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Bimodal fission of Hs^*

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Abstract. Mass and energy distributions of fission fragments obtained in the reactions $^{22}\text{Ne} + ^{249}\text{Cf}$, $^{26}\text{Mg} + ^{248}\text{Cm}$, and $^{22}\text{Ne} + ^{238}\text{U}$ have been measured. A special attention will be paid on the properties of mass-energy distribution of fission fragments obtained in the reaction $^{26}\text{Mg} + ^{248}\text{Cm}$ at an excitation energy of 35 MeV. At this energy shell effects should become more effective in fission, the TKE distribution of symmetric fragments obtained in the reaction $^{26}\text{Mg} + ^{248}\text{Cm}$ differs strongly from a Gaussian shape. Besides a low-energy component, a high-energy component, not foreseen in the LDM, arises. This is attributed to the fact that both fission fragments are close to the spherical neutron shell $N = 82$. It means that for the compound nucleus $^{274}\text{Hs}^*$, formed in the reaction $^{26}\text{Mg} + ^{248}\text{Cm}$, the phenomenon of bimodal fission was observed for the first time. For the compound nucleus $^{260}\text{No}^*$ formed in the reaction $^{22}\text{Ne} + ^{238}\text{U}$ at the initial excitation energy of 41 MeV the bimodal fission as well as superasymmetric fission were observed.

1. Introduction

The question about symmetric and asymmetric modes in low energy nuclear fission arose immediately after the discovery of nuclear fission. An extensive set of experimental data on mass and energy distributions of fragments in the spontaneous and low energy fission of nuclei up to element with $Z=104$ have confirmed the validity of a hypothesis about the existence of independent fission modes stated by Turkevich and Niday in 1951[1]. The numerous theoretical works showed that multimodality is caused by the valley structure of the deformation potential energy surface of a fissioning nucleus. Following the Brosa model [2], the four fission modes can be distinguished: the Super Long symmetric mode; the Standard I mode caused by the influence of proton $Z = 50$ and neutron $N = 82$ shells; the standard II mode determined by deformed nuclear shells with $Z \approx 54-56$ and



$N \approx 86-88$ and the Super Short mode, manifesting itself when both light and heavy fission fragments are close to the double magic tin with $A \approx 132$.

Bimodality means the co-existence of two fission modes with different total kinetic energies for the same symmetric mass division. The phenomenon of bimodal fission was discovered in the 1980's for the case of spontaneous and low energy fission of nuclei in the Fm-Rf region [3]. Some spontaneously fissioning isotopes of Fm, Md, and No were found to exhibit symmetric fragment mass distributions, whose widths are changing very rapidly from nucleus to nucleus. For example, for spontaneous fission of ^{258}Fm the mass distribution is unusually narrow, while for the neighboring nucleus ^{259}Md with only one more proton it is rather broad. Even more spectacular are the distributions of TKE, which are double humped. The high-energy mode is linked to a narrow mass distribution while the low-energy mode has a wide mass distribution.

This behavior of TKE distributions strongly differs from the Gaussian shape distributions found in fission of all other actinides. It is important to note that bimodal fission appears for Fm isotopes ($Z=100$) and more heavy elements when both fission fragments are close to spherical proton ($Z=50$) and/or neutron ($N=82$) shells.

By theory, bimodal fission is explained by the existence of two different paths on the potential energy surface leading to fission. One path is described by the liquid drop model (LDM), while for the other path shell effects play an important role. The LDM path leads to elongated scission configurations while the shell effect path corresponds to compact configurations. Both paths result in symmetric (or nearly so) mass distributions, but the high TKE valley is narrower while the low TKE valley is much wider. This explains the difference in width of the mass distributions.

The competition between various fission modes and diminishing of shell effects with increasing projectile energy is still an open question. To investigate the properties of bimodal and superasymmetric fission the mass and energy distributions of fission fragments of Hs and No isotopes were measured.

2. Experiment

The experiments were carried out at the Flerov Laboratory of Nuclear Reactions using beams of ^{22}Ne , ^{26}Mg ions extracted from the U-400 cyclotron at energies around the Coulomb barrier. The energy resolution was $\sim 2\%$. Beam intensities on targets were 1-2 pA. Layers of $^{238}\text{UF}_4$, ^{248}Cm , and ^{249}Cf , 120-200 $\mu\text{g}/\text{cm}^2$ thick, deposited on a 40-50 $\mu\text{g}/\text{cm}^2$ carbon backings, were used as targets.

