes completely

- Evolution of fission probabilities with the excitation energy
- Fission yield dependence on excitation energy or temperature

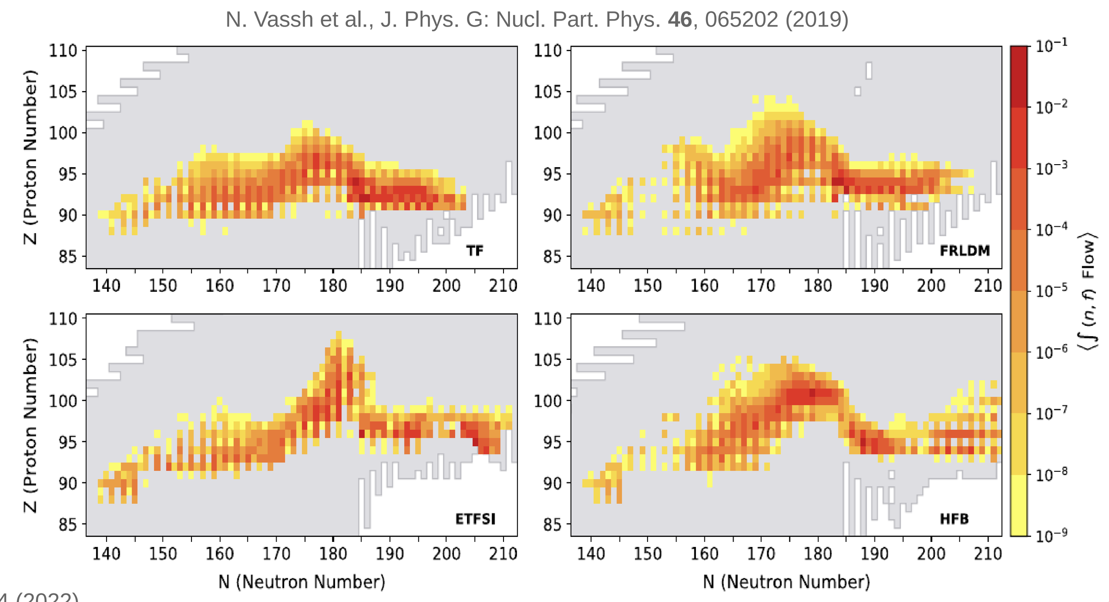
N. Colonna et al., Eur. Phys. J. A **56**, 48 (2020)





A.C. Berriman et al., Phys. Rev. C **105**, 064614 (2022)

N. Vassh et al., J. Phys. G: Nucl. Part. Phys. **46**, 065202 (2019)



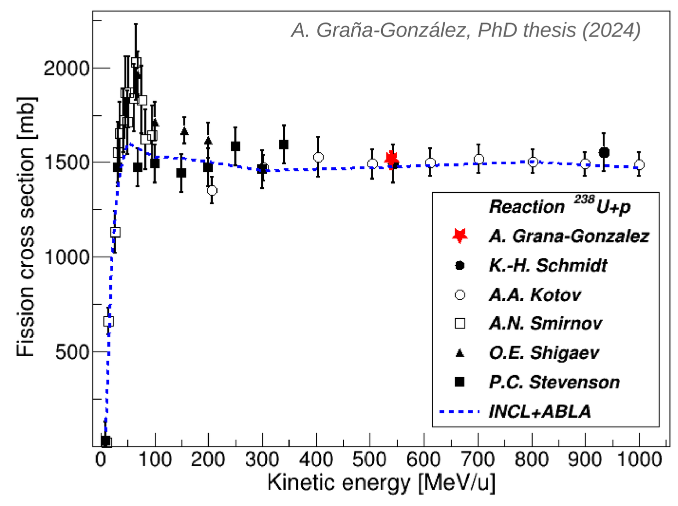
Dynamical reaction models for training

The collision is described by means of a two-step process usually applied in spallation, fragmentation, and charge-exchange reactions: the collision itself, where part of the nucleons contained in the target nucleus are removed or modified and some excitation energy and angular momenta are gained by the remnant; and subsequent de-excitation processes by evaporation of particles or, if applicable, by fission

