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Analyses of Hypernuclei Produced Via Fission and Evaporation

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Abstract: In heavy-ion reactions, nuclei and hypernuclei yields can be emitted from target/projectile rediuals in peripheral collisions. The evaporation and fission yields are investigated at 0.25-2.5 MeV/nucleon excitation energy intervals for source nuclei ${}^{235}U$, ${}^{235}_{\Lambda}U$, ${}^{235}_{\Lambda\Lambda}U$, ${}^{235}_{3\Lambda}U$, ${}^{235}_{4\Lambda}U$, ${}^{168}Ho$, ${}^{168}_{\Lambda}Ho$, ${}^{168}_{\Lambda\Lambda}Ho$, ${}^{168}_{3\Lambda}Ho$, and ${}^{168}_{4\Lambda}Ho$. We have reproduced mass distributions via computer codes by using hyper-SMM model which is based on the statistical multifragmentation model for hypernuclei. Our results can be used for the analyses of the future experiments at FAIR(GSI) and NICA(Dubna).

Keywords: Evaporation, Fission, Hypernuclei, Statistical Multifragmentation Model

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Fisyon ve Buharlaşma ile Üretilen Hiperçekirdeklerin Analizi

Öz: Ağır iyon reaksiyonlarında çekirdekler ve hiperçekirdekler yanal çarpışmalarda hedef/mermi çekirdek artıklarından saçılabilir. ${}^{235}U$, ${}^{235}_{\Lambda}U$, ${}^{235}_{\Lambda\Lambda}U$, ${}^{235}_{3\Lambda}U$, ${}^{235}_{4\Lambda}U$, ${}^{168}Ho$, ${}^{168}_{\Lambda}Ho$, ${}^{168}_{\Lambda\Lambda}Ho$, ${}^{168}_{3\Lambda}Ho$ ve ${}^{168}_{4\Lambda}Ho$ kaynak çekirdekleri için 0.25-2.5 MeV/nükleon uyarma enerji aralıklarında buharlaşma ve fisyon ürünleri araştırılmıştır. Hiperçekirdekler için istatistiksel çok katlı parçalanma modeli temelinde hiper-SMM modelini kullanarak bilgisayar kodlarıyla kütle dağılımlarını elde ettik. Sonuçlarımız FAIR (GSI) ve NICA (Dubna)'daki gelecek deneylerin analizlerinde kullanılabilecektir.

Anahtar Kelimeler: Buharlaşma, Fisyon, Hiperçekirdekler, Istatistiksel Çok Katlı Parçalanma Modeli

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1. Introduction

During the last 20 years, the investigations are increased to understand the properties of hypernuclei as theoretically and experimentally. One of the main purposes in experiments is to obtain and analyze the hypernuclei to understand phenomenology in nuclear physics. The hyperons (λ, Σ, Ω, Ξ) obtained in high-energy reactions gives an opportunity to extend traditional nuclear studies and widens horizons for studying particle physics and nuclear astrophysics (see, e.g., Hashimoto et al., 2006; Schaffner et al., 1993; Gal et al., 2012; Buyukcizmeci et al., 2013; 2018; 2019; 2020; and references therein). So far, a lot of experiments were devoted to study associated with fission, evaporation and multifragmentation processes, particular, ALADIN (Kreutz et al., 1993; Botvina et al., 1987; 1995; Xi et al., 1997; Ogul et al., 2011), EOS (Scharenberg et al., 2001), ISIS (Viola et al., 2001; Pienkowski et al., 2002), FASA

(Karnaukhov et al., 2008) and other experimental collaborations have provided very high-quality data. There are many dynamical and statistical models were developed for the theoretical purposes. Especially, the hybrid approaches take into account the descriptions of the non-equilibrium dynamical reaction stage, and the following decay of the equilibrated nuclear sources as properly depending on limitited conditions. Additionally, the statistical models were very successful (SMM (Bondorf et al., 1995) and MMMC (Li et al., 1993)) for the description of the fragment production, so it is started to generalization of model for production of hypernuclei by Botvina and Pochodzalla in 2007 (Botvina and Pochodzalla, 2007).

2. Material and Methods

In this study, we have used the statistical multifragmentation model modified for single and multi-Lambda nuclei and called as hyper-SMM (Botvina and Pochodzalla, 2007; Buyukcizmeci et al., 2013; 2018; 2019; 2020; Botvina et al., 2016).

