Formation of drip-line nuclei in rapid neutron capture process

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Introduction

Elements found in nature are generally formed by the thermonuclear fusion process, up to Fe, Co or Ni. After the formation of Fe or Co, direct fusion process becomes endothermic, and the isotopes beyond Fe are formed by rapid neutron capture process ($r-$process). The $r-$process is one of the dominant mode for the formation of heavier elements. Approximately half of the heavier nuclei beyond Fe are formed in nature by this process [1–3]. Basically two types of neutron capture processes occur for astrophysical nucleosynthesis which have been first identified by Burbidge et. al. [1] and Cameron et al [2]. The neutron capture processes which are based on neutron flux are characterised by rapid- and slow-process. The $r-$process, which occurs at large neutron density, enables the production of neutron-rich nuclei close to the drip-line while the $s-$process has sufficient time for beta disintegration and produces the nuclei near β-stability line. In the present work, we use the well established relativistic mean field (RMF) approach to study the neutron drip-line nuclei for $Cu - Nb$ isotopic chain to build a $r-$process path for the formation of drip-line and heavy nuclei i.e. the rapid neutron capture process. This process path is compared with the prediction of macro-microscopic finite range droplet (FRDM) model [5].

Relativistic mean field (RMF) formalism

From last three decades, the RMF theory is applied successfully to study the structural properties of nuclei throughout the periodic table [4] starting from the proton drip-line to the neutron drip-line. The starting point of the RMF theory is the basic Lagrangian containing Dirac spinors interacting with the meson fields [4]

$$\begin{aligned}
\mathcal{L} &= \bar{\psi}_i\{i\gamma^\mu\partial_\mu - M\}\psi_i + \frac{1}{2}\partial^\mu\sigma\partial_\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 \\
&- \frac{1}{3}g_2\sigma^3 - \frac{1}{4}g_3\sigma^4 - g_s\bar{\psi}_i\psi_i\sigma - \frac{1}{4}\Omega^{\mu\nu}\Omega_{\mu\nu} \\
&+ \frac{1}{2}m_w^2V^\mu V_\mu - g_w\bar{\psi}_i\gamma^\mu\psi_i V_\mu - \frac{1}{4}\vec{B}^{\mu\nu}\vec{B}_{\mu\nu} \\
&+ \frac{1}{2}m_\rho^2\vec{R}^\mu\vec{R}_\mu - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - g_\rho\bar{\psi}_i\gamma^\mu\vec{\tau}\psi_i\vec{R^\mu} \\
&- e\bar{\psi}_i\gamma^\mu\frac{(1-\tau_{3i})}{2}\psi_i A_\mu.
\end{aligned}$$

We use the recently reported well known NL3* parameter set. To take care of the pairing interaction, the standard constant gap BCS - pairing approach is used and the centre of mass energy is also included.

Results and discussions

It is shown in the figure that, the peak value of BE/A for Nb at A = 124 in RMF and at A=127 in FRDM indicating the most stable isotope of the series in the respective models. One-neutron separation energy S_n gives a key idea to calculate the neutron drip-line of nuclei. On the basis of S_n, we calculate the neutron drip-line and suggest a path for rapid neutron capture ($r-$process) for the medium mass nuclei $Z = 29 - 41$.

One might assume that formation of heavy elements take the victory over the $\beta^- -$ deacy but the truth is a bit more complicated. The astrophysical events which maintain a very high temperature may have a possibility of

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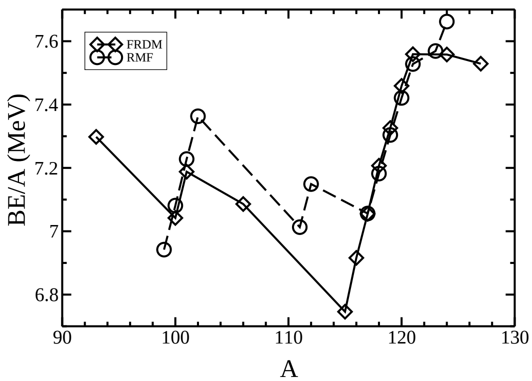

FIG. 1: The BE/A versus mass number A for the neutron drip-line nuclei of $Cu-Nb$ isotopic series.

