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Fission dynamics at high excitation energies investigated in complete kinematics measurements

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Abstract. Light-charged particles emitted in proton-induced fission reactions on ^{208}Pb have been measured at different kinetic energies: 370A, 500A, and 650A MeV. The experiment was performed by the SOFIA collaboration at the GSI facilities in Darmstadt (Germany). The inverse kinematics technique was combined with a setup especially designed to measure light-charged particles in coincidence with fission fragments. The data were compared with different model calculations to assess the ground-to-saddle dynamics. The results confirm that transient and dissipative effects are required for an accurate description of the fission observables.

1. Introduction

Measurements of light particles have been used as a "clock" to estimate the fission time [1, 2] because they are emitted along the fission path up to the scission-point configuration. In particular, Lestone et al. [2] used fusion-fission reactions to investigate the pre- and postsaddle fission times by comparing proton- and α-particle multiplicities with statistical model calculations. Their work demonstrated that this observable is sensitive to dissipation. Similar conclusions were obtained by Fröbrich and Gontchar [3] by comparing the same data with dynamical calculations based on the Langevin equation.

In this work we took advantage of the high excitation energies, and low angular momenta and shape distortion induced by spallation reactions. In this kind of reaction, light-charged particles can be emitted during the first stage of the reaction, the so-called intranuclear cascade, or in the deexcitation of the compound nucleus. In the latter case, we can assume that light-charged particles are mostly emitted before the saddle point because of the shorter saddle-to-scission paths, where the most probable deexcitation channels are the emission of neutrons and γ-rays. The measurement of these particles in coincidence with fission is a difficult task in direct kinematics experiments due to the fact that fission fragments cannot always be detected, and it is even harder to identify them in terms of their atomic or mass number [4]. For this reason, our novel experimental setup together with the inverse kinematics technique represent an ideal scenario because fission fragments and light-charged particles leave the target with high kinetic energies in the forward direction, facilitating their detection with high efficiency and precision.

2. Experiment

The description of the experimental setup used in this work can be found in Refs. [5, 6], and here, we only describe the most important features.

A multisampling ionization chamber and a time projection chamber were placed upstream of a liquid-hydrogen target to provide us the beam identification and the position of the beam on the target, respectively. Then, a double multisampling ionization chamber, placed downstream of the liquid-hydrogen target, was used to detect both fission fragments simultaneously and permitted us an unambiguous identification of fission [6]. In addition, the tracking capabilities of this last detector allowed us to select fission events produced at the target position [7]. Light-charged particles were detected in a Time-of-Flight Wall (ToF Wall) placed behind the target at a distance of 140 cm. This detector consisted of two detection planes made of segmented plastic-scintillators, each 50 cm long, 6 cm wide and 1 cm thick. The first plane was formed by six horizontal paddles and the second one by six vertical paddles, which left a square hole of 12.5×12.5 cm^2 in the center for the transmission of the fission fragments.

3. Results

In Fig 1(a) we display the probability for the emission of particles with $Z = 1$ in fission events as function of the total multiplicity of light-charged particles per event for the reaction ^{208}Pb + p at 370A (open triangles), 500A (solid circles), and 650A (open squares) MeV. The maximum of these distributions appears for small values of the total multiplicity, as expected because most of the fissioning systems are produced in peripheral collisions where only a few number of nucleons are removed. Then, the tails observed towards larger multiplicities can be attributed to the production of lighter fissioning nuclei with higher excitation energies [8]. As can also be seen in the figure, the probability for fission events with large multiplicities of light-charged particles emitted in coincidence, as well as the maximum of the distributions, increase with the bombarding energy. This tendency can be attributed to the increase of the violence of the reaction, which means more particles are emitted during the intranuclear cascade and deexcitation processes.

In Fig. 1(b) we show the average values of the multiplicity distributions of Fig. 1(a) as a function of the projectile bombarding energy. These data are compared with different model calculations performed by using the intranuclear cascade model INCL4.6 [9] coupled to the deexcitation code ABLA07 [10]. As can be observed in the figure, dynamical calculations based on the Kramers approach and considering a constant value of the reduced dissipation parameter of $\beta = 4.5 \times 10^{21}$ s^{-1} deduced in previous works [11, 12] (long-dashed line) overestimate the data. However, ABLA07 calculations considering dissipative and transient time effects for the same value of the reduced dissipation parameter (solid line) provide a good description. Therefore, these calculations reveal that this observable is sensitive to transient time effects.

On the other hand, ABLA07 calculations assuming values of $\beta = 10 \times 10^{21}$ s^{-1} (dotted line) and $\beta = 20 \times 10^{21}$ s^{-1} (dot-dashed line) clearly underestimate the data. This fact indicates that this observable is also sensitive to the value of the reduced dissipation parameter. This comparison also allows us to contrain the dissipation parameter obtaining a value around $\beta = 4.5 \times 10^{21}$ s^{-1} that is in excellent agreement with the results found in other works [2, 3, 11, 12, 13, 14].