In the Grand Canonical approach, average yields of individual fragments $Y_{\mathrm{A,Z,H}}$ is given by as follows:

$$\mathrm{g}_{\mathrm{A,Z,H}} \cdot V_f \frac{A^{3/2}}{\lambda_T^3} \cdot \exp\left[-\frac{1}{T}\left(-(F_{\mathrm{A,Z,H}} - \mu_{\mathrm{A,Z,H}})\right)\right],$$

and where $\mu_{\mathrm{A,Z,H}} = A\mu + Z\nu + H\xi$, with the mass A, charge Z, and the Λ-hyperon number H. T is the temperature, $F_{\mathrm{A,Z,H}}$ is the internal free energies of these fragments, V_f is the free volume available for the translation motion of the fragments, $\mathrm{g}_{\mathrm{A,Z,H}}$ is the spin degeneracy factor of species with A, Z, and H, $\lambda_T = (2\pi\hbar^2/m_N T)^{1/2}$ is the baryon thermal wavelength, m_N is the average baryon mass. The chemical potentials μ, ν, and ξ are responsible for the mass number, charge, and strangeness conservation in the system, and they can be numerically found from the corresponding conservation laws accounting for the total baryon number A_0, the total charge Z_0, and the total hyperon number H_0 in the system. In this model the statistical ensemble includes all break-up channels include baryons and excited fragments. The primary fragments are formed in the freeze-out volume V. $V = V_0 + V_f$, where $V_0 = A_0/\rho_0$ ($\rho_0 \cong 0.15\,\mathrm{fm}^{-3}$ is the normal nuclear density), and $V_f = K \cdot V_0$ is the free volume, with $K \cong 2$, as similar in experiments. The binding energy E_A^{bh} of one hyperon at the temperature T inside a hypernucleus with (A, Z, H) is defined as $E_A^{bh} = F_{\mathrm{A,Z,H}} - F_{\mathrm{A-1,Z,H-1}}$. The details of hyper-SMM model including the description of evaporation, fission and multifragmentation processes can be found in our previous publications (see, e.g. Botvina and Pochodzalla, 2007, Buyukcizmeci et al., 2013; 2018; 2019; 2020; Botvina et al., 2016).

In this work, we consider the generalization of the evaporation developed in Refs. (Bondorf et al., 1995; Botvina et al., 1987; Buyukcizmeci et al., 2005; Imal et al. 2015) and extended version for hypermatter (Botvina et al., 2016). One of the deexcitation of heavy nuclei (*A*≥100) is the fission of nuclei. This fission races with particle emission, and it is simulated with the Monte Carlo method at each step of the evaporation-fission cascade. In hyper-SMM, according to the Bohr-Wheeler statistical approach assumption, the partial width for the normal compound nucleus fission is proportional to the level density at the saddlepoint. The height of the fission barrier is determined by the Myers-Swiatecki prescription. We have used the results of the extensive analysis of nuclear fissility and branching ratios as in Ref. (Bondorf et al., 1995). Similar to the evaporation case, we consider hypernuclei with a small number of absorbed hyperons, the level density properties and the fission mechanism will not change considerably according to normal nuclei. The modification should concern the terms depending on the mass formulas because heavy hypernuclei are more strongly bound. For this reason, the fission barrier for hypernuclei will be higher than that normal nuclei.

3. Results and Discussion

Fig. 1 illustrates the mass distributions of ${}^{235}_{4\Lambda}\mathrm{U}$ source after decay at excitation energies E*=0.25, 0.5, 0.75 and 1 MeV/nucleon. These low excitation energies are selected to see how the mass distributions of produced fragments depending on the decay processes such as evaporation and fission. Since it is very instructive to understand evolution of the mass distributions, we also show total nuclei, normal nuclei and hypernuclei distributions separately in the panels. As can be seen clearly, while the normal nuclei distributions have much more light nuclei on the left hand side peaks (green symbols), the hypernuclei distributions shift to the neutron rich side (black symbols) as expected. Since hypernuclei system has at least one Λ up to four, the binding energy will be higher and more stable and neutron rich hypernuclei will appear in the system after decay even if probability of existence of them is lower than normal nuclei. One can see that at low excitations (1 MeV per nucleon) we have standard evaporation and fission. In the top-left panel of Fig. 1, it is clearly seen triple peak of asymmetric fission yields at excitation energy 0.25 MeV/nucleon. The symmetric fission yields appear symmetric distribution (Gaussian type) at excitation energies 0.5, 0.75 and 1 MeV/nucleon. In the regions for (*A*≥100) heavy evaporated residue peak appear with lower probability.