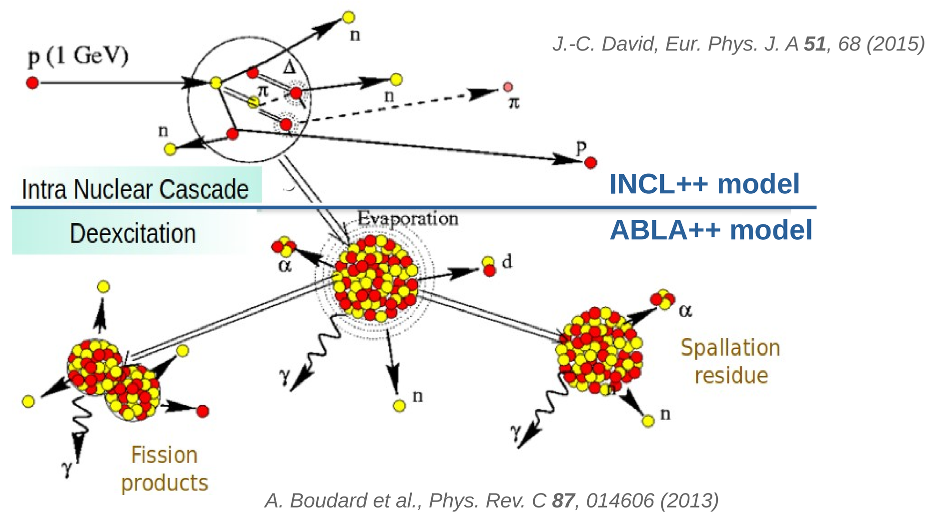
In this work the collision between the light particle and the nucleus is described by the Liege intranuclear cascade model INCL++. The collision is modeled as a sequence of binary collisions between the nucleons (hadrons) present in the system. Nucleons move along straight trajectories until they undergo a collision with another nucleon or until they reach the surface, where they eventually escape. The latest version of INCL also includes isospin- and energy-dependent nucleus potentials calculated according to optical models as well as isospin-dependent pion potentials

D. Mancusi et al., Phys. Rev. C **90**, 054602 (2014); Phys. Rev. C **91**, 034602 (2015)

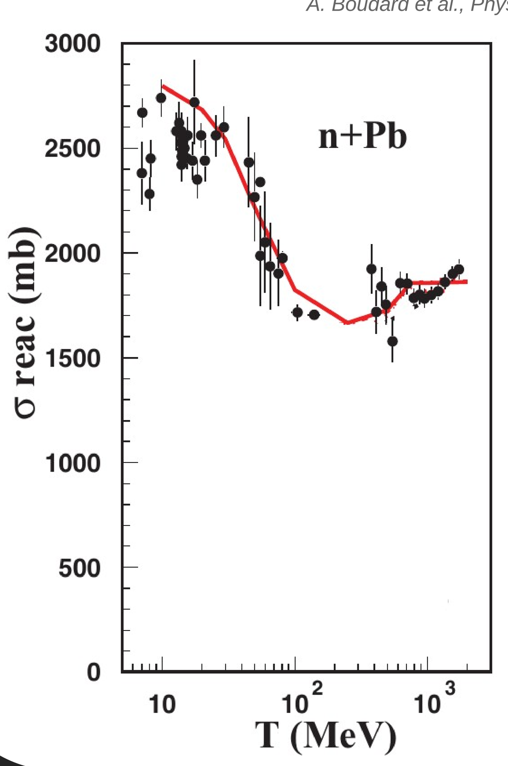
A. Graña-González, PhD thesis (2024)

