Formation of medium heavy mass nuclei through r-process

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Introduction

The astrophysical site of the r-process, the rapid neutron-capture process that makes half of the elements heavier than iron, remains a long-standing mystery of nucleosynthesis. Upto Fe, the elements are produced by rapid neutron capture process and after that the fusion process changes to endothermic process. While large uncertainties remain about the site of the r-process and its exact location, it is thought to occur in environments with a high density of free neutrons. There are a number of astrophysical scenarios suggested as possible sites [1, 2]. But the neutron capture processes depends on neutron flux that are defined by rapid- and slow-process. At high neutron density the r-process takes place very nearer to the drip-line nuclei, whereas s-process has enough time for beta disintegration which helps for the production of nuclei nearer to the beta stability line. Here, in this work we are trying to investigate the formation of medium heavy mass nuclei i.e. from Ga-Pd through r-process and determine the path by using relativistic mean-field (RMF) formalism with DD-ME2 force parameter set. The calculated outcomes are able to correlate with the macro-microscopic finite range droplet model (FRDM) data [3, 4]. So, we study the binding energy (B.E) of the nuclei, nuclear radii such as neutron radius (r_n), proton radius (r_p), matter radius (r_m) to know the structural properties of all the nuclei. As a necessary requirement for the determination for the r-process path we calculate the one neutron separation energy (S_n) as well as two neutron separation energy (S_{2n}).

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Theoretical formalism

The relativistic concept comes from the interaction of nucleons through mesons. The quantum hydrodynamics (QHD) [5, 6] says, nucleus can be formed in a system by coupling the dirac nucleons with the exchange meson through an effective Lagrangian. So the Lagrangian density is defined in meson-exchange model as;

$$L = L_N + L_m + L_{int} \quad (1)$$

L_N represents the Lagrangian of free nucleon,

$$L_N = \bar{\psi}(i\gamma_\mu \partial^\mu - m)\psi \quad (2)$$

L$_m$ consists of the free meson field and electromagnetic field as;

$$\begin{aligned} L_m = &\frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{2}m_\sigma{}^2\sigma^2 \quad (3)\\ &-\frac{1}{2}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2}m_\omega{}^2\ \omega_\mu\ \omega^\mu \\ &-\frac{1}{4}\overrightarrow{R}_{\mu\nu}\overrightarrow{R}^{\mu\nu} + \frac{1}{2}m_\rho{}^2\overrightarrow{\rho}_\mu\overrightarrow{\rho^\mu} - \frac{1}{4}\ F_{\mu\nu}F^{\mu\nu} \end{aligned}$$

L_{int} represents the Lagrangian of interaction part

$$\begin{aligned} L_{int} = &-g_\sigma\bar{\psi}\psi\sigma - g_\omega\bar{\psi}\gamma^\mu\psi\omega_\mu - g_\rho\bar{\psi}\overrightarrow{\tau}\gamma^\mu\psi.\overrightarrow{\rho}_\mu (4)\\ &-e\bar{\psi}\gamma^\mu\psi\ A_\mu \end{aligned}$$

Results and discussion

In this paper, we investigate the formation of medium-heavy mass nuclei through rapid neutron capture process (r-process) path from Ga Pd using relativistic mean field formalism (RMF) with DDME-2 force parameter set [5],[6]. We calculate the ground state properties such as binding energy, nuclear radii such as neutron radius (r_n), proton radius (r_p), matter radius (r_m), one neutron separation

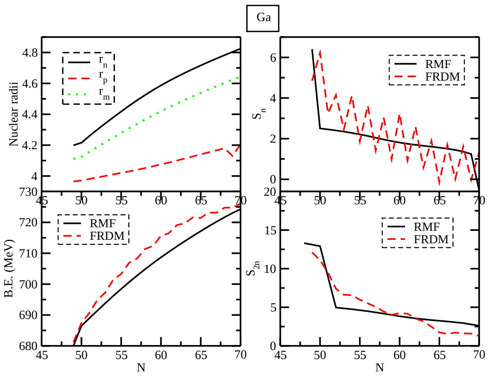

FIG. 1: Plot of binding energies, nuclear radii, one-neutron separation energy (S_n) and two-neutron separation energy (S_{2n}) verses neutron number (N) of Ga element

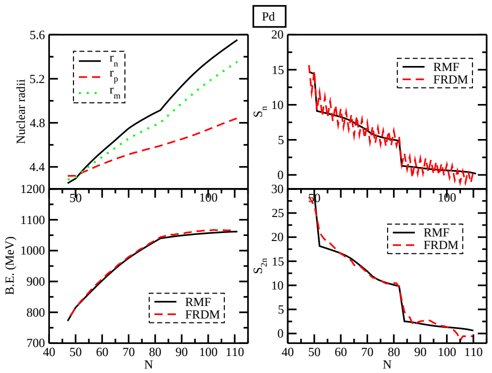

FIG. 2: Plot of binding energies, nuclear radii, one-neutron separation energy (S_n) and two-neutron separation energy (S_{2n}) verses neutron number (N) of Pd element

energies (S_n) and two neutron separation energies (S_{2n}) also shown in figures 1 and 2. We have compared our calculated results with the available FRDM results [3, 4] and it can be seen that the evaluated results are in good agreement with the FRDM results.

In this r-process, the nucleus Fe or Ni captures the neutron until the formation of a neutron-rich nuclei. Then this unstable neutron-rich nuclei undergoes β-emission and formed a less neutron-rich Cu nuclei. Now this procedure continues and built a new heavier element which is shown below.

$$^{81-88}Ga \xrightarrow{\beta} {}^{83-97}Ge \xrightarrow{\beta} {}^{83-103}As \xrightarrow{\beta} {}^{85-104}Se \xrightarrow{\beta} {}^{94-103}Br \xrightarrow{\beta} {}^{95-107}Kr \xrightarrow{\beta} {}^{94-102}Rb \xrightarrow{\beta} {}^{106-113}Sr \xrightarrow{\beta} {}^{107-112}Y \xrightarrow{\beta} {}^{110-122}Zr \xrightarrow{\beta} {}^{111-123}Nb \xrightarrow{\beta} {}^{114-124}Mo \xrightarrow{\beta} {}^{119-125}Tc \xrightarrow{\beta} {}^{126-127}Ru \xrightarrow{\beta} {}^{127-128}Rh \xrightarrow{\beta} {}^{128-129}Pd....$$

This r-process path is determined with the approximation that when the two neutron separation energy lies in between 2-4 MeV and is obtained near the drip line as suggested in Ref. [1].

Conclusion

In conclusion, the structural properties such as binding energy, nuclear radii for different elements from Ga to Pd nuclei are calculated by using RMF formalism with DDME-2 force parameter set. The evaluated results are in agreement with FRDM results in the isotopic chain. The one neutron- and two neutron separation energies are also evaluated from the calculated binding energies. The r-process path for the formation of medium mass heavy and super-heavy nuclei suggested here may be useful for the future experiment.

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