The evaporation channels will race with fission channels with increasing excitation energy. The size of evaporated heavy residues decreases with increasing energy and number of light particles and neutron numbers increase as expected. These findings are consistent with fission and evaporation processes which was investigated in Refs. (Eren et al., 2007; 2013) for normal nuclei and in Ref. (Botvina et al., 2016) for hypernuclei.

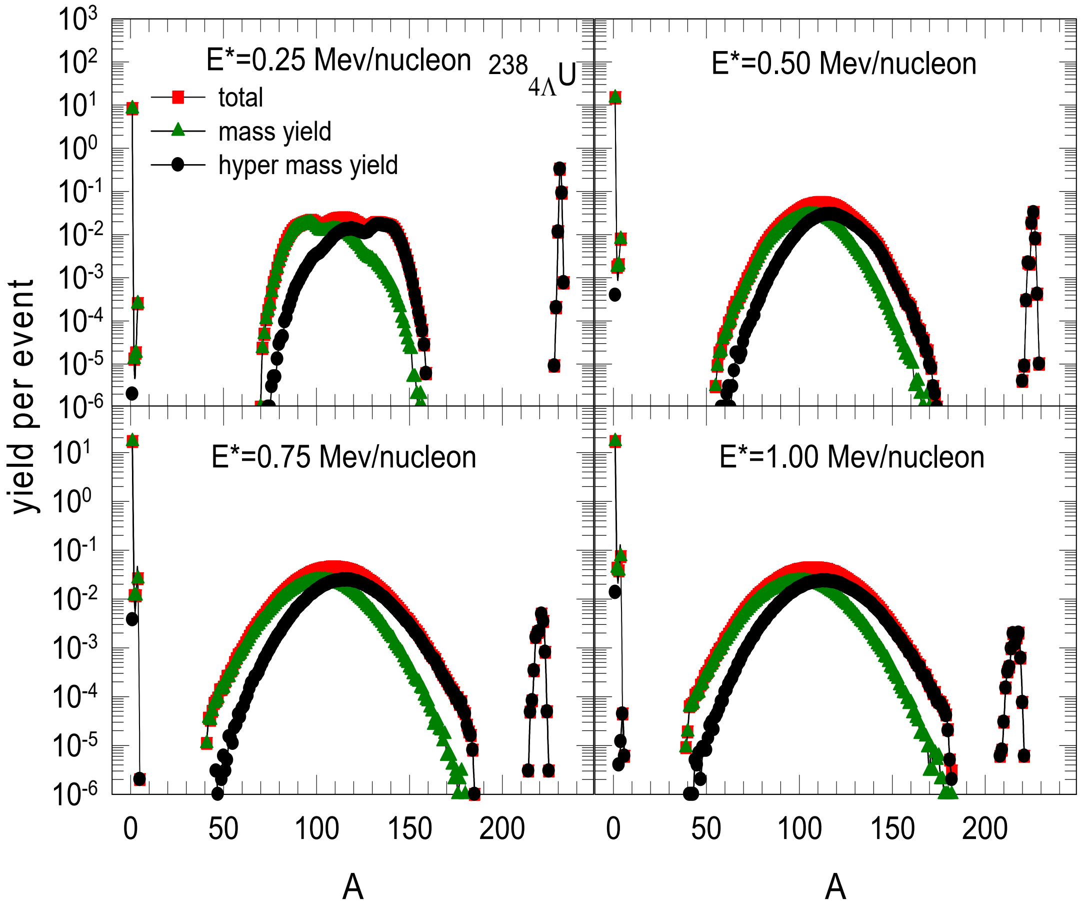

Figure 1. SMM predictions of yields of nuclei and hypernuclei per event versus their mass number, after disintegration of excited systems containing four Λ hyperons. Initial mass number $A_0 = 235$, charge number $Z_0 = 92$, hyperon number $H_0 = 4$, and excitation energies E*=0.25, 0.5, 0.75 and 1 MeV/nucleon of the system are shown in the panels. Total yields, normal nuclei and hypernuclei yield are shown as red, green and black symbols, respectively.