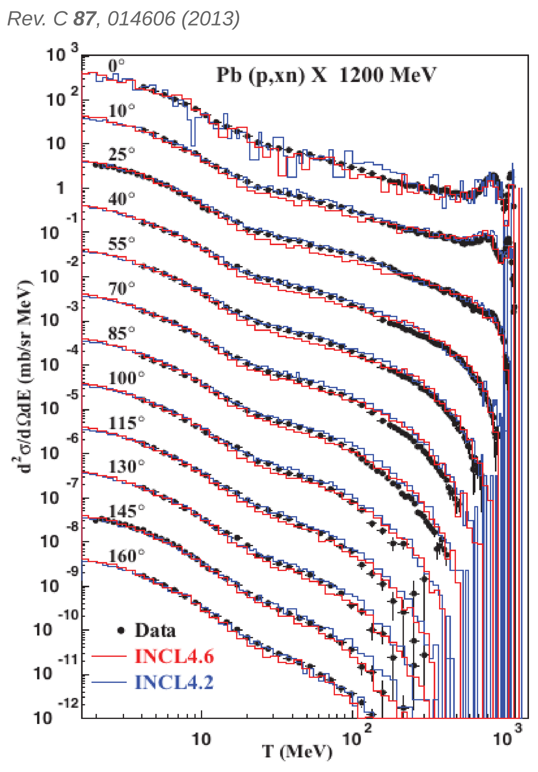


J.-C. David, Eur. Phys. J. A **51**, 68 (2015)

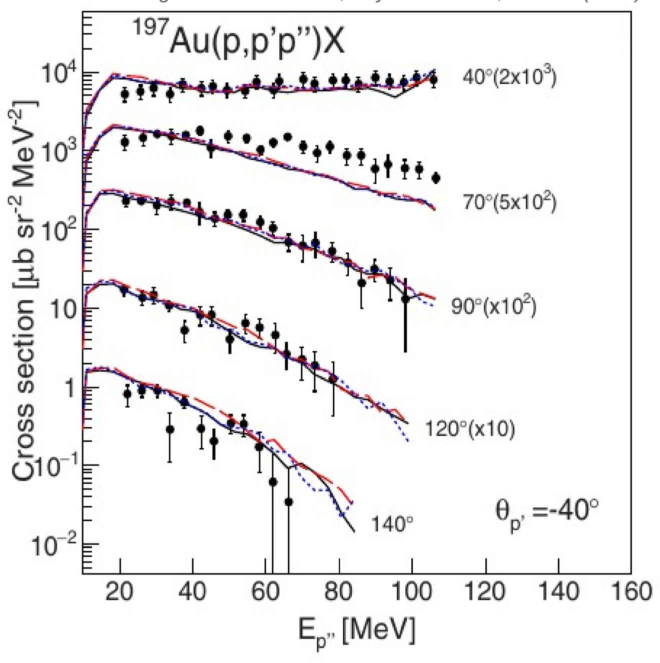


A. Boudard et al., Phys. Rev. C **87**, 014606 (2013)

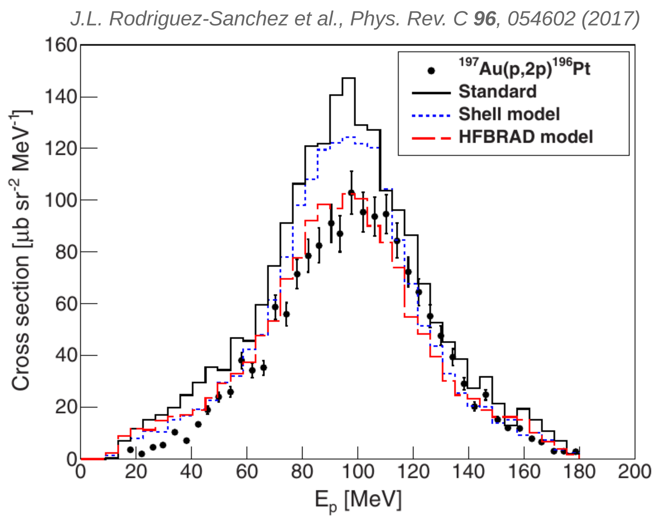




J.L. Rodriguez-Sanchez et al., Phys. Rev. C **96**, 054602 (2017)



