FISSION OF HIGHLY EXCITED ^{88}Mo COMPOUND NUCLEUS*

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Here, a detailed view of the fusion-fission channel analysis is presented. Experimental data were analysed, and compared to calculations done with statistical model code GEMIINI++. Presented is a good agreement between calculations and experimental data. Results prove that GEMINI++ calculations can be used to reproduce experimental fusion-fission cross sections as well as fission fragments velocities.

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1. Introduction

An experimental study of fusion-evaporation and fusion-fission channels for the ^{88}Mo compound nucleus, produced at different excitation energies in the reaction ^{48}Ti+^{40}Ca at 300 and 600 MeV beam energies, has been presented in papers [1, 2]. The present work deals with the investigation of fusion-fission channel for the ^{88}Mo compound nucleus at two different excitation energies, produced in the reaction ^{48}Ti+^{40}Ca at 300 and 600 MeV beam energy. This investigation was motivated by the fact that it has not been known whether the symmetric fission occurs in ^{88}Mo at high compound nucleus temperatures. For heavy nuclei, the energy of the saddle point increases with fragment mass asymmetry, hence mass symmetric fission is

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the most probable. In light nuclei, the situation is opposite, the energy of the saddle point decreases with mass asymmetry, hence emission of light charged particles or light clusters becomes more probable. These two regions are separated by the Businaro–Gallone point [3], for which the saddle barrier has a plateau as a function of mass asymmetry. From the experimental point of view, the Businaro–Gallone point seems to be located between $A = 85$ and $A = 145$, and/thus the studied ^{88}Mo falls into that region.

2. Experiment and data analysis

The experimental data were taken at LNL, Italy by the HECTOR+GARFIELD collaborations. The experimental setup contained the GARFIELD [4] array for light charged particle identification and energy measurement, the HECTOR [5] detectors for γ-energy measurements and 32 phoswich detectors from FIASCO experiment [6] for heavy fragments (residues, fission fragments and elastic/inelastic scattered particles) detection. The ^{48}Ti beam at the energy of 300 and 600 MeV bombarded ^{40}Ca target, producing in the fusion reaction ^{88}Mo compound nuclei with excitation energies of 124 and 261 MeV. Reaction parameters, as well as properties of compound nucleus, are presented in Table I. A more detailed description of this experiment, with a complete analysis of light charge particles (LCP) energy spectra and high-energy γ rays emitted from decay of the Giant Dipole Resonance (GDR), is available in Refs. [1, 2].

TABLE I

Parameters of the ^{48}Ti + ^{40}Ca reaction, where: $E^{\rm b}_{\rm LAB}$ is beam energy; $v_{\rm CN}/c$ is velocity of compound nucleus (CN) divided by the speed of light; $E^*_{\rm CN}$ is CN excitation energy; $\langle T_{\rm CN}\rangle$ is CN temperature (calculated as in Ref. [2]); $T^{\rm max}_{\rm CN}$ — maximum CN temperature (calculated from $T = \sqrt{\frac{U}{a(U,l)}}$ formula, where U is the thermal excitation energy and $a(U,l)$ is the level density parameter dependent on U and angular momentum l, as in Ref. [2]); $\sigma_{\rm fus}$ — cross section for fusion (Bass model [7,8]); $\sigma_{\rm ER}$ – cross section for residues; $l_{\rm max}$ — maximal angular momentum value.

$E^{\rm b}_{\rm LAB}$ [MeV]	$v_{\rm CN}/c$ [%]	$E^*_{\rm CN}$ [MeV]	$\langle T_{\rm CN}\rangle$ [MeV]	$T^{\rm max}_{\rm CN}$ [MeV]	$\sigma_{\rm fus}$ [barn]	$\sigma_{\rm ER}$ [barn]	$\frac{\sigma_{\rm ER}}{\sigma_{\rm fus}}$ [%]	$l_{\rm max}$ [$\hbar$]
300	6.27	123.8	3	3.2	1.32	0.53	40	78
600	8.91	260.7	4.5	4.8	0.76	0.15	20	84

In this paper, the main focus will be put on the fission fragments data, which were acquired by phoswich and GARFIELD detectors. The phoswiches were placed at forward angles, $5^\circ < \theta < 13^\circ$ corresponding to 0.1 sr. Heavy fragments or evaporation residues selection was done by gating on energy deposit E in the first layer of the phoswich (gA) *versus* the time of flight (TOF), see Fig. 1.

