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Analysis for Fragmentation Products of Proton-Induced Reactions on Pb with Energy up to GeV

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Abstract: The mass and charge distribution of residual products produced in the spallation reaction needs to be studied because it can provide useful information for the disposal of nuclear and the radiation damage in the spallation target. The mass and charge distribution of the spallation products is studied by using quantum molecular dynamic (QMD) models. The simulation results are well agreed with the experimental data of the spallation fragment and empirical formula. However, QMD model does not include the fission process; the calculations can not reproduce the fission fragment. The fission model is introduced into QMD model to investigate the fragment products from proton-induced reactions on Pb. The results are in good agreement with the experimental data.

Key words: Fragment products, Quantum molecular dynamic, Fission model

INTRODUCTION

Nowadays, the research on the energy generation and nuclear waste transmutation by means of neutron generated from interaction of high current proton beam with heavy target has attracted considerable attention [1~3]. In this system, the spallation neutron source is an important link for transmutation and applications. The mass and charge distribution of residual products in the spallation reaction needs to be studied because it can provide useful information for disposal of nuclear wastes, the residual radioactivity generated by the system and the radiation damage in the spallation target. The quantum molecular dynamic (QMD) models has been used to study the

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heavy- and light-ion induced reactions rather sucessfully [4]. We use the QMD model to investigate the double differential cross section of (p, xn) and (p, xp) reactions with the incident proton energy up to GeV, and the time scale of the reaction mechanism in the process of reaction is studied. The reaction process can be divided into three stages, the direct, the cascade and the evaporation stages with corresponding time scale of about lower than 30 fm/c, between 30 ～100 fm/c and more than 100 fm/c, respectively [5].

Lead, tungsten and Pb-Bi alloy constitutes an ideal spallation target, since its neutron yield is high, and it is very transparant to neutron of energy below 1 MeV, it also has excellent thermodynamical properties which make it easy to dissipate the intense heat produced by the proton beam.

In this work, the charge and mass distributions of proton-induced reactions on lead with incident energies of 322 and 590 MeV are investigated. Two regions of product nuclides can be clearly distinguished of the experimental data.The fission products locate approximately at the half of the the mass of the target while the typical spallation products are in the vicinity of the target. The QMD simulations are in good agreement with the experimenat data of spallation products and the empirical formula. However, the fission mechanism is not taken into account in the QMD model; the QMD simulations can not predict the fission products in the fragment products of the target.

We found that the excitation energy for a few spallation residual nuclei is higher than their fission barrier, and they can undergo fission beyond the QMD simulations. However, the excitation energies are not much so higher than the fission barrier; therefore, the statictical fission model is introduced into the QMD model to investigate the fission products in the fragment products of the target. In this work, the mass distribution of the fragment products induced from proton incident on the lead with proton energies of 322, 660, and 759 MeV are studied. The results simulated by QMD plus fission models are in good agreement with the experimental data.

1 QMD AND FISSION MODELS

In QMD model, each nucleon is presented by a Gaussian wave packet in both the coordinate and momentum space in the following way,

$$f_i(\boldsymbol{r},\boldsymbol{p},t)=\frac{1}{\pi\hbar^3}\exp(1-(\boldsymbol{r}-\boldsymbol{r}_i(\mathrm{t}))^2/2L^2)\times\exp(-(\boldsymbol{p}-\boldsymbol{p}_i(t))^2 2L^2/\hbar^2)$$

where L is a parameter that represents the spatial spread of wave packet, $\boldsymbol{r}_i(t)$ and $\boldsymbol{p}_i(t)$ denote the center of the wave packet in the coordinate and momentum space, respectively.

If A_i, Z_i and E_i denote the mass, charge number and the excitation energy of ith fragment product nuclide, respectively, and E_i is higher than the fission barrier of the nuclide when QMD simulation stops, A_i, Z_i and E_i are given by QMD results. The formation cross section of the fission product, where the mass and charge number are A and Z, can be written as [6] ,

$$\sigma(A,Z)=\sum_i\sigma_i(A,Z)=\sum_i\sigma_{i\mathrm{f}}\frac{1}{[2\pi C_i]^2}\exp\left\{\frac{\left[\left[A-\left(\frac{A_i}{2}+\frac{v_i}{2}\right)\right]\right]}{2\pi C^2{}_i}\right\}$$

where v_i is the number of fission neutrons and C_i denotes the width of the Gaussian distributionm adjusted parameter, and in the present work, $C_i = 25$ is adopted. The variable $\sigma_{i\mathrm{f}}$ is the fission cross section of the ith fragment production nuclide calculated by

$$\sigma_{i\mathrm{f}}=\sigma_i\frac{\Gamma_{\mathrm{f}}}{\Gamma_{\mathrm{tot}}}$$

where Γ_{f} is the formation cross section of ith fragment nuclide and simulated by QMD model, Γ_{tot} is the total width. The fission model is detailed in reference[6].