Binary reaction products were detected in coincidence by the two-arm time-of-flight spectrometer CORSET [4]. Each arm of the spectrometer consists of a compact start detector and a position-sensitive stop detector, both based on microchannel plates. The distance between the start and stop detectors was 12-15 cm. A typical mass resolution of the spectrometer in these conditions is $\sim 2-3$ u.

The data processing assumes standard two-body kinematics. Primary masses, velocities, energies, and angles in the center-of-mass system of reaction products were calculated from measured velocities and angles in the laboratory system using the momentum and mass conservation laws with the assumption that the mass of the composite system is equal to $M_{\text{target}} + M_{\text{projectile}}$. Neutron evaporation before scission is not taken into account. This is justified by the fact that even at the highest reaction energies not more than 4 neutrons could be emitted. Hence, considering that the spectrometer resolution is 2-3 u, the neutron emission will not lead to visible effects on the mass-energy distributions. Fragment energy losses in the target, backing, and the start detector foils were taken into account.

The identification of the binary reaction channel with full momentum transfer and the removal of products of sequential and incomplete fission reactions, induced fission of target and targetlike nuclei, or reactions on impurity atoms in the target was based on the analysis of the kinematic diagram (the velocity vectors of two detected reaction products) in the center-of-mass system [5].

3. Analysis and results

4. Bimodal fission of Hs and No

The mass and energy distributions for the induced fission of $^{271,274}\text{Hs}^*$ formed in the reactions $^{22}\text{Ne} + ^{249}\text{Cf}$ and $^{26}\text{Mg} + ^{248}\text{Cm}$ at excitation energies below and above the Coulomb barrier are shown in figure 1.

For the both reactions at energies well above the Coulomb barrier the mass distributions exhibit a near Gaussian shape as predicted by LDM for the fission of relatively hot nuclei. In the framework of the LDM, the average kinetic energy has a parabolic dependence on the fragment mass and practically does not depend on the excitation energy and angular momentum of the compound nucleus. As one can see in figure 1, such behaviour of TKE is confirmed by experimental data.

