Formation of twin and double hypernuclei from Ξ^- absorption at rest on ^{12}C

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1. Introduction

The Ξ^- absorption at rest is the most effective way to produce double hypernuclei which give us precious information of the low-energy YY interaction. In addition to double hypernuclei, one finds interesting fragmentation patterns called twin hypernuclei, such as $^{12}\mathrm{C} + \Xi^- \rightarrow {}^{4}_{\Lambda}\mathrm{H} + {}^{9}_{\Lambda}\mathrm{Be}$ in KEK E-176 experiment [1]. In this experiment, the formation probabilities of double and twin hyperfragment formation may be estimated to be 5$\sim$10 % and 10$\sim$20 %, respectively. These probabilities are very hard to understand by statisitcal decay models of double hyperon compound nucleus [2] and DWIA analysis [3] as can be seen in table 1. Thus the experimental data suggest the importance of some dynamical effects, which cannot be mocked up by a simple escaping probability of one Λ particle at the primary elementary reaction, $\Xi^- p \rightarrow \Lambda\Lambda$.

In this study, we apply microscopic transport model combined with statistical decay model to the Ξ^- absorption reaction to clrarify the formation mechanism of twin and double hypernuclei simultaniously. We adopt Antisymmetrized Molecular Dynamics (AMD) [5] with Quantal Langevin force (AMD-QL) [6], which takes into account the quantal energy fluctuations of the expectation value of energy. These fluctuations seem to be important in the Ξ^- absorption reaction in which the excitation energy is very small ($\approx$ 3MeV).

2. Models

The starting point of our model is AMD [5]. In AMD, the quantum states are constructed by the following Slater determinant of Gaussian wave packets.

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$$|\boldsymbol{Z}\rangle = \frac{1}{\sqrt{A!\,\det\boldsymbol{B}}}\,\det\left[|\boldsymbol{z}_i(\boldsymbol{r_j})\rangle\right]\ , \tag{1}$$

$$|\boldsymbol{z}_i(\boldsymbol{r_j})\rangle = \left(\frac{2\nu_i}{\pi}\right)^{3/4}\exp\left[-\nu_i(\boldsymbol{r}_j-\boldsymbol{z}_i/\sqrt{\nu_i})^2+\frac{1}{2}\boldsymbol{z}_i^2\right]\chi_i(j)\ ,\ B_{ij}=\langle\boldsymbol{z}_i|\boldsymbol{z}_j\rangle\ , \tag{2}$$

where χ_i represents the spin-isospin wave function and the parameter ν_i is (inversely) related to the variance of the Gaussian wave packet; both are assumed to remain constant in time. The real and imaginary parts of the parameter $\{\boldsymbol{z}_i\}$ of the Gaussian wave packet (2) include the mean position $\boldsymbol{d}_i$ and the mean momentum $\boldsymbol{k}_i$, respectively. Applying the time-dependent variational principle to total wave function $|\boldsymbol{Z}\rangle$, we obtain the equation of motion for the paramters $\{\boldsymbol{z}_i\}$,

$$\dot{\boldsymbol{z}}_i=\frac{i}{\hbar}\boldsymbol{F_i}\ ,\quad \boldsymbol{F_i}=-\sum_j C^{-1}_{ij}\frac{\partial\mathcal{H}}{\partial\bar{\boldsymbol{z}}_j}\ ,\quad C_{ij}=\frac{\partial^2\log\det\boldsymbol{B}}{\partial\bar{\boldsymbol{z}}_i\partial\boldsymbol{z}_j}. \tag{3}$$

Here, $\mathcal{H}=\langle\boldsymbol{Z}|\hat{H}|\boldsymbol{Z}\rangle$ is the expectation value of the total energy. Above equation of motion describes the motion of particles in the mean field. In addition to the equation of motion, two body collision term, which describes the two body collisions allowed by Pauli principle, is included. Two body collsion term partially describes the fluctuations from the mean field. These fluctuations are considered to be indispesable for the description of fragmentation process. In Ξ^- absorption reaction, various kinds of fragmentation such as single hypernuclei formation with Λ emission, double hypernuclei formation and twin hypernuclei which is the fragmentation for two single hypernuclei are observed. Then we need large fluctuations to describe these fragmentation processes. However, in Ξ^- absorption reaction, fluctuations caused by two body collision term are largely suppressed by Pauli principle since the excitation energy of this reaction is very small. Therefore, we need different sources of fluctuations to describe experimentaly obserbed various fragmentation.