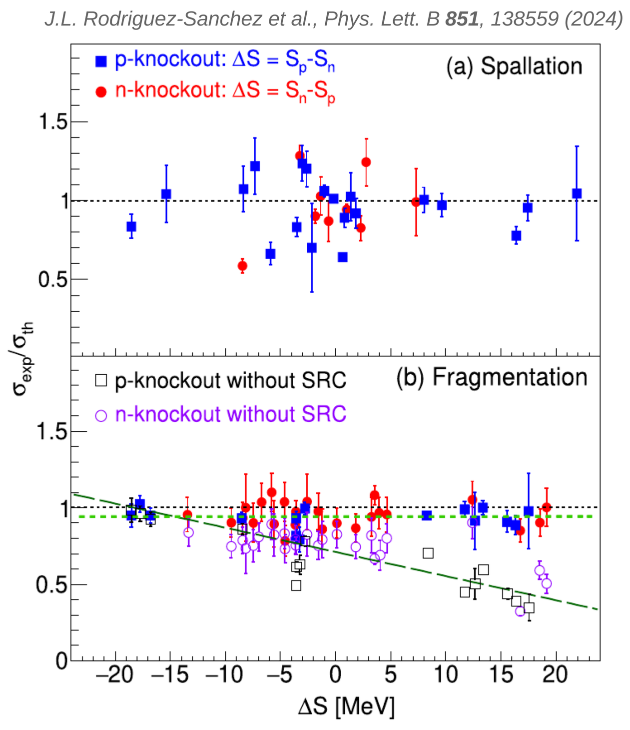
J.L. Rodriguez-Sanchez et al., Phys. Rev. C **96**, 054602 (2017)



INCL features

- Emission of n, p and pions
- Clusters: d, t, $^{3-10}$He, $^{4-12}$Li, $^{6-12}$Be, …
- Short-range correlations (np pairs)
- Exp. particle separation energies
- P and E conservation for collisions
- Direct and inverse kinematics
- Energy range up to ~20 GeV/u

J.L. Rodriguez-Sanchez et al., Phys. Lett. B **851**, 138559 (2024)