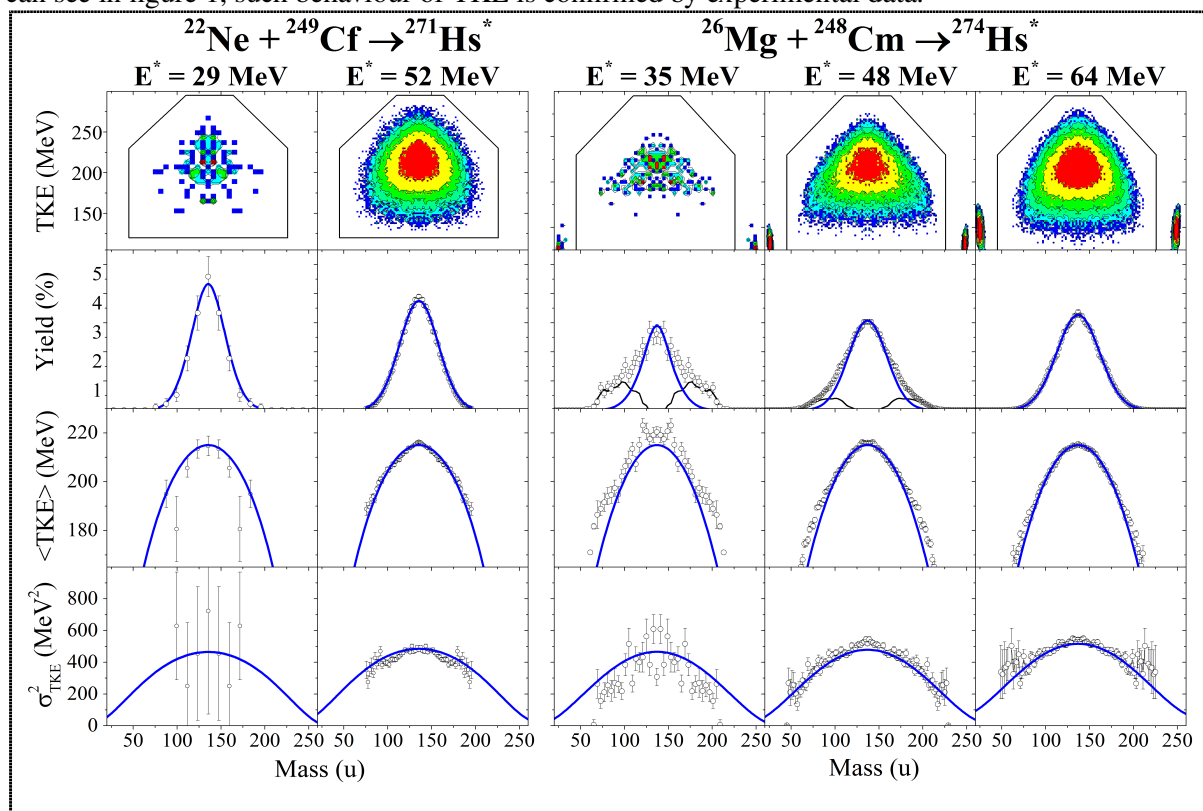


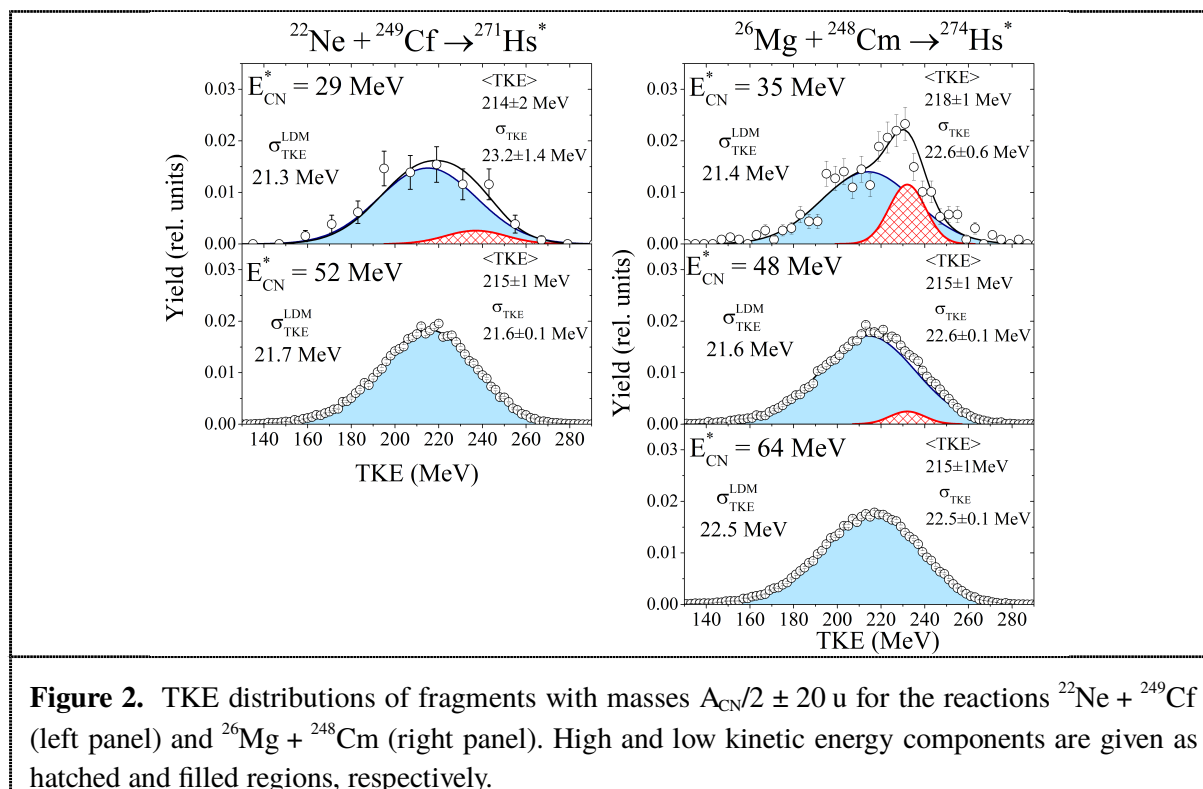
Figure 1. The mass-energy distributions of binary products for the $^{22}\text{Ne} + ^{249}\text{Cf}$ and $^{26}\text{Mg} + ^{248}\text{Cm}$ reactions. From top to bottom: the (TKE, M) matrices for binary products; the mass yields, the average total kinetic energy and its dispersion as a function of mass for fission-like fragments inside the outlined contour on the (TKE, M) matrices.

