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Estimations of beta-decay energies through the nuclidic chart by using neural network

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HIGHLIGHTS

- Beta decay energy is characteristic of unstable nuclei.
- Atomic masses of nuclei can be calculated by using beta decay energy.
- Artificial neural network is capable for the estimation of beta decay energy.

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ABSTRACT

One of the main characteristics of unstable nuclei is beta-decay energy (Q_β). It is determined by different methods such as beta endpoint measurements, counting in coincidence with annihilation radiation, electron capture $(EC)/\beta^+$ ratio method, method of gamma absorption with X-ray coincidence. Beta-decay energy is a roughly linear function of atomic and mass numbers. Due to the fact that artificial neural network (ANN) is sufficient for nonlinear function approximation, in this study by using the nuclear masses from Hartree–Fock–BCS method, Q_β values have been obtained by ANN. It is seen that the estimations of the ANN are consistent with the calculated data within some deviation.

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1. Introduction

Beta-decay energy (Q_β) is one of the main properties of unstable nuclei. Its experimental and theoretical determinations have an importance. Q_β values can be determined by various ways such as beta endpoint measurements, counting in coincidence with annihilation radiation, electron capture $(EC)/\beta^+$ ratio method, method of gamma absorption with X-ray coincidence, etc. (Alkhazov et al., 1993). Beta-decay energy is an approximately linear function of atomic and mass numbers. Some modifications have been made by considering parity, shell and deformation effects. Experimental beta-decay energies of nuclei can be verified in $Z>82$, $N>126$ region. Whereas unknown energies can be calculated by means of alpha–beta energy cycles, using the reliable alpha spectroscopic data. Moreover, some beta-decay energies can be obtained with the help of energy cycles from alpha-decay energy systematics (Kolesnikov and Krylova, 1966). Besides, by using beta-decay endpoint energies which are also important for understanding of the beta-decay process and for determination of the decay scheme of the nuclei (Krecak et al., 2001), Q_β values can be obtained. Using the results, the nuclear masses of the nuclei can be calculated with some errors. Since it is often only way to determine the atomic masses of nuclei far from stability, accurate measurements of Q_β have also an importance (Keller et al., 1991). Moreover, two-nucleon separation energies and mass excesses can be derived (Graefenstedt et al., 1990).

Recently, artificial neural networks (ANNs) have been used in many fields in nuclear physics as in the other fields, such as determination of one and two proton separation energies (Athanassopoulos et al., 2004), developing nuclear mass systematic (Athanassopoulos et al., 2004), identification of impact parameters in heavy-ion collisions (David et al., 1995; Bass et al., 1996; Haddad et al., 1997), estimating beta-decay half-lives (Costris et al., 2007), computation of gamma-ray energy absorption buildup factors (Kucuk et al., 2013), obtaining potential energy curves (Akkoyun et al., 2013) and estimating nuclear rms charge radius (Akkoyun et al., 2013). ANN is a mathematical tool that mimics the human brain functionality. The neurons in the network are connected to each other by adaptive synaptic weights. The main

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idea is identification of these weights for approach the solution of the problem. The data used for this purpose is training data. The fundamental task of ANN is to give outputs as a consequence of the computation of the inputs. Beta-decay energy (Q_β) is an approximately linear function of atomic and mass numbers. However, ANN is sufficient for nonlinear function approximation (Hornik et al., 1989). In this work, we have estimated Q_β values of the nuclei by using ANN. The data for the ANN has been taken from Goriely et al. (2001) in which Q_β values have been obtained based on the Hartree–Fock–BCS method with the Skyrme force MSk7 (Tondeur et al., 2000). The trained ANN has been tested on Sn and Gd nuclei data which have never been seen in the training stage. According to the results, this method can be safely used for estimation of Q_β values of the atomic nuclei through the nuclidic chart.

2. Artificial neural network (ANN)

Artificial neural networks (ANNs) (Hornik et al., 1989) are powerful mathematical models that mimic the human brain. They consist of several neurons which are processing units and the neurons are connected to each other via adaptive synaptic weights. By this synaptic connections, the neurons in the different layers communicate to each other and the data is transmitted between them. In our study, we have used feed-forward ANN with three layers in order to obtain beta decay energies (Q_β) of the nuclei. The first layer called input layer consists of two neurons, the hidden layer is composed of 50 neurons and the last one is the output layer with a neuron. The number of hidden layers depends on the problem nature. But, one hidden layer is generally sufficient. If there is an insufficient number of hidden neuron, it may be difficult to obtain convergence during training. Besides, in the case of using many hidden neurons, the network may lose its generalization ability (Medhat, 2012). In our study, the inputs have been chosen as to be atomic (Z) and neutron (N) numbers. The output has been beta-decay energy (Q_β). The used architecture of the ANN has been 2-50-1 (Fig. 1) and the total numbers of adjustable weights have been 150 according to formula given by

