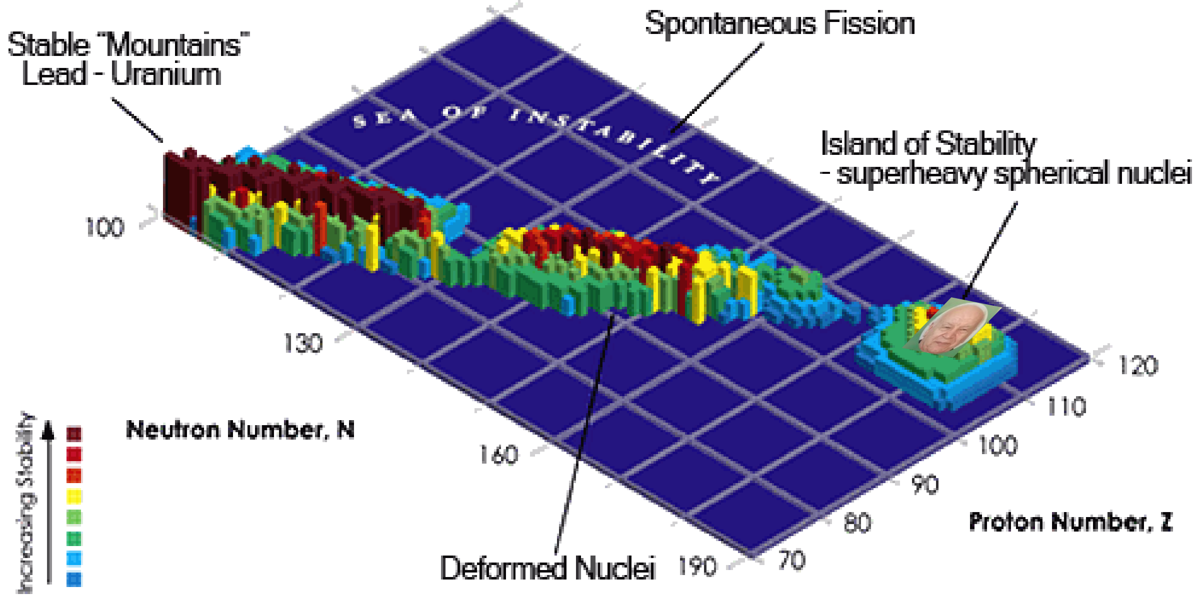
Trees and Island — Machine learning approach to nuclear physics

- for prediction for data of damping parameter, shell correction energies, quadrupole deformation, pairing gaps, level densities and giant dipole resonance for large number of nuclei.

Острів стабільность елементів



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Загальний принцип дії нейронної мережі

- Consider a set of data where the input variables $x_{i,1}, x_{i,2}, \ldots, x_{i,j}$ (features) give a resultant output y_i through some process.

  The aim is to find a model M, such that, $M(x_{i,1}, x_{i,2}, \ldots, x_{i,j}) = y_i$, where $i, j = 1, 2, \ldots$

- In a typical ML scenario, a training set of a given data is used to teach the algorithm patterns in the output y_i's.

The output y_i is a discrete number, indicating classes or *limited number of possible states* where the data can exist.

Нейрона мережа: Дерева

Gradient boosted trees (GBT) is a ML technique aimed at minimizing the loss function. Here, we demonstrate machine learning methods in nuclear physics using GBT.

Передбачення енергетичного рівня нуклонів

$$a(E^*) = \tilde{a}\left[1 + \frac{\delta W}{E^*}\{1 - \exp(-\gamma E^*)\}\right]$$

ã is the asymptotic value of nuclear level density parameter. The damping coefficient, denoted by gamma, is obtained by fitting gamma spectrum [20] and deltaW denotes the shell correction energy which is given as the difference betweenthe experimental binding energy of a nucleus and the binding energy calculated from the liquid drop model.

This calculated data for 290 nuclei from Z = 11 to 98 [23] were used for □ calculations. 6735 nuclei from Z = 8 to 99 [23] were used for □W prediction. These values of □W are calculated using Mengoni-Nakajima mass formula [24]. The prediction from this data for the damping coefficient is given by Fig. 1 and for shell correction energy is given by Fig. 2. The prediction for □ has the standard deviation as 0.00035, which shows an excellent prediction by the GBT method, and for □W is 0.553, which shows a good prediction.

- The famous liquid drop model was proposed by Gamow and for which Bethe and von Weizsäcker [13, 14] proposed a semi empirical mass formula to describe a nucleus. This formula is written in terms of volume, surface, Coulomb interaction, mass asymmetry and pairing energies.