TABLE I: The predicted neutron drip-lines in RMF are compared with the FRDM [5] calculations.

Nucleus	RMF	FRDM	Nucleus	RMF	FRDM
Cu	99	93	Kr	118	118
Zn	100	100	Rb	119	119
Ga	101	101	Sr	120	120
Ge	102	106	Y	121	121
As	111	115	Zr	123	124
Se	112	116	Nb	124	127
Br	117	117			

photo-disintegration against the neutron capture because of significant role of gamma radiation flux. These gamma rays interact with the nuclei to break off the most loosely bound protons, neutrons, or alpha particles. The gamma photons literally break apart nuclei to form lighter elements. But instantly they are recaptured by other nuclei which binds them more tightly. In this series the ^{99}Cu captures the neutrons and reaches to the waiting point and then convert to the other isotopes with increasing proton number using β^-− decay process. The series reaches to the ^{124}Nb isotope by following neutron capture and β^-− decay process. The prediction of rn-path using RMF model for the given isotopic series are as follows:

^{99}Cu $\xrightarrow{\dagger}$ ^{99}Zn $\xrightarrow{\star}$ ^{100}Zn $\xrightarrow{\dagger}$ ^{100}Ga $\xrightarrow{\star}$ ^{101}Ga $\xrightarrow{\dagger}$ ^{101}Ge $\xrightarrow{\star}$ ^{102}Ge $\xrightarrow{\dagger}$ ^{102}As $\xrightarrow{\star}$ ^{103}As $\xrightarrow{\star}$ ^{104}As $\xrightarrow{\star}$ ^{105}As $\xrightarrow{\star}$ ^{106}As $\xrightarrow{\star}$ ^{107}As $\xrightarrow{\star}$ ^{108}As $\xrightarrow{\star}$ ^{109}As $\xrightarrow{\star}$ ^{110}As $\xrightarrow{\star}$ ^{111}As $\xrightarrow{\dagger}$ ^{111}Se $\xrightarrow{\star}$ ^{112}Se $\xrightarrow{\dagger}$ ^{112}Br $\xrightarrow{\star}$ ^{113}Br $\xrightarrow{\star}$ ^{114}Br $\xrightarrow{\star}$ ^{115}Br $\xrightarrow{\star}$ ^{116}Br $\xrightarrow{\star}$ ^{117}Br $\xrightarrow{\dagger}$ ^{117}Kr $\xrightarrow{\star}$ ^{118}Kr $\xrightarrow{\dagger}$ ^{118}Rb $\xrightarrow{\star}$ ^{119}Rb $\xrightarrow{\dagger}$ ^{119}Sr $\xrightarrow{\star}$ ^{120}Sr $\xrightarrow{\dagger}$ ^{120}Y $\xrightarrow{\star}$ ^{121}Y $\xrightarrow{\dagger}$ ^{121}Zr $\xrightarrow{\star}$ ^{122}Zr $\xrightarrow{\star}$ ^{123}Zr $\xrightarrow{\dagger}$ ^{123}Nb $\xrightarrow{\star}$ ^{124}Nb

$\star$ indicates the neutron capture process.
$\dagger$ indicates the β^-− decay process.

It is evident from Table I that the predictions of neutron drip-line nuclei by RMF using NL3* parameter matches well with FRDM results [5] except few cases. We have taken an uncertainty of 0.5 MeV in our calculation and defined the drip-line when S_n reaches to this value or below. In general, there is not much discrepancy in neutron drip line produced by FRDM or RMF model.

Summary

It is also revealed that isotopes of Nb with mass number $A \sim 124$ are found to be most stable in the isotopic chain. Based on the information of S_n, drip-line and waiting point a rapid neutron capture path is suggested for $Z = 29 - 41$. While comparing the $r-$process path taking the structural informations of RMF results with the FRDM binding energy, we noticed a large abundance of element for a particular species with a small difference in S_n. The prediction of the present $r-$process path may be a gate way for the formation of neutron-rich as well as superheavy nuclei.

References

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