$$p \times h + h \times r = h \times (p + r) = h \times (2 + 1) = 3h = 150 \tag{1}$$

where h is hidden layer neuron number, p and r are input and output layer neuron numbers, respectively. No bias has been used. The input neurons collect data from the outside and the output neuron gives the results. The hidden neuron activation function has been tangent hyperbolic (Eq. 2) which is sigmoidlike function. For details of ANN, we refer the reader to Haykin (1999)

$$\tanh = \frac{(e^x - e^{-x})}{(e^x + e^{-x})} \tag{2}$$

The ANN process is composed of two main stages, training and test stages. One has to train network by known data and then to feed the trained network with unknown data in order to obtain ANN outputs. In the training stage of this work, Levenberg–Marquardt back-propagation algorithm (Levenberg, 1944; Marquardt, 1963) has been used for the training of the ANN. The purpose of the training stage is to minimize the difference between the desired and ANN (predicted) outputs by convenient modifications of synaptic connections. Also it is desired that the constructed ANN for a given type of data in the training stage should work for the any other part of the data which belongs to the same type of the data. This property is called as *generalization ability* of the ANN. If the predictions of the test set data are reliable, the ANN is considered to have consistently learned the inherent functional relationship existing between input and output data. The error function which measures this difference has been root mean square deviation (*RMSD*) given by

$$RMSD = \sqrt{\frac{\sum_{i=1}^{N} (Q_{HF} - Q_{ANN})^2}{N}} \tag{3}$$

where N is the number of training or test data points, whichever applies, Q_{HF} and Q_{ANN} are desired and ANN (predicted) outputs, respectively.

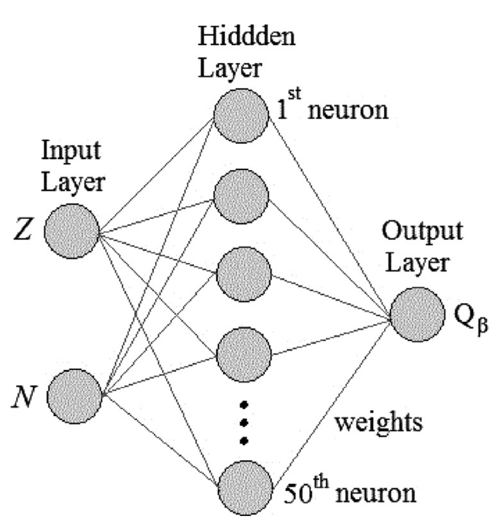

Fig. 1. The ANN topology (2-50-1) used in this work. The inputs are atomic (Z) and neutron numbers (N), the output is beta-decay energy (Q_β).

3. Results and discussion

As mentioned in Section 1, a complete nuclear mass table, which was calculated via Hartree–Fock–BCS with the Skyrme force MSk7 has been taken from Goriely et al. (2001) and has been used for beta-decay energy (Q_β) estimations of ANN. Both spherical and deformed Hartree–Fock–BCS codes were employed for Hartree–Fock–BCS calculations in the study of Goriely et al. (2001). The masses of the nuclei in this method have been calculated by the formula given below

$$M(A,Z) = E_{HF} + NM_n + ZM_H - a_{el}Z^{2.39} \tag{4}$$

where Z, N and A are atomic, neutron and nuclear mass numbers, respectively, $M_n = 8.071$ MeV, $M_H = 7.289$ MeV and electronic binding energy $a_{el} = 1.433 \times 10^{-5}$ MeV. Actually in the region of light nuclei ($A < 36$), the Hartree–Fock–BCS method works not so good. Still, we considered all nuclei with $Z, N \geq 8$. In the beta-decay process, mass number (A) remains unchanged and atomic number (Z) varies one unit. Therefore, beta-decay energy of a nucleus (A, Z) can be calculated by

$$Q_\beta = (M(A,Z) - M(A,Z+1) - m_e)c^2 \tag{5}$$

where $M(A,Z)$, $M(A,Z+1)$ and m_e are masses of mother nucleus, daughter nucleus and electron, respectively. In the next section, ANN training and estimations on these Q_β values have been mentioned.

3.1. Construction of ANN for beta-decay energies (Q_β)

In this work, Q_β values have been estimated by using ANN. Q_β values are one of the characteristics of the nuclei. Therefore, we have used neutron (N) and proton (Z) numbers of the nuclei as inputs of the ANN. The output of the ANN is Q_β related to these numbers. After several trials in this study, it is seen that one hidden layer with 50 hidden neurons is sufficient. There are 8871 different data according to the different isotopes. Almost 80% of

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