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Bimodal fission of ^{270}Sg ($Z=106$) in the sub-barrier fusion of ^{22}Ne and ^{248}Cm

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Mass-energy distributions of the ^{270}Sg ($Z=106$) compound nucleus fission fragments have been studied in the reaction ^{22}Ne+^{248}Cm at two energies of neon projectiles, $E_{lab}(^{22}\mathrm{Ne})=102$ and 127 MeV, with the use of a two-arm time-of-flight spectrometer. The high-energy fission mode has been found at lower energies due to the manifestation of the spherical neutron shell $N\approx 82$ in the fission fragments. [S0556-2813(99)07305-7]

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The problem of symmetric and asymmetric fission modes in the mass distribution of fission fragments in low-energy nuclear fission arose immediately after the reaction itself was discovered. Today it is well established that at low excitation energies the asymmetric fission mode is observed in the mass-energy distribution (MED) of fission fragments for all nuclei with $A>200$ without exception. In the case of pre-actinide nuclei, the symmetric mode corresponding to the liquid drop model prevails, whereas the contribution of the asymmetric component does not exceed 0.5% [1]. For the nuclei in the region of Ra and Ac [2,3] and light isotopes of Th [3,4] a three-humped mass distribution with a comparable contribution of both components is characteristic at low excitation energies. For the actinide nuclei with $Z=90$–100 and $A=232$–256 the asymmetric mode prevails at spontaneous as well as at induced fission at excitation energies of up to 30–40 MeV [5,6].

The situation is fundamentally different with the nuclei in the fermium region and heavier ones. Although the two-humped distribution of fission fragments with different peak/valley ratios [7] is characteristic of the spontaneous fission of light fermium isotopes $^{246-257}$Fm, as is the case with all actinides, the anomalously ''narrow'' symmetric mass distributions with the high total kinetic energy (TKE) of fission fragments of about 235 MeV [8] is observed for the cases of ^{258,259}Fm and ^{259,260}Md. At the same time, the component with a large width and medium TKE≈200 MeV, characteristic of the asymmetric fission of these nuclei, is present in the mass distributions in the form of a pediment. Such properties of the nuclear fission in the Fm region have been defined as bimodality of the MED of fission fragments [8].

The above variety of the properties of the fission fragment MED, observed in the low-energy or spontaneous fission of nuclei with $A>200$, has been understood qualitatively and in some cases quantitatively, including the anomaly of fermium properties. It has become possible due to employing a new theoretical concept of multimodal nuclear fission, the foundation of which is the notion of the valley structure of the potential energy surface in the multidimensional space of the fissioning nucleus deformations [9–13]. Proceeding from this concept the authors of numerous publications (see, for example, the review in [6]) connect the observed MED characteristics with the quantity and properties of the fission valleys at the potential energy surface calculated for a specific nucleus. Four main fission modes have been distinguished in theoretical calculations as well as experimentally. In accordance with [13], the modes are as follows: superlong, the symmetric mode *S*; standard I mode, the mode connected with the fission valley where the formation of fission fragments close to the doubly magic ones with $A=132$ ($Z=50, N=82$) takes place; standard II mode, the mode connected with formation of a deformed shell near $A\approx 140$ ($Z\approx 54$–$56, N\approx 86$) and also in the heavy fission fragment; the supershort mode, manifesting itself only when light and heavy fission fragments are close in their nucleon composition to the doubly magic tin with $A\approx 132$. As the experiments showed [8] this situation is realized only in the case of the heaviest nuclei starting from ^{258}Fm.

The latest studies of the properties of the ^{262}Rf ($Z=104$) spontaneous fission [14] demonstrate that bimodality is observed also for this nucleus, and when it undergoes fission into two equal parts the fission fragments already contain 52 protons and 79 neutrons.

The MED of $^{252-257}$Fm and ^{258}Md fission fragments at medium excitation energies ($E^*\approx 18$ MeV) has been studied in Ref. [15]. It has been shown there that the complex structure of the fission fragment MED is observed, though less distinctly, at these excitation energies too.

When the excitation energy of superheavy nuclei reaches the value $E^*>50$ MeV, the fission fragment MED becomes closer to the liquid drop distribution in regard to the properties, and no structure peculiarities are observed [16].

This paper presents results of the fission fragment MED obtained in the study of the fission of the compound nucleus ^{270}Sg ($Z=106$) formed in the fusion reaction ^{22}Ne+^{248}Cm at neon energies of 102 and 127 MeV which leads to initial excitation energies of the compound nucleus of $E^*=28$ and 50 MeV, respectively. The Coulomb barrier in the laboratory system calculated according to the Bass model [17] is $B_{\mathrm{Bass}}=117$ MeV. The lower projectile energy of 102 MeV at which we performed the measurements is 15 MeV below the Bass barrier. Similarly, the fission cross section goes down with the fusion cross section by 1.5×10^3 times, as compared with the case of 127 MeV projectiles, which are 10 MeV above the Bass barrier.

The choice of the above-mentioned reactions is based upon three reasons.

First, traditional ways of studying the properties of superheavy elements, i.e., studying the spontaneous fission of nuclei with $Z=105$, 106, and up, have evidently exhausted themselves since the accumulation of a large number of nuclei of these elements and subsequent investigation of their fission present practically an untractable experimental task. That is why an investigation of the MED of superheavy element fission fragments using the sub-barrier fusion-fission reactions in which low excitation energies can be available is in our opinion the most acceptable and promising tool.

Second, the nucleus ^{270}Sg chosen by us for the investigations has 164 neutrons and as it undergoes fission into two equal parts the number of neutrons in both fission fragments is the magic number 82 (without taking into account the prescission neutrons ν_{pre}).

In the third place, the nuclei ^{22}Ne and ^{248}Cm are deformed in the ground states which must lead to a higher fusion cross section below the Coulomb barrier which is necessary for reaching the lower excitation energies at which the shell effects responsible for the fission modes are important.

The experiment was carried out at the U-400 