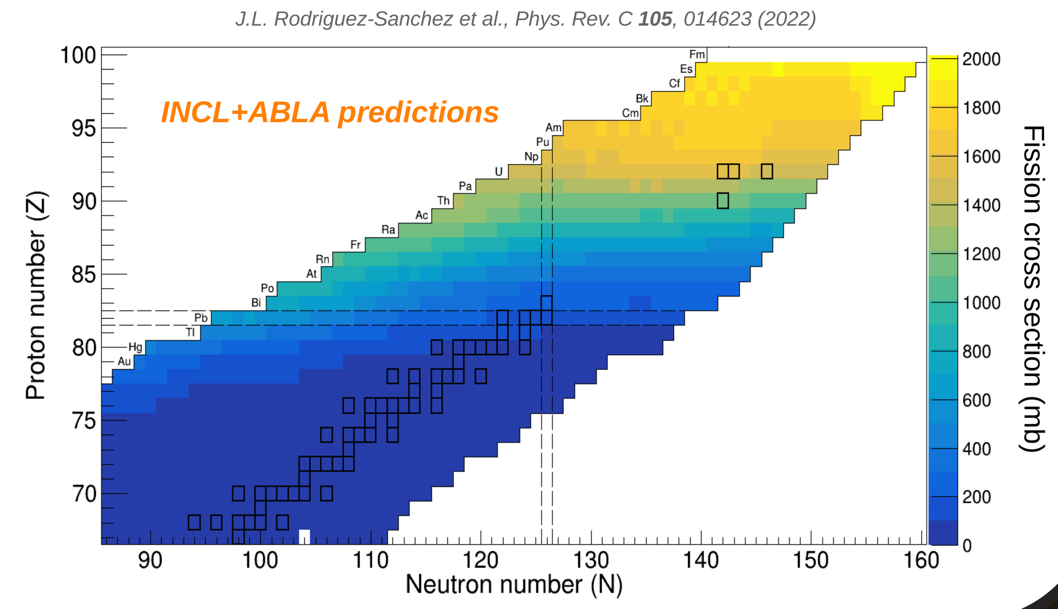


ABLA++ describes the deexcitation of a nuclear system emitting γ-rays, neutrons, light-charged particles, and intermediate-mass fragments (IMFs) or fission in case of hot and heavy remnants

The fission decay width is described by the Bohr-Wheeler transition-state model and corrected later by dissipative and transient time effects modeled by the solution of the Fokker-Planck equation. This approach has provided reasonable results for nuclei around the stability valley

B. Jurado et al., Phys. Lett. B **553**, 186 (2003); C. Schmitt et al., Phys. Rev. C **81**, 064602 (2010); Y. Ayyad et al., Phys. Rev. C **89**, 054610 (2014); J.L. Rodriguez-Sanchez et al., Phys. Rev. C **90**, 064606 (2014); Y. Ayyad et al., Phys. Rev. C **91**, 034601 (2015); J.L. Rodriguez-Sanchez et al., Phys. Rev. C **92**, 044612 (2015)

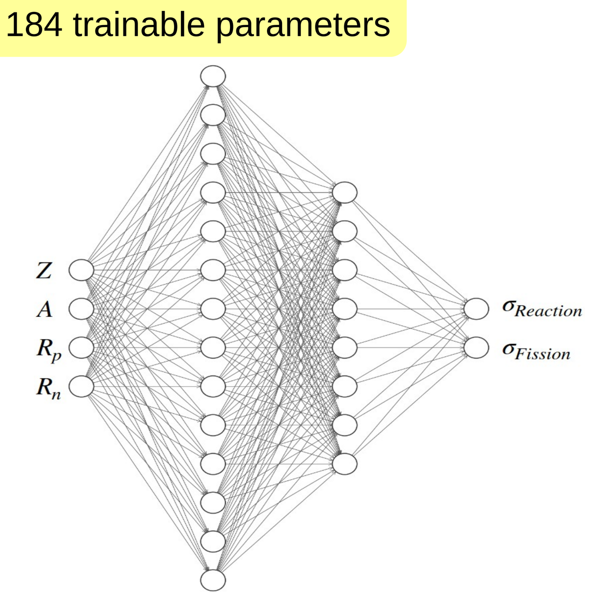
J.L. Rodriguez-Sanchez et al., Phys. Rev. C **105**, 014623 (2022)