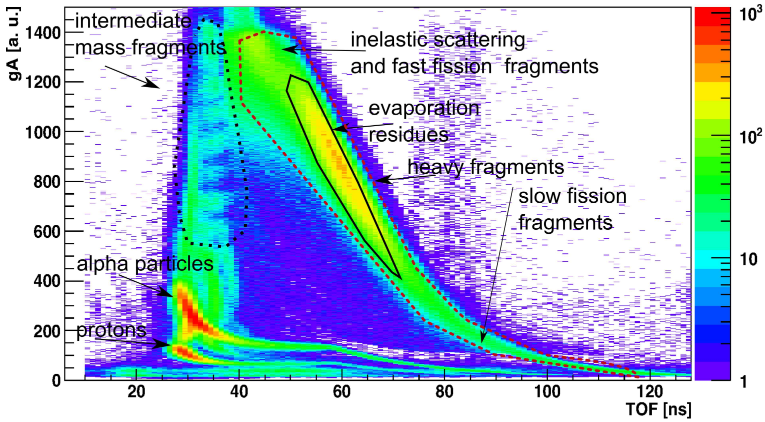

Fig. 1. 2D plot of the E (gA parameter) and TOF dependence for the phoswich detector (solid line — evaporation residues, dotted line — intermediate mass fragments and dashed line — heavy fragments). Data for the reaction of ^{48}Ti beam at the 600 MeV energy.

The selection of fission channel was more problematic than fission-evaporation due to additional processes such as deep inelastic that produce fragments with similar velocity and mass that the fission fragments had. However, this background can be minimalised by selection of angular correlations between two fragments and their relative velocity. Additional cuts on the fragment's Z can be used to distinguish between the symmetric and asymmetric fission. In this work, fragments with Z ranging from 2 to 15 were classified as intermediate mass fragments (IMF). Only events with one heavy fragment and IMF or two heavy fragments (selections marked in Fig. 1) were recognised as fission. First class is arbitrarily assigned to asymmetric fission, while second one is identified as the symmetric fission. For the fission, there should be momentum conservation in the center-of-mass system (CM), the two fragments are emitted back-to-back in CM. Due to the evaporation from the excited fission fragments and to finite angular resolution, the precise kinematic correlation has been spread out (see Fig. 2 (top) and 2 (bottom) for symmetric and asymmetric fission, respectively). To consider two fragments as coming from fission, the angle between their velocities $\Theta_{\rm rel}^{\rm cm}$ defined with Eq. (1) should be in the range of $160^\circ < \Theta_{\rm rel}^{\rm cm}$, and $\phi_{\rm rel} = |\phi_1 - \phi_2|$ should be in the range between $140^\circ < \phi_{\rm rel} \leq 180^\circ$

$$\Theta_{\rm rel}^{\rm cm} = \arccos \frac{\vec{v_1} \cdot \vec{v_2}}{\|\vec{v_1}\| \|\vec{v_2}\|}\,, \tag{1}$$

