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Study of 2n-Removal and Total Reaction Cross Section Induced by ^{11}Li in BUU Framework

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Abstract The σ_R and σ_{-2n} have been calculated via the BUU model by using soft EOS and $0.8\sigma_{\rm Cug}$. The density distribution which come from RMF model has been introduced to replace the normal used square-type distributions in BUU calculation. The calculated results can reproduce the experimental data well for various reaction systems. Here σ_{-2n} is calculated as the difference between σ_R of halo nucleus and core nucleus, by assuming $\sigma_{\rm corr}\approx 0$. It indicates that this assumption works very well in the BUU calculation.

Key words neutron halo, total reaction cross section, 2n-removal reaction cross section

With the development of radioactive ion beams it has become possible to study the properties of nuclei far from β-stability line. By the pioneering experiment of Tanihata et al in 1985[1], an abnormally large interaction cross section σ_I was observed for ^{11}Li. It indicates that the loosely bound two neutrons are expected to have a very spatially extended density distribution surrounding the ^{9}Li core, forming a neutron-halo structure. The halo structure of ^{11}Li seems to be consistent with all the experimental measurements that include the enhancement of σ_I[1], the enhancement of two-neutron removal cross section σ_{-2n}[2] and narrow peak in the momentum distribution of the ^{9}Li fragment produced in fragmentation reaction[3]. Further experimental and theoretical investigations also suggested the existence of neutron halo in other neutron-rich nuclei[4—11].

It is of particular importance to develop a theoretical method to study the reaction mechanism of exotic nuclei. A useful tool to study σ_R is the microscopic Glauber multiple-scattering theory[12]. One of the simplest approximation to calculate σ_R is the optical limit. It has been widely used for deducing the nuclear matter radii from σ_I and σ_R. However, it has been pointed out that it may not be a good approximation if one applies the model to a halo nuclei at intermediate energy[13,14]. Thus, the few-body limit of Glauber model was introduced to study the loosely bound system, where a halo nucleus is decomposed into a core part and a halo part. It was found that the new method gives a smaller cross section than that obtained from the optical limit if one uses the same wave function. This model is recently being commonly used to deduce the radii of halo nuclei. In the framework of the above Glauber Model, a theory is presented to calculate the nuclear parts of various fragmentation cross sections, such as σ_R, σ_I, σ_{-n} and σ_{-2n}[14—16].

On the other hand, the Boltzmann - Uehling - Uhlen -

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beck(BUU) equation[17,18] has been introduced into the calculation of σ_R[19—21]. This model incorporates the Fermi motion, mean field, individual nucleon-nucleon(N-N) interactions and the Pauli blocking effect in calculation. It can be used to extract Equation-Of-State(EOS) and in-medium N-N cross section $\sigma_{NN}^{\text{in-medium}}$ via fitting experimental data like collective flow and balance energy etc. Within the framework of BUU model, the average N-N collision number can be obtained as a function of the impact parameter (b) by assuming a reasonable parameterization of σ_{NN}. According to Poisson statistic, the nucleon fraction $T_n(b)$ that has experienced n times two-body collisions during the course of nucleus-nucleus reaction can be easily obtained. The sum of $T_n(b)$ over $n(n \geqslant 1)$ represents the total probability of N-N collisions and is related closely to the absorption probability of nuclear reaction. For simplicity, a square-type density distribution is used to replace the surface diffused distributions. The width of the density distribution as an unique parameter was obtained by fitting the σ_R's at relativistic energies. More details can be found in Refs.[19—21]. Then the BUU calculations can reproduce the experimental data quite well in a wide energy range. Since the medium effect is different in various incident energy ranges and the real density distribution is rather different from the square-type, the above assumptions are too simple. It is also interesting that whether the BUU model can be used to calculate other fragment cross section, such as σ_{-n} and σ_{-2n}. In this letter, we apply the BUU model to investigate both σ_R and σ_{-2n} by using the density distributions which is calculated fron the nonlinear relativistic mean-field model(RMF)[22,23]. It is concluded that the calculated results can reproduce the experimental values well.

Let us consider the reaction of ^{11}Li with a target nucleus T, as a typical example. The reaction can be summarized in this frame as[14—16]

$$^{11}\text{Li}\{|\Psi_0\rangle\} + \text{T}\{|-\boldsymbol{K},\Theta_0\rangle\} \rightarrow$$
$$^{11}\text{Li}\{|-\boldsymbol{q},\Psi_\alpha\rangle\} + \text{T}\{|-\boldsymbol{K}-\boldsymbol{q},\Theta_\beta\rangle\}, \quad (1)$$

where the initial ^{11}Li with the intrinsic wave function Ψ_0 is at rest in the projectile rest frame, while the target nucleus with the intrinsic wave function Θ_0 and relative momentum $-\hbar\boldsymbol{K}$. At the final stage of the reaction the ^{11}Li goes to the state Ψ_α specified by α with momentum transfer $-\hbar\boldsymbol{q}$. The target nucleus receives a momentum transfer of $-\hbar\boldsymbol{q}$ and goes to state β. It is defined that $\alpha = 0$ and $\beta = 0$ stand for the respective ground states. Then the σ_R is obtained by summing the cross section of reaction over the possible final state($\alpha\beta$), except for $\alpha\beta = 00$. The σ_I is obtained by summing all possible states except for $\alpha = 0$. More details can be found in Refs.[14—16].