Beta deformation

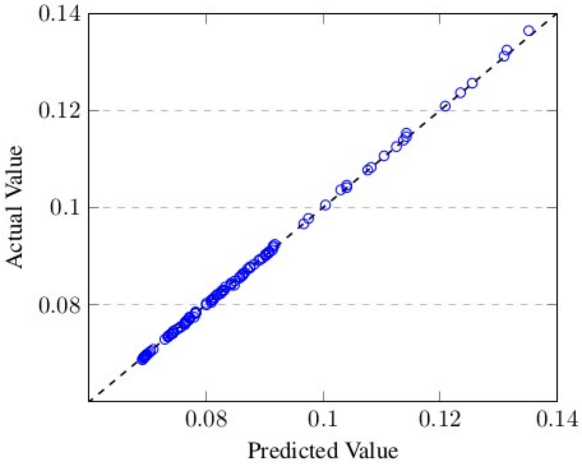


Figure 1: Predictions for the test set for γ values show a standard deviation of 0.00035 and a standard error of order 10^{-5}. The data is trained and tested on a data set of 290 nuclei.

- Level density parameter (LDP) is the most important extracted quantity to understand nuclear observables like neutron resonances and reaction cross sections [30]. Recent semiclassical trace formula (STF) [31] evaluates the temperature- dependent LDP within 10%-15% of the experimental values for magic and semi magic nuclei. This trace formula models nucleus using Harmonic oscillator [32] with spin-orbit interactions [33]. This formalism also incorporates the shell effects in the nucle

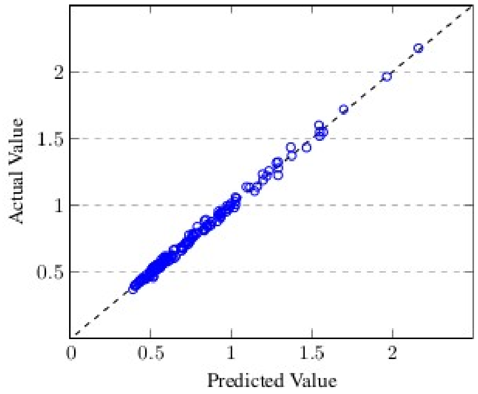
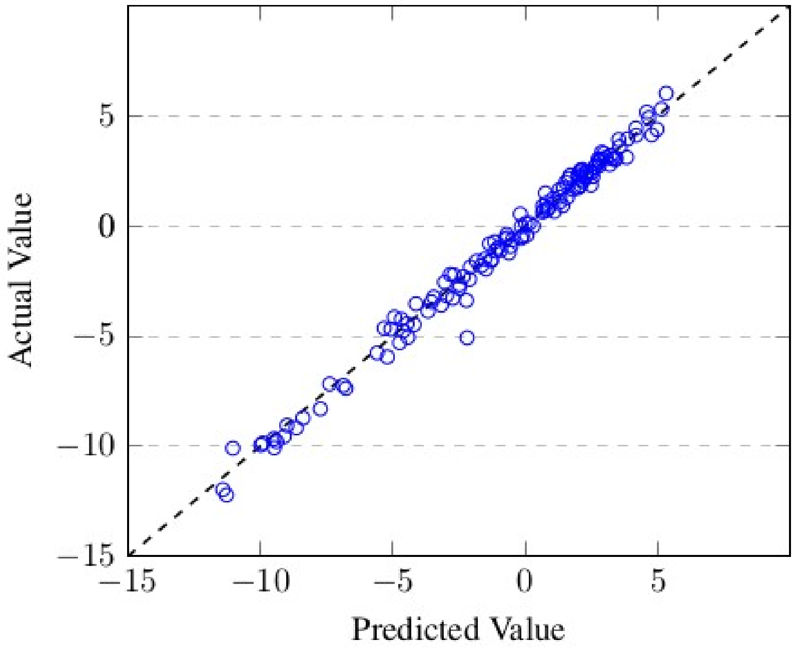


Figure 5: Prediction of test set for pairing gaps for neutron. The model is trained and tested on 8979 nuclei and give a standard deviation of 0.037 and standard error of the order 10^{-4}.

Superheavy elements

The synthesis of superheavy elements (SHE) (Z > 104) is a big challenge in nuclear physics and is of great contemporary interest due to its importance in heavy ion fusion reactions. The variation of LDP with the number of nucleons is generally seen to have an A/n trend, where A is the mass number of the nucleus and n is the positive real number. Calculations suggest that for SHE, n is about 11-13 [36]. We use the ML models generated from GC and STF to predict the level densities of some super heavy elements as in Table