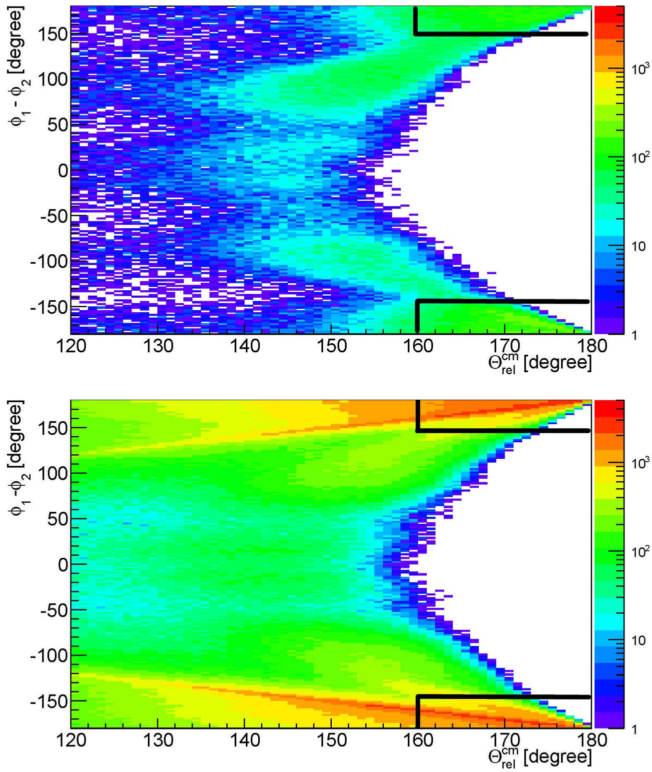

Fig. 2. 2D plots of the fission fragments ϕ difference $(\phi_1 - \phi_2)$ *versus* their $\Theta_{\rm rel}^{\rm cm}$, for the (top) symmetric fission case, and the (bottom) asymmetric one. The region marked with the line corresponds to the "good fission" events gating condition. Data for the reaction of ^{48}Ti beam at the 600 MeV energy.

where $\vec{v_1}$ and $\vec{v_2}$ are fragments CM velocity vectors. Applying the described above selection rules and additionally requiring that relative velocity between fragments fulfil Viola systematics [9], one can obtain information about probability of asymmetric and symmetric fission. For reactions at both beam energies, asymmetric fission is the dominating process, involving $\sim 80\%$, $\sim 90\%$ of fission events for 300 and 600 MeV beam energies, respectively. This result is in agreement with data obtained from other experiments for $^{90-98}$Mo isotopes [12, 13].

3. Statistical model — GEMINI++ calculations

The GEMINI++ (re-written in C++ GEMINI maintained by R. Charity), a Monte Carlo simulation code based on statistical model, has been successfully used for the description of charged particle decay and fission fragments, emission following heavy-ion fusion reactions, in the wide-mass and excitation energy regions. In the present study, a new modified version of GEMINI++ code was employed, allowing to treat explicitly the GDR emission [10].