Recently Quantal Langevin model (QLM) [6] has been developed to incorporate the inherent energy fluctuations of wave packets such as the Slater determinant of Gaussian wave packets since they are time-dependent and not the energy eigenstates. In this work we take into account these inherent energy fluctuations for dynamics as the souce of fluctuations from the mean field evolution. In detail, following the QLM, we modify the AMD equation of motion to the Langevin type equation as follows.

$$\dot{\boldsymbol{z}}_i=\frac{i}{\hbar}\boldsymbol{F_i}+\beta'_{\mathcal{H}}\sum_{kl}g_{ik}g_{kl}\boldsymbol{F'_l}+\sum_k g_{ik}\boldsymbol{\zeta_k}\ ,\quad \beta'_{\mathcal{H}}=\frac{\mathcal{H}-E}{\sigma'^2_E}\ . \tag{4}$$

The stochastic term which includes white noise ζ appearing here is referred to as the *Quantal Langevin* force and this gives the energy fluctuations for the system. Here, we remove the energy fluctuations related to the fragment CM motion and we employ the matrix $\boldsymbol{g}$ that contains off-diagonal parts reflecting single-particle overlaps so that the energy is unaffected by the fluctuation for fragments close to their ground states. Here, we call the resulting model AMD-QL. We describe the dynamical process of the

Ξ^- absorption reaction with AMD-QL and decay of excited fragments appearing after dynamical process is described by the multi-step binary statistical decay model denoted Cascade.

3. Results for the Ξ^- absorption reaction

The initial wave function of the Ξ^- particle is calculated by assuming the interaction between Ξ^- and ^{12}C to be the Woods-Saxon potential and the Coulomb potential [4]. In this study, we assume that Ξ^- is absorbed from p state and the strength of Ξ^--^{12}C Woods-Saxon potential is $V_0 = -16$ MeV. Once the Ξ^- wave function is known, the absorption point of Ξ^- is calculated by the density overlap between protons in ^{12}C and Ξ^-. In AMD-QL the expectation value of energy can fluctuate due to the Langevin force. This fluctuation comes from the energy dispersion of wave packets and can be large in the strongly interacting region. Therefore, we also allow the energy fluctuation in the initial $\Xi^- p \to \Lambda\Lambda$ elementary process. Specifically, initial momenta of two Λ's are chosen to be those in a free space, for simplicity.

Due to the energy fluctuation present in AMD-QL, the Λ emission probability is drastically enhanced and the probability of double hypernuclei decreases (11.4%) in the dynamical process. The mechanism of the Λ emission is as follows. When the two Λ particles gradually lose the single-particle energy and are going to be absorbed into the compound nucleus, one Λ is usually kicked by the Langevin force and can go outside of the compound nucleus. Then the Λ emission process dominates in the AMD-QL simulation.

On the contrary to the results of AMD-QL, with AMD simulation two Λ particles are easily absorbed into the compound nucleus, since Λ particles easily lose most of the single particle energies due to collisions with other nucleons. In AMD this kind of energy loss frequently occurs and double hyperon compound nucleus formation becomes dominant (80.3 %).