By assuming the core plus halo neutrons structure of ^{11}Li, a basic relation is established between σ_I or σ_R and σ_{-2n}:

$$\sigma_{-2n}(^{11}\text{Li} + \text{T}) = \sigma_I(^{11}\text{Li} + \text{T}) - \sigma_I(^{9}\text{Li} + \text{T}) =$$
$$\sigma_R(^{11}\text{Li} + \text{T}) - \sigma_R(^{9}\text{Li} + \text{T}) + \sigma_{\text{corr}}(^{11}\text{Li} \rightarrow {}^{9}\text{Li}) \simeq$$
$$\sigma_R(^{11}\text{Li} + \text{T}) - \sigma_R(^{9}\text{Li} + \text{T}), \quad (2)$$

Ogawa et al[14]. estimated the difference between σ_R and σ_I. It was found to be less than a few percent at high energy. However, the difference is expected to be larger at an energy lower than 100MeV/u. In this calculation, σ_{corr} is assumed to be zero in a wide energy range and the validity is discussed later. Thus σ_{-2n} is approximate as the difference between the σ_R's of ^{11}Li and ^{9}Li in the BUU framework by using soft EOS and $0.8\sigma_{\text{Cug}}$ for σ_{NN}. The density distribution, which is the most important input of the BUU model, is calculated by a nonlinear relativistic mean-field model(RMF)[22,23]. Here we use the set of force parameters NLZ[24] (NL denotes nonlinear, and Z indicates the consistent zero-point energy of c.m. motion) which is frequently used by many group in the RMF calculation. More detailed studies indicates that RMF calculations with other sets of force parameters[25] will also give similar density distributions. As shown in Fig.1, the open circles are the experimental σ_R of ^{12}C + ^{12}C and ^{11}Li + ^{12}C reaction systems respectively. The solid lines indicate the calculated results. It can be seen that the BUU calculations reproduce the experimental σ_R very well in a wide energy range for both stable and exotic reaction systems, by introducing the more natural density distribution into the BUU model to replace the normal square-type distributions.

Then, σ_{-2n}(^{11}Li + ^{12}C) is calculated using Eq.(1) and Eq.(2) in the framework of BUU model, where the σ_{corr} is assumed to be zero. It should be noted that the calculated values correspond to the nuclear part of the measured σ_{-2n} values. The results are shown in Fig. 2.

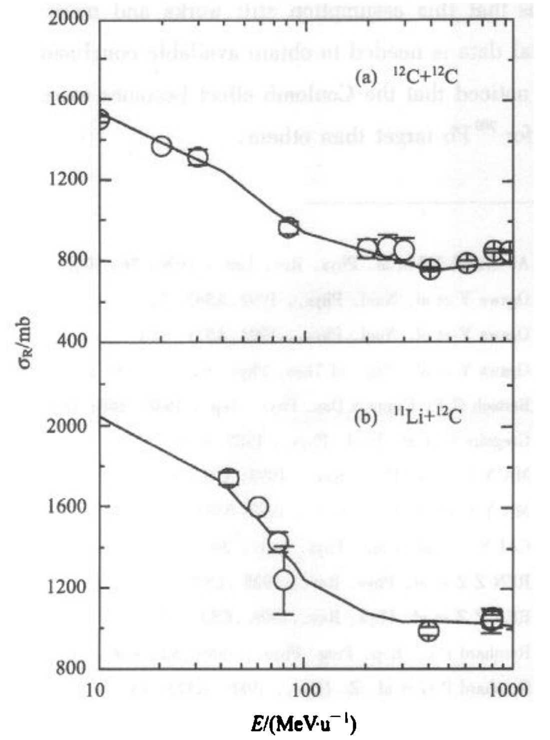

Fig.1. The variation of σ_R with incident energy for ^{12}C + ^{12}C and ^{11}Li + ^{12}C systems respectively. Open circles represent the experimental data taken from literatures[2,4], while the solid curves represent our BUU calculation.