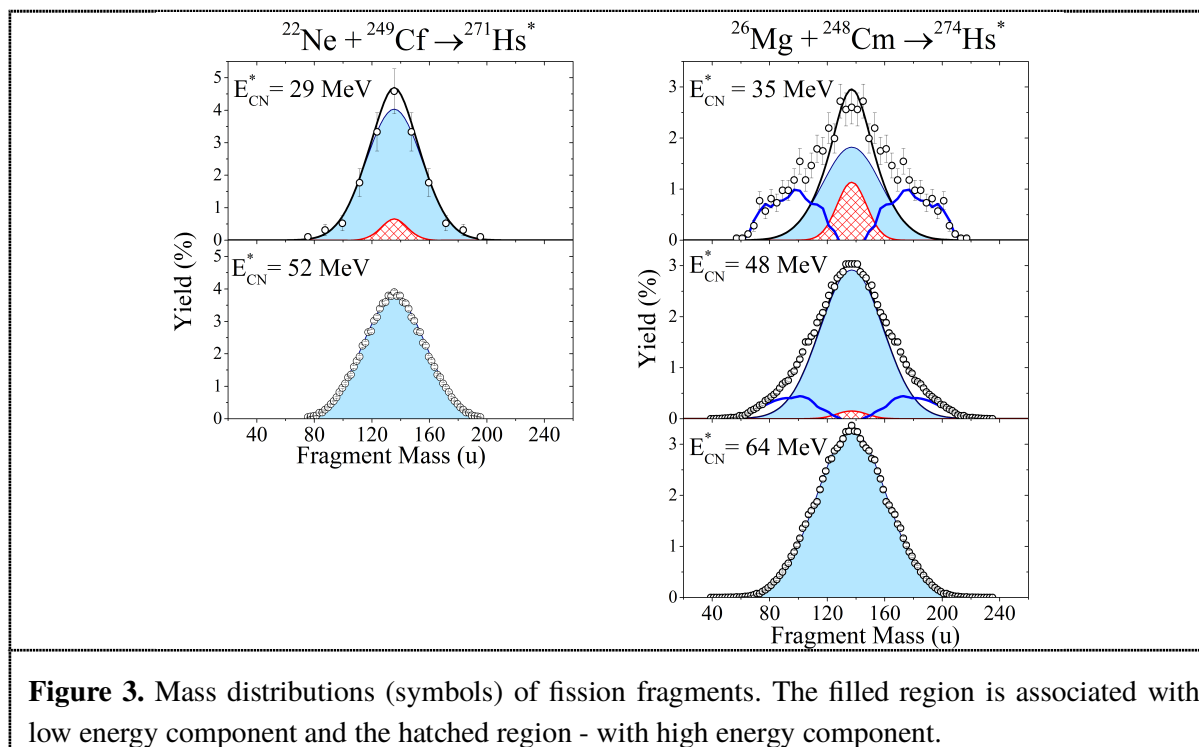
For the $^{26}\text{Mg} + ^{248}\text{Cm}$ reaction at an excitation energy of 35 MeV of the CN, some deviations from LDM predictions are observed for fragments, both symmetric and asymmetric. The increased yields of fragments with masses 70-100 u may be caused by the quasifission process since the interaction energy

is ~ 10 MeV less than the Bass barrier, and the orientation effects on the reaction dynamics become apparent at this energy.