A remarkable result of the dynamical AMD-QL simulation is the appearance of twin hyperfragments, $\Xi^- + {}^{12}\mathrm{C} \to {}^{9}_{\Lambda}\mathrm{Be} + {}^{4}_{\Lambda}\mathrm{H}$ (0.1%), ${}^{8}_{\Lambda}\mathrm{Li} + {}^{5}_{\Lambda}\mathrm{He}$ (0.23%), ${}^{5}_{\Lambda}\mathrm{He} + {}^{5}_{\Lambda}\mathrm{He} + {}^{3}\mathrm{H}$ (0.05%), ${}^{5}_{\Lambda}\mathrm{He} + {}^{4}_{\Lambda}\mathrm{H} + {}^{4}\mathrm{He}$ (0.1%), while no twin hyperfragment formation has been seen in the dynamical stage of AMD. In Fig.1 we show density evolution of a typical twin hyperfragment (${}^{8}_{\Lambda}\mathrm{Li} + {}^{5}_{\Lambda}\mathrm{He}$) formation event in AMD-QL dynamical simulation. In the initial state, ^{12}C has three α cluster structure. The elementary process $\Xi^- p \to \Lambda\Lambda$ changes one proton of the α cluster to Λ. In this event, we can see that a Λ picks up ^{7}Li and ${}^{8}_{\Lambda}$Li is finally produced. Most of the twin hyperfragments produced in the dynamical stage of AMD-QL directly reflects the 3-α cluster structure of ^{12}C as in Fig.1. These fragments are produced at the early stage of reaction ($\sim$ 50 fm/c). In addition to twin hyperfragments, we can see frequent light-fragment emission, like ^{4}He, ^{3}H, and ^{7}Li (14.1 %). We analyze the effect of the initial energy fluctuation for the twin hyperfragment production and found that the probability decreases to one fifth of the present value if the initial energy fluctuation is not allowed. So both the initial energy fluctuation and the stochastic energy fluctuation caused by the Langevin force play significant roles for the production of twin hyperfragments.

In AMD-QL, a large part of dynamically produced fragments, including twin hyperfragments, have excitation energies small enough to survive the statistical decay stage

because of the quantal nature of the intrinsic fragment motion. Therefore, the statistical decay plays only a minor role in AMD-QL as can be seen form table 1.

Finally, the AMD-QL (plus Cascade) calculation shows that the production of double hypernuclei is suppressed by Λ emission in the dynamical stage and directly produced twin hypernuclei remain in the final state. These results provide a qualitative understanding of KEK-E176 experiment.

It should be kept in mind that there are still ambiguities in AMD-QL. The key quantity concerning fluctuations, the matrix $\boldsymbol{g}$, is taken somewhat arbitrarily. Therefore, in the future, it would be of interest to determine $\boldsymbol{g}$ from a more fundamental point of view.

A serious issue recognized in this study is the large underestimatation of the formation probability of twin hypernuclei. One possibility for resolving this problem lies in the interaction of $\Lambda\Lambda$. Another possibility is that the nuclear sturucture of ^{12}C or the level desity of compound nuclear states of ${}^{13}_{\Lambda\Lambda}\mathrm{B}^*$ is intimately related with the production of twin hypernuclei.

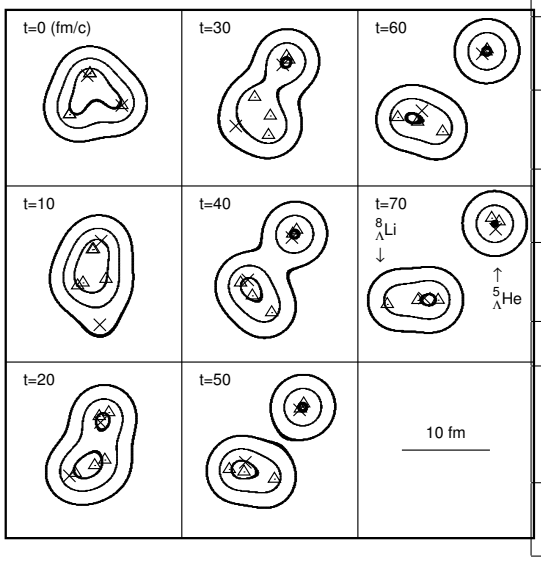

Figure 1. Time-evolution of the matter density in a typical twin hyperfragment production event, $^{12}\mathrm{C} + \Xi^- \rightarrow {}^{5}_{\Lambda}\mathrm{He} + {}^{8}_{\Lambda}\mathrm{Li}$, calculated with AMD-QL. Crosses and triangles indicate the Λ and proton positions, respectively. Neutrons are omitted for simplicity.

	Double Hyp.	Twin Hyp.
AMD-QL	11.4%	0.48%
AMD-QL +Stat. decay	11.1%	0.53%
AMD	80.3%	0.0%
AMD +Stat. decay	46.4%	2.1%
DWIA [3]	4.75%	0.11%
Statistical decay model [2]	66.0%	14.0%
Exp.	**3**% $\sim$ **10**%	**6**% $\sim$ **20**%

Table 1. Formation probability of double hypernuclei and twin hypernuclei

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