All the experimental data are indicated by solid points[2,14]. The solid curves are the present calculated results. The dashed curve is the calculated result of Glauber model, which is come from Ref.[14]. Fig.2(a) displays the energy dependence of σ_{-2n} of ^{11}Li + ^{12}C system. It can be seen that σ_{-2n} decreases with increasing energy in both low and high energy range gently. At energies around 100MeV/u, it decreases fast with the energy. The reason, maybe, is that the reaction mechanism is very complicated in this energy range. Whatever the experimental data of σ_{-2n} in this energy range is rather rare. More experimental measurements are necessary to estimate the roles of different mechanisms simultaneously and test the validity of our assumption ($\sigma_{corr} \simeq 0$) at intermediate energy. The variations of σ_{-2n} and σ_R of ^{11}Li at 800MeV/u with various targets are plotted as a function of $A^{1/3}$, as shown in Fig.2(b) and Fig.2(c) respectively. The nice agreement between theory and experiment is obtained. The present calculation gives the similar trend of σ_{-2n} as the result of Glauber model[14]. It confirms that the assumption ($\sigma_{corr} \simeq 0$) works very well at high energy. Since the experimental values include both the nuclear and Coulomb contributions, here the nuclear part of σ_{-2n} is 853mb, which is close to the value calculated in the diffractive eikonal model[26]. It is inferred from recently study[14] that the nuclear-Coulomb interference would become more important at $b \simeq 9-20$fm. Thus for ^{11}Li + ^{208}Pb reaction system, the Coulomb effect on σ_{-2n} plays a more important role than for other reaction systems.

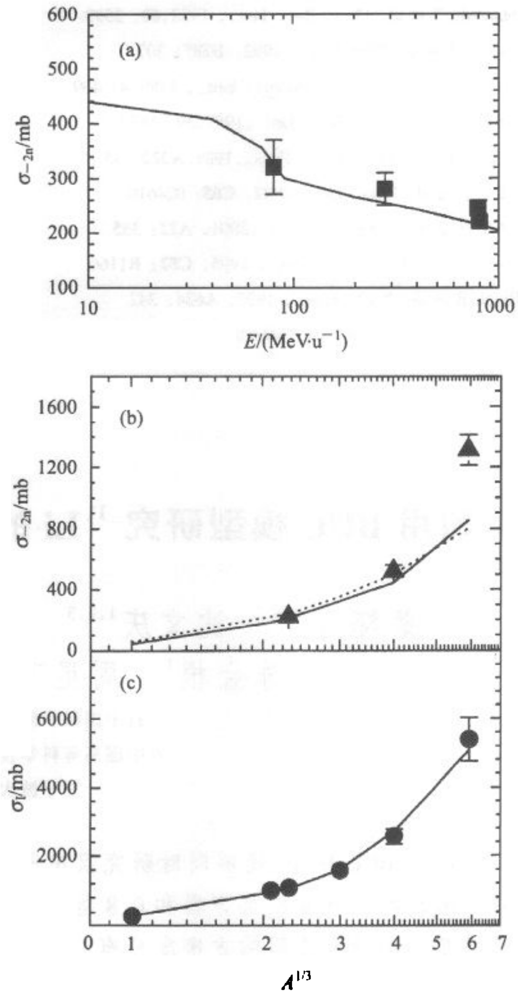

Fig.2. (a) Energy dependence of σ_{-2n} of ^{11}Li + ^{12}C; (b) The Variation of σ_{-2n} of ^{11}Li at 800MeV/u with $A^{1/3}$; (c) The Variation of σ_I of ^{11}Li at 800MeV/u with $A^{1/3}$.

In conclusion, the σ_R and σ_{-2n} have been calculated via the BUU by using soft EOS and $0.8\sigma_{Cug}$. The density distributions which come from RMF model have been introduced to replace the normal used square-type distributions in the BUU calculation. Then the BUU calculations can reproduce the experimental σ_R and σ_{-2n} very well for various reaction systems. Here σ_{-n} and σ_{-2n} have been calculated as the difference between σ_R of halo nucleus and core nucleus, by assuming $\sigma_{corr} \simeq 0$. It indicates that this assumption works very well at high energy, which was mentioned at Refs.[14,27]. At intermediate energy, it seems that this assumption still works and more experimental data is needed to obtain available conclusion. It is also noticed that the Coulomb effect becomes more important for ^{208}Pb target than others.

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利用BUU模型研究^{11}Li的核反应总截面和双中子剥去截面

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摘要 发展了BUU模型,能够同时研究双中子晕结构核^{11}Li引起反应的核反应总截面和双中子剥去截面.计算中使用软的核物质状态方程和0.8倍的核子-核子碰撞截面.同时还用相对论平均场模型计算的中子和质子密度代替通常使用的方密度分布,计算结果可以很好地拟合不同反应系统的实验数据.假定对于晕核及其核芯核,彼此的核反应总截面与相互作用截面之间的差别相同,那么^{11}Li的双中子剥去截面可以表示成^{11}Li及其核芯核^{9}Li引起反应的核反应总截面之差,研究结果表明这一假定可以适用于高能,对于中能核反应需要更多的实验数据来检验.

关键词 中子晕 核反应总截面 双中子剥去截面

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