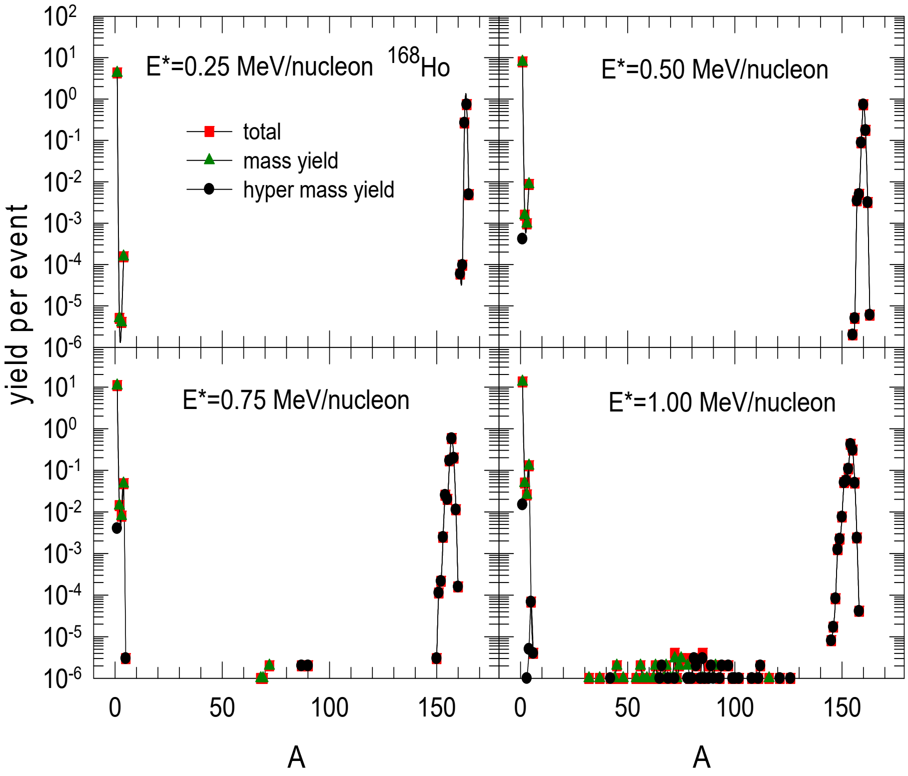

Figure 2. The same as Fig. 1, but for $A_0 = 168$, $Z_0 = 67$ and $H_0 = 4$ source nucleus.

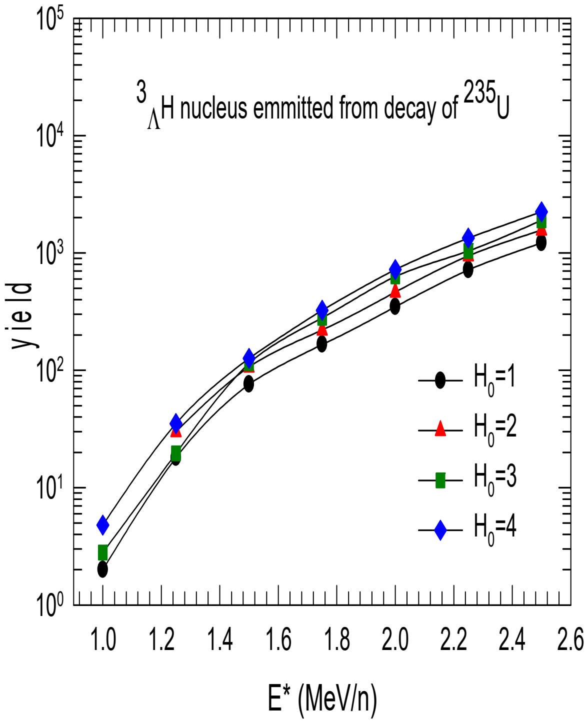

Figure 3. Relative yields of $^{3}_{\Lambda}$H after decay of excited initial hypernuclei $A_0 = 235$, $Z_0 = 92$, $H_0 = 1, 2, 3$ and 4, as function of excitation energy of initial nuclei. To increase the visibility, each data from bottom to top was increased by 20 percent.