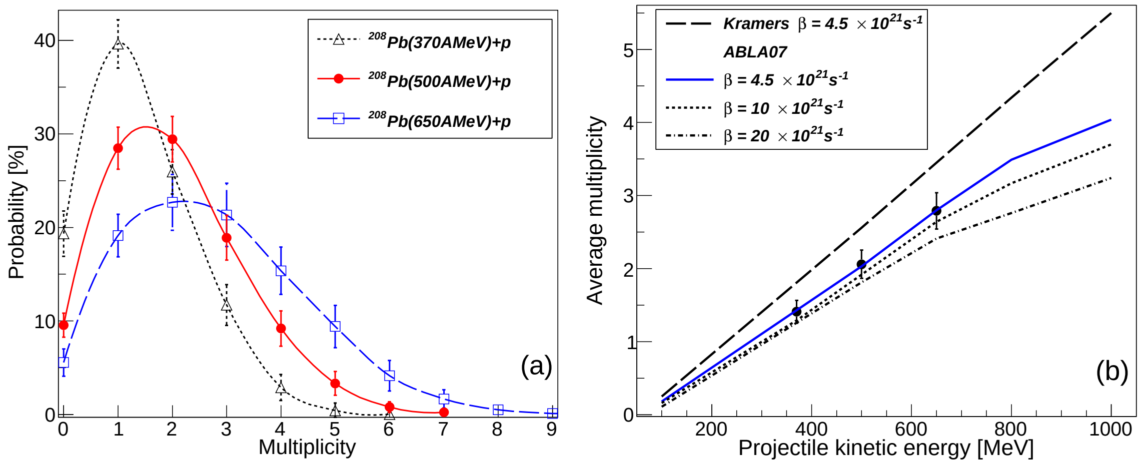

Figure 1. (Color online) (a) Multiplicity distribution of particles with $Z = 1$ for the reaction ^{208}Pb + p at different kinetic energies: 370A (open triangles), 500A (solid circles), and 650A (open squares) MeV. The lines are to guide the eye. (b) The average multiplicity of particles with $Z = 1$ from (a) are compared with different model calculations (lines).

4. Conclusions

We have investigated proton-induced fission of ^{208}Pb in inverse kinematics at different bombarding energies. We have used a highly efficient detection setup that permitted us for the first time to identify the atomic number of the fission fragments in coincidence with the light-charged particles. The data were compared to different model calculations, and the results obtained with respect to the temperature dependence of the dissipation parameter and its magnitude are consistent with the conclusions obtained in most of the works related with the investigation of fission [1, 3, 11, 12, 14, 13, 15, 16]. Moreover, we also conclude that dissipative and transient time effects are needed to explain the measured multiplicities of light-charged particles at high excitation energies above 100 MeV.

References

[1] Hinde D J *et al* 1989 *Nucl. Phys.* A **502** 497
[2] Lestone J P 1993 *Phys. Rev. Lett.* **70** 2245
[3] Fröbrich P *et al* 1993 *Nucl. Phys.* A **556** 281
[4] Lott B *et al* 2001 *Phys. Rev.* C **63** 034616
[5] Martin J F *et al* 2015 *Eur. Phys. J.* A **51** 174
[6] Rodríguez-Sánchez J L *et al* 2015 *Phys. Rev.* C **91** 064616
[7] Rodríguez-Sánchez J L *et al* 2014 *Phys. Rev.* C **90** 064606
[8] Rodríguez-Sánchez J L *et al* 2015 *Phys. Rev.* C **92** 044612
[9] Boudard A *et al* 2013 *Phys. Rev.* C **87** 014606
[10] Kelić A, Ricciardi M V and Schmidt K H, Proceedings of Joint ICTP-IAEA Advanced Workshop on Model Codes for Spallation Reactions, ICTP Trieste, Italy, 48 February 2008, edited by Filges D, Leray S, Yariv Y, Mengoni A, Stanculescu A and G. Mank (IAEA INDC(NDS)-530, Vienna, 2008), pp. 181-221.
[11] Schmitt C *et al* 2010 *Phys. Rev.* C **81** 064602
[12] Ayyad Y *et al* 2015 *Phys. Rev.* C **91** 034601
[13] Nadtochy P N *et al* 2010 *Phys. Lett.* B **685** 258
[14] Ye W and Tian J 2016 *Phys. Rev.* C **93** 044603
[15] Jacquet D and Morjean M 2009 *Prog. Part. Nucl. Phys.* **63** 155
[16] Vardaci E *et al* 2015 *Phys. Rev.* C **92** 034610