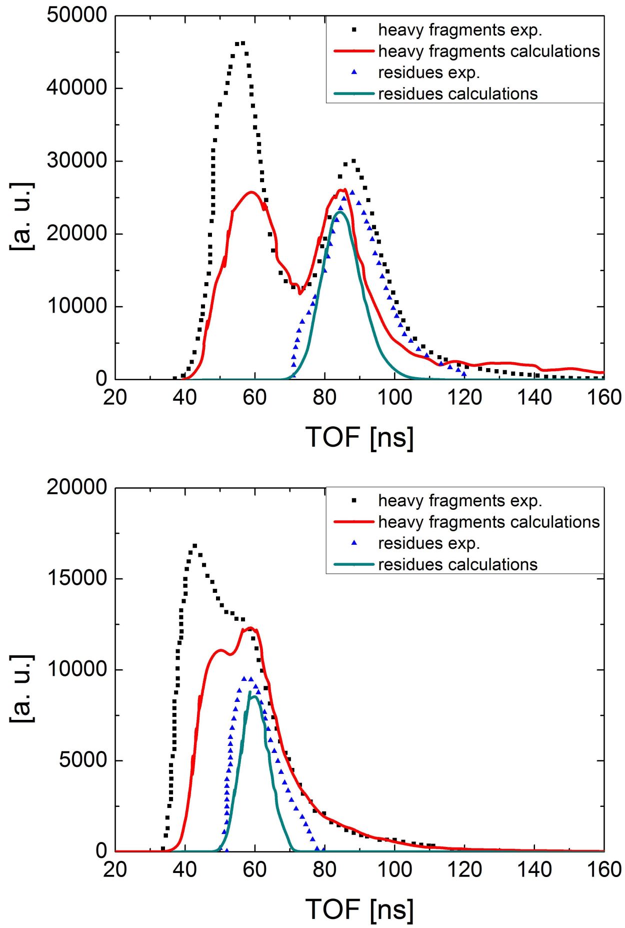

Fig. 3. Time-of-flight spectra for heavy fragments detected in the phoswich scintillators, the comparison between experimental values and calculations done with GEMINI++ code. (top) 300 MeV Ti^{48} and (bottom) 600 MeV Ti^{48} beam, on the ^{40}Ca target.

The GEMINI++ produces event-by-event data which can be sorted out in different ways. For the presented analysis, the output of GEMINI++ calculations was sorted in the same way as experimental data using the same sorting code. All the conditions required for the measured data were taken into account in the calculations including experimental angular coverage of GARFIELD and phoswich detectors. Moreover, detectors response functions were also taken into account, allowing to compare calculated and experimental results. Referring to work [11], statistical model parameters, such as the level density $\tilde{a}_{\rm eff}$ and the spread of the LCP Coulomb barrier taken into account by a parameter w in the transmission coefficients, were set to their default values. The *Yrast* parameters and fission barrier $B_{\rm f}$ as a function of angular momentum J was set to RLDM parametrization [14]. These values were confirmed to be proper for studied reaction, by reproducing LCP energy spectra from fusion-evaporation events, described in Ref. [1]. The fission delay parameter $\tau_{\rm d}$ (set to 10 zs) and the fission barrier height $B_{\rm f}$ (parametrisation of RLDM [14]) play an important role in occurrence of the fission process and its competition to the particle decay. To check the performance of the statistical model code for the fission data, experimental TOF of heavy fragments was compared to the calculated one.

In Fig. 3, the result of calculations using GEMINI++ is compared with measured data. Normalisation was performed to the experimentally obtained fusion-fission cross section [1], because we found that such way of normalising provides a much better agreement of calculations with the data than using $\sigma_{\rm ER}$ or $\sigma_{\rm fiss} = \sigma_{\rm fus} - \sigma_{\rm ER}$ values from Table I as scaling factors. This comparison demonstrates that GEMINI++ code can reasonably reproduce competition between evaporation and fission channels in studied mass and excitation energy ranges. One can also see a very good agreement for TOF related to residues and slow fission fragments, while there is a huge discrepancy for the low TOF values. This can be explained by the fact that in the calculations, the deep inelastic process, which will produce fast heavy fragments, was not taken into account.

The main result obtained with the use of GEMINI++ code is the absolute cross section for the fusion-fission process. It was estimated by taking into account the overall efficiency of the detector, which was provided by comparison of the GEMINI++ calculations with the experimental data. Fusion-fission cross-section values obtained for the reaction ^{48}Ti+^{40}Ca are: $\sigma_{\rm fiss} = 115 \pm 3$ mbarn and $\sigma_{\rm fiss} = 417 \pm 114$ mbarn [1], for 300 and 600 MeV beam energies, respectively.

4. Conclusions

For the ^{88}Mo excited compound nucleus, asymmetric fission is the dominating process, which is a finding consistent with previous works in the $^{90-98}$Mo region [12, 13].

Experimental time of flight (TOF) of heavy fragments (including residues and fission fragments) is in reasonable agreement with predictions of GEMINI++ code. Results show that GEMINI++ calculations can be used to reproduce experimental fusion-fission cross sections as well as fission fragments velocities. Such information will be useful for planning of future investigations of the nuclear properties at extreme angular momentum and temperature, where fission process plays an important role. This kind of experiments may include searching for Poincaré shape transition [15], which is expected to occur at angular momentum near and above the region where the fission barrier vanishes.

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