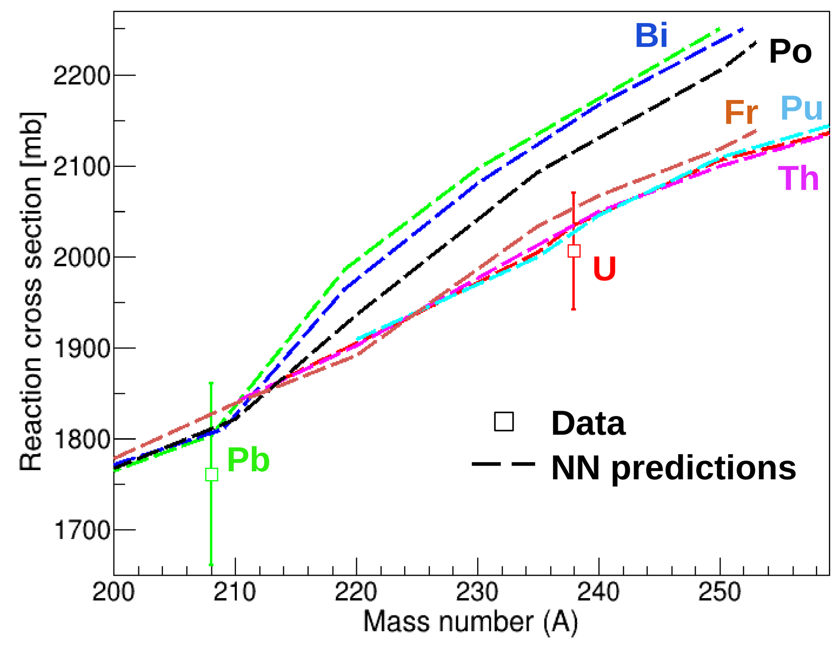
Neural network predictions

The neural network (NN) model was trained using data from INCL+ABLA models, which accurately describe experimentally observed fission and total cross sections. The input layer of the network received information on nuclear charge (Z), mass (A), and radii of proton (R_p) and neutron (R_n) density profiles. The architecture comprised four layers with a total of 184 trainable parameters

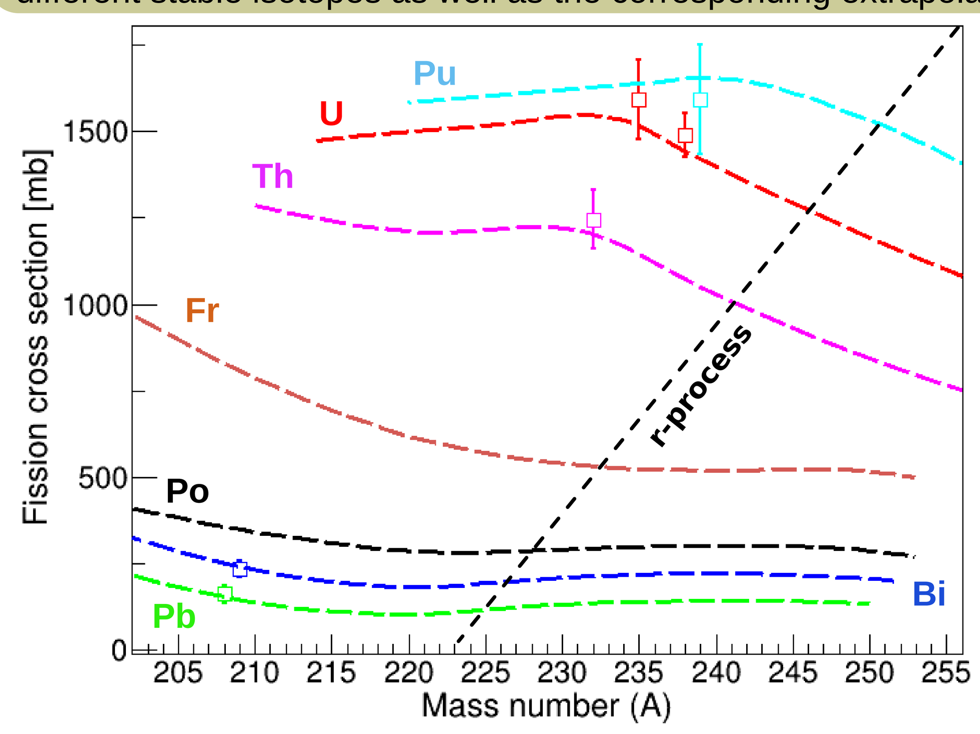
The activation functions employed across the NN layers were LeakyReLU, Sigmoid, LeakyReLU and LeakyReLU. Adam was used for backpropagation. The absolute loss function indicated that the model reproduced both fission and total cross sections with an estimated error of 1-2%. Notably, this model can extrapolate results to exotic nuclei, for which no experimental data or models currently exist



The neural network is able to predict reaction cross sections for different stable isotopes and also allows for the extrapolation to the neutron-rich side