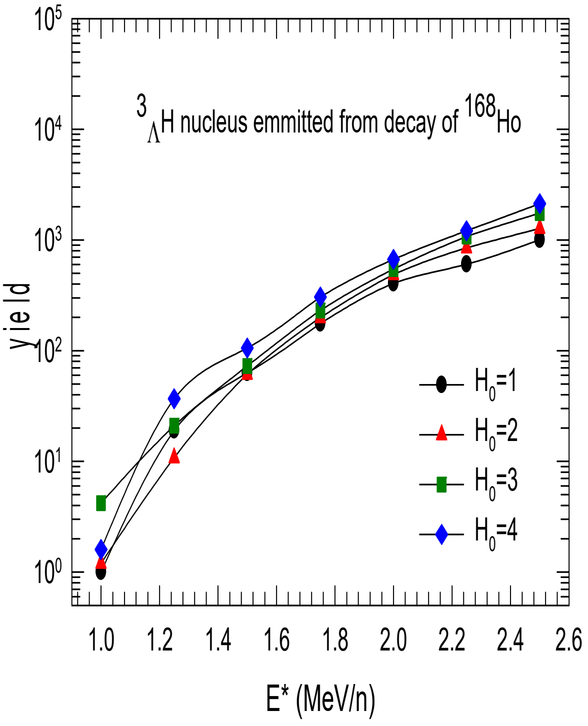

Figure 4. The same as Fig. 3, but for $A_0 = 168$, $Z_0 = 67$.

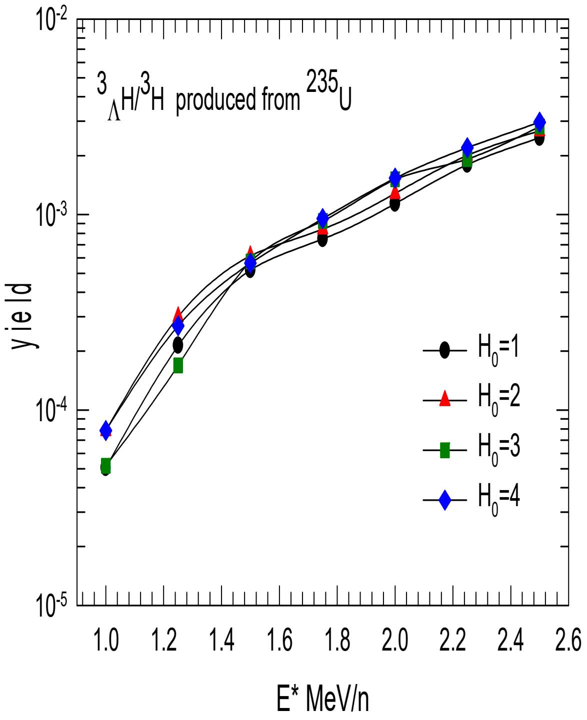

Figure 5. $^{3}_{\Lambda}$H/ ^{3}H isotope ratios produced after decay of an excited hypernuclear system for $A_0 = 235$, $Z_0 = 92$ with source Λ hyperon number $H_0 = 1, 2, 3$ and 4 at different excitation energies. To increase the visibility, each data from bottom to top was increased by 20 percent.

In Fig. 2, we consider as source with $A_0 = 168$, $Z_0 = 67$, and $H_0 = 4$ to see how distributions change for low fissibility. One can clearly see only evaporation products of ^{168}Ho on the top panels, there are no fission events at excitation energies 0.25 and 0.5 MeV/nucleon. In the bottom panels, only few fission products can be found with very low probability. In our calculations, fission barriers of nuclei are modified for the cases including single and multi-Λ nuclei as is done in Ref (Botvina et al., 2016).

Fig. 3 and 4 illustrate the relative yields over one million events of $^{3}_{\Lambda}$H after emitted via evaporation after decay of excited hypernuclei, $^{235}_{\Lambda}$U, $^{235}_{\Lambda\Lambda}$U, $^{235}_{3\Lambda}$U, $^{235}_{4\Lambda}$U, $^{168}_{\Lambda}$Ho, $^{168}_{\Lambda\Lambda}$Ho, $^{168}_{3\Lambda}$Ho, and $^{168}_{4\Lambda}$Ho at excitation energies in between 1-2.6 MeV/nucleon. There is an ordering for the evolution of $^{3}_{\Lambda}$H depending on Λ number of sources and increasing probability with energy. As a further step, $^{3}_{\Lambda}$H/ ^{3}H isotope ratios produced after decay of an excited hypernuclear system for $^{235}_{\Lambda}$U, $^{235}_{\Lambda\Lambda}$U, $^{235}_{3\Lambda}$U, and $^{235}_{4\Lambda}$U, sources are presented in Fig. 5. We believe that fission products and isotope ratios for hypernuclei can be measured in the future experiments at GSI and NICA.

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