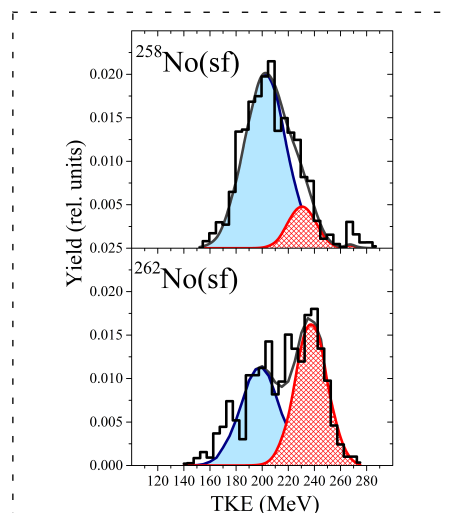
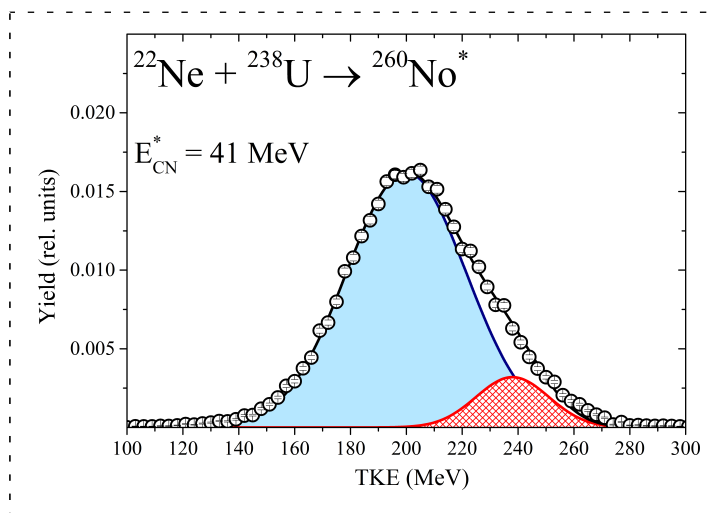
The TKE distributions for symmetric fragments with masses $A_{\text{CN}}/2 \pm 20$ u for both reactions are presented in figure 2. At the highest excitation energy the TKE distributions are well described by single Gaussian with the parameters coming from the LDM, whereas at subbarrier energies the TKE distributions of symmetric fragments have a complex structure. The mean TKEs and the dispersions of TKE are also higher than predicted by LDM. At the same time the mass distributions for both nuclei are symmetric. The structural features of the TKE distributions at low excitation may arise due to the fact that in symmetric fission both fragments are close to the spherical neutron shells with $N = 82$. A similar behaviour could be observed when both fission fragments are close to the spherical proton shell $Z = 50$. Thus the properties of mass and TKE distributions show the characteristic features for bimodal fission.

The TKE distributions of symmetric fragments of the $^{26}\text{Mg} + ^{248}\text{Cm}$ reaction at $E^* = 35$ MeV may be deconvoluted into two Gaussians, the constituent peaks lying near ~ 214 MeV and ~ 230 MeV. The lower energy corresponds to the linear dependency of the TKE on the Coulomb parameter established in the LDM, while the higher energy component is close to those found by Hulet for Fm, Md and No spontaneous fission [3]. Hence, for the reaction Mg + Cm leading to $^{274}\text{Hs}^*$, bimodal fission is observed. It should be noted that when the excitation energy of the compound nucleus is increased the high energy component decreases.





The yields of fission fragments that correspond to compact and elongated fission modes in the mass distribution being described by a Gaussian were weighted using the estimations that we have got from the TKE decomposition (for details see Ref. [6]). The results of this fitting procedure are shown in figure 3.



The TKE distribution of symmetric fragments obtained in the $^{22}\text{Ne} + ^{238}\text{U}$ reaction at an excitation energy of $^{260}\text{No}^*$ of 41 MeV is shown in figure 4. For this reaction the contribution of high energy component is about 7%. In the case of spontaneous fission of ^{258}No and ^{262}No [7] the contributions of high energy component are about 14% and 54%, respectively (see figure 5).

5. Supersymmetric fission of No

For the first time the supersymmetric mode was observed in the compound nuclei fission in Pb region [8]. The enhancement of the mass yield in the region 65-75 u for the light fragment in the fission of ^{213}At and ^{210}Po compound nuclei is connected with the influence of double magic Ni ($Z = 28$, $N = 50$) and double magic Sn ($Z = 50$, $N = 82$). Notice that in this case the ratio $A_H/A_L \approx 2$, and the yield is around 0.01%. The supersymmetric fission mode with mass ratio of $A_H/A_L \approx 2.5$, caused by the closed shells $Z = 28$ and $N = 50$, was also found in thermal-neutron-induced fission of actinides nuclei [9]. In this case only the light fragment is close to the double magic Ni and the yield of supersymmetric mode does not exceed $10^{-4}\%$.

The question about the possibility of supersymmetric fission with mass ratio $A_H/A_L = 208/48 = 4.3$ when both fission fragments are close to the double magic ^{48}Ca and double magic ^{208}Pb arises. Such specific fission channel can be expected in the fission of ^{256}No ($^{48}\text{Ca} + ^{208}\text{Pb}$).