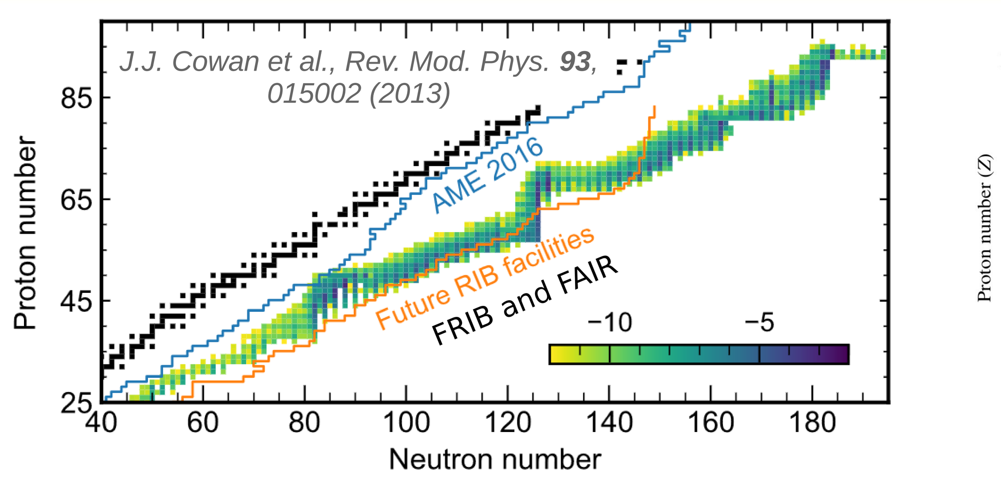


It also provides a good agreement with fission cross sections for different stable isotopes as well as the corresponding extrapolation

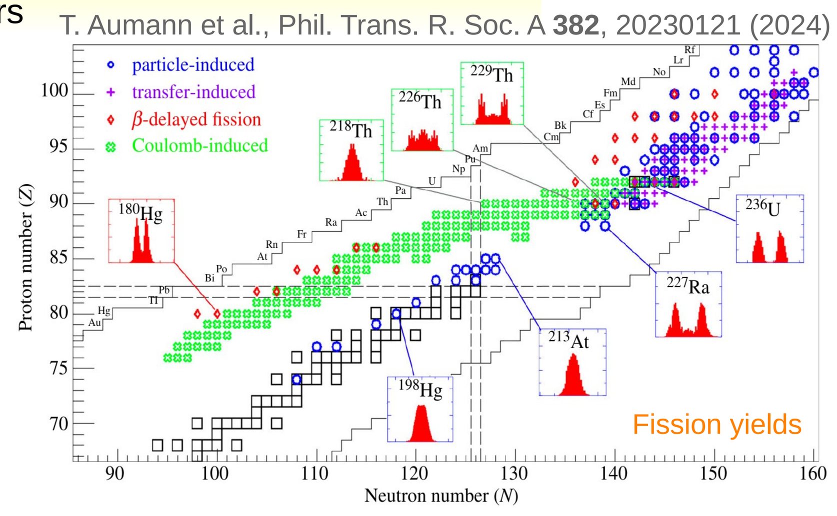


Outlook

Nuclear chart with stable nuclei (black squares), the limit of known masses from the 2016 Atomic Mass Evaluation (blue line), the future reach of radioactive ion-beam (RIB) facilities like FRIB and FAIR, and abundance results at neutron freeze-out from an r-process calculation based on the FRDM masses and combined with Thomas Fermi fission barriers



T. Aumann et al., Phil. Trans. R. Soc. A **382**, 20230121 (2024)



Training neural networks with recent fission yields of exotic nuclei measured at GSI/FAIR with Coulomb-induced fission reactions in inverse kinematics and combining this set of data with previous measurements

Improvement of the prediction of fission probabilities and fission yields for very neutron-rich nuclei around the r-process path

N. Vassh et al., J. Phys. G: Nucl. Part. Phys. **46**, 065202 (2019)