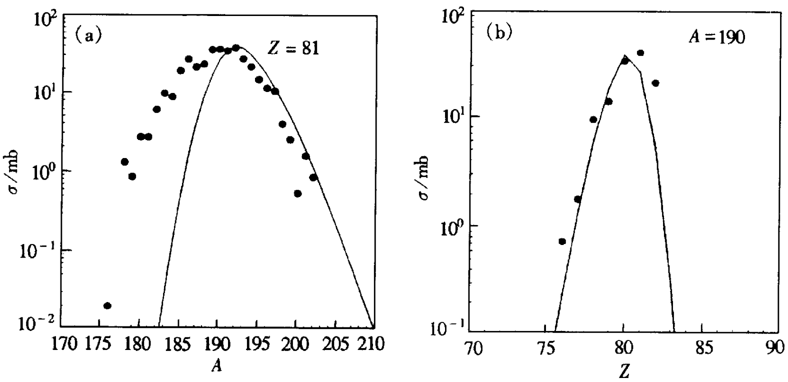

Fig. 1 The formation cross section with Z=81 and A = 190

Fig. 1 shows the formation cross section with charge number Z = 81 and A=190 with incident energy of 590 MeV. The dots denote the QMD calculations and the lines denote the K. Summerer's empirical formula[7]. Fig.1(a) shows the mass distribution of residual nuclei with Z = 81, when A>191 side, the results of QMD reproduce the empirical formula. Well, however, at A <191 side, the QMD results larger than that of empirical formula. As the empirical formula is obtained by parameterizing the experimental data measured by radiochemical method, only the nuclear fragment having considerable long life time can be measured. So it is reasonable that the QMD prediction are higher than experimental data at A <191 side since the nuclei of Z = 81 and A < 191 side are very neutrons deficient and therefore very unstable. Fig. 1 (b) shows the charge distribution of the residual nuclides with A =190, the condition is the same as Fig. 1(a).

Fig. 2 shows the mass distribution of proton-induced reactions on natural lead with incident energy 322 MeV. The dots denote the QMD simulations, line in Fig. 2 (a) denotes the empirical formula and squares denote the measured data [8] .

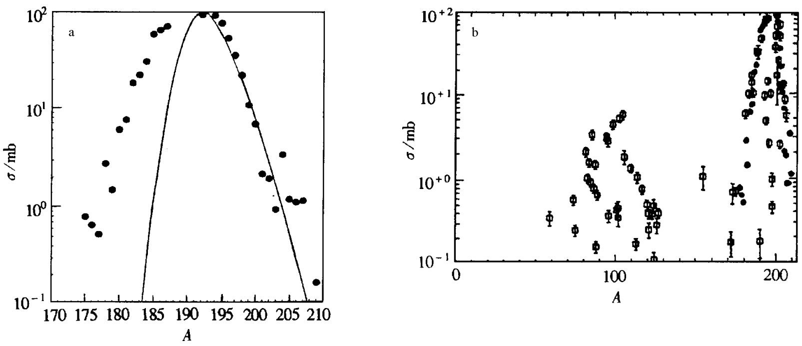

Fig. 2 Mass distribution proton-induced reaction on natural lead with incident energy of 322 MeV

From Fig. 2, it is clear that the QMD simulations reproduce well the spallation products in the fragment products of the target. However, the fission process is not taken into the QMD model; it can not predict the fission products.

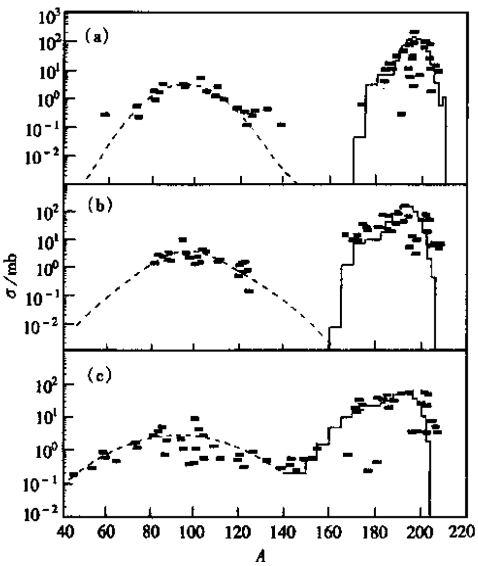

Fig. 3 The mass distribution proton-induced reactions on lead with incident energies of 322, 660 and 759 MeV, respectively

Fig. 3 shows the mass distribution induced from proton incident on lead with energies of 322, 660 and 759 MeV, respectively. The squares denots the measured data[7], the line denotes the simulation of QMD plus FISSION models calculating. It is clear that the results simulated by plus FISSION models are in agreement with the experimental data.

2 SUMMARY AND DISCUSSION

In present work, the QMD is used to investigate the mass and charge distribution of proton-induced reactions on lead target with the energies up to GeV. The QMD can reproduce well the spallation products of the fragment products, however, it can not predict the fission products of the fragment products since the fission model is not considered in the QMD model. The statictical fission model is introduced into the QMD model to investigate the fission products of the fragment product of the spallation target. We use the QMD plus statictical fission model to study the fragment products from proton-induced reactions on lead with the energies of 322, 660 and 759 MeV. The results simulated by using QMD plus statictical fission model are in good aggreement with the measured data.

From the present work, we can conclude that QMD model is a useful approach for the intermediate energy proton induced reaction and the QMD plus statictical fission model can be applied to analyze fragment distributions of proton-induced reactions with intermediate energy rather successfully.

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能量到GeV的质子入射铅靶的散裂产物分布研究

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摘　要： 由中高能质子入射靶引起的散裂碎片的分布关系到散裂靶经长期辐照后的放射性废物的累积。在量子分子动力学模型（QMD）中考虑剩余核的裂变过程（FISSION），利用QMD＋FISSION模型研究了322，660，759 MeV的质子入射铅靶的散裂产物的分布。计算结果很好地再现了实验测量值。

关键词： 散裂产物 量子分子动力学 裂变模型