Superheavy elements

Element	Z	GC	n_{GC}	STF	n_{STF}
^{267}Rf	104	27.44	9.73	19.85	13.45
^{268}Db	105	27.62	9.70	19.88	13.48
^{269}Sg	106	27.67	9.72	19.98	13.46
^{270}Bh	107	24.51	9.81	19.98	13.51
^{270}Hs	108	27.10	11.20	19.98	13.51
^{278}Mt	109	27.40	10.14	19.97	13.92
^{281}Ds	110	27.44	10.21	19.97	14.07
^{282}Rg	111	27.40	10.29	19.97	14.12
^{285}Cn	112	27.44	10.39	19.94	14.29
^{286}Nh	113	27.40	10.43	19.95	14.33
^{289}Fl	114	27.44	10.53	19.93	14.50
^{290}Mc	115	27.62	10.50	19.93	14.55
^{293}Lv	116	27.44	10.67	19.92	14.70
^{294}Ts	117	27.66	10.62	19.94	14.75
^{294}Og	118	27.55	10.67	19.94	14.75
^{315}Uue	119	27.44	11.48	19.93	15.81
^{299}Ubn	120	27.55	10.85	20.22	14.79
^{320}Ubu	121	27.40	11.68	19.96	16.04
^{306}Ubb	122	27.43	11.15	21.26	14.39

Table 1: Level desities predictied for the Super Heavy elements by GC model based on fermi gas model and semiclassical trace formula (STF). The values are close to the trend of $A/10$ for GC and $A/(13-14)$ for STF.

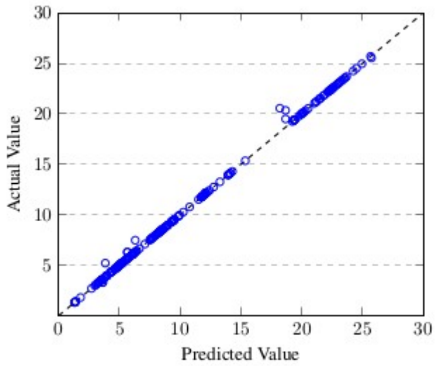


Figure 7: Training and testing on the temperature dependent Level Density Parameter by Semiclassical trace formula for 32 nuclei at various temperatures (3000 data points) gives the standard deviation of 0.3 and standard error of 0.005. Comparison with Fig. 6 shows that the model trained with STF gives better predictions.

- Giant Dipole Resonance During a photonuclear reaction signatures of the nuclei behaving like a giant dipole with collective oscillations are observed. These oscillations are called as Giant Dipole Resonance (GDR). It corresponds to the fundamenta Giant Dipole ResonanceDuring a photonuclear reaction, signatures of the nuclei behaving like a giant dipole with collective oscillations are observed. These oscillations are called as Giant Dipole Resonance (GDR). It corresponds to the fundamental absorption frequency of electric dipole radiation of the nucleus acting as a whole. It is often simply understood asoscillations in the nucleus of the neutrons against the protons.

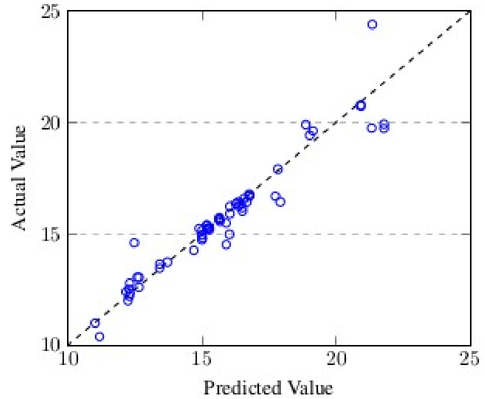


Figure 8: Training and testing the experimental first peak energy values for GDR for 180 nuclei. It shows the standard deviation of 0.76 and standard error of 0.056.

Observable	σ (2 features)	σ (7 features)
Damping parameter	0.00170	0.00035
Shell Correction Energy	0.910	0.553
β_2 deformation	0.018	0.015
Proton pairing gap	0.040	0.037
Neutron pairing gap	0.640	0.037
LDP (GC)	0.790	0.730
LDP (STF)	0.600 (3 features)	0.300 (8 features)

Conclusion

Nuclear data has been studied extensively using a machine learning algorithm. Phenomenological quantities like damping factor and shell correction energies, quantities with quantum mechanical origin like pairing gaps, evaluated values of quadrupole deformations, statistical quantities of level densities and experimental quantities of first peak energy of giant dipole resonances have been modelled. The predictions from these models show a very good agreement with the actual values with standard deviations ranging from 0.00035 to 0.73. To compare with contemporary literature, similar investigations on time series analysis [39], molecular physics [40], astrophysics [41], economics [42, 43] and climate studies [44] report standard deviations ranging between 0.02 to 75.0. Our results, thus, are well acceptable, particularly as they are better by two orders of magnitude for damping parameter, □. We use these predictions to calculate the level density parameter of the superheavy elements in the island of stability, the values obtained T - sharpen the expected values from proposed theories. We also show how the engineered features increase the accuracy of the predictions by the generated models.