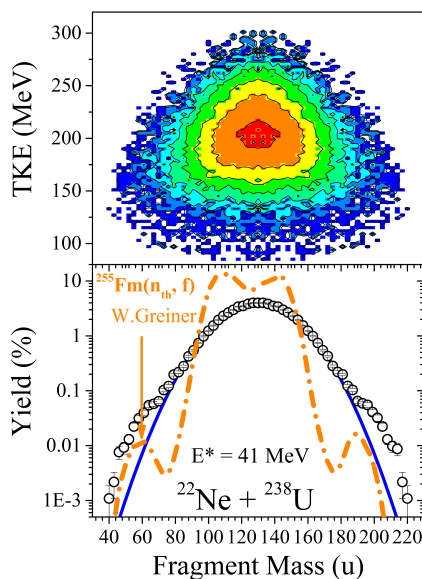


Figure 6. Double differential cross section and mass yield for the $^{22}\text{Ne} + ^{238}\text{U}$ reaction. Thick line represents the LDM calculation, dash-dot line is W. Greiner calculations for $^{255}\text{Fm}(n_{in}, f)$

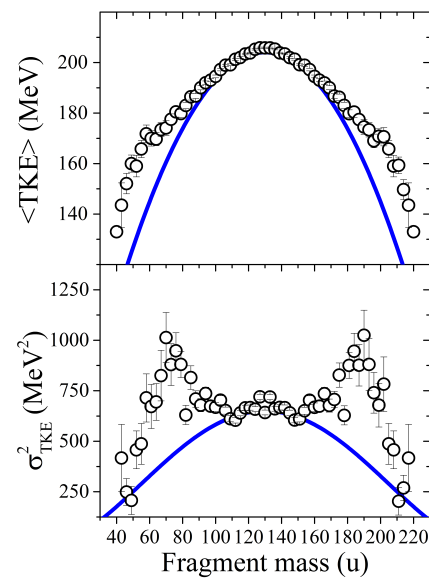


Figure 7. The mean TKE and its' dispersion as a function of fragment mass. The thick lines represent the LDM calculations.

To clarify this question the projectile-target combination $^{22}\text{Ne} + ^{238}\text{U}$ was chosen. The obtained mass and energy distributions of fragments are shown in figures 6 and 7. The mass distribution of the symmetric fragments has a nearly Gaussian shape and the average TKE shows a parabolic dependence on fragment mass typical for fission of excited compound nuclei as established by the LDM, whereas in the mass region around 52/208 u, that corresponds to the formation of fissioning pair of two magic

nuclei Ca/Pb, an increase of fragment yields was observed. Moreover the total kinetic energy for these fragments is found to be about ~30 MeV higher than predicted by the LDM. The higher TKE indicates that the asymmetric fragments originate from more compact scission configuration as compared to normal fission, since the most part of final TKE is due to the Coulomb repulsion between fragments, and the shape elongation of the scission configuration determines the TKE.

In the low panel of figure 6 the experimental mass distribution obtained in the present investigation is compared with the predictions of Walter Greiner for thermal neutrons induced fission of ^{255}Fm . According to this calculation the yield of about $10^{-2}\%$ is expected due to the influence of the closed shells, while for spontaneous fission of ^{255}Fm the yield of $10^{-4}\%$ is expected for this superasymmetric mode [10]. In present work the superasymmetric mode with ratio $A_H/A_L \approx 4.3$ caused by the influence of double magic Ca ($Z = 20$, $N = 28$) and double magic Pb ($Z = 82$, $N = 126$) has been observed in fission of excited $^{260}\text{No}^*$ compound nucleus. At excitation energy of 41 MeV the yield of these fragments is about $5 \times 10^{-2}\%$.

6. Conclusion

The reactions $^{22}\text{Ne} + ^{249}\text{Cf}$, $^{26}\text{Mg} + ^{248}\text{Cm}$, and $^{22}\text{Ne} + ^{238}\text{U}$ have been studied at energies below and above the Coulomb barrier.

For the compound nucleus $^{274}\text{Hs}^*$ formed in the reaction $^{26}\text{Mg} + ^{248}\text{Cm}$ at the initial excitation energy $E^* = 35$ MeV and $^{271}\text{Hs}^*$ formed in the reaction $^{22}\text{Ne} + ^{249}\text{Cf}$ at the initial excitation energy $E^* = 29$ MeV the phenomenon of bimodal fission was observed.

For the compound nucleus $^{260}\text{No}^*$ formed in the reaction $^{22}\text{Ne} + ^{238}\text{U}$ at the initial excitation energy $E^* = 41$ MeV the bimodal fission as well as superasymmetric fission with mass ratio $A_H/A_L \approx 4.3$ were observed for the first time.

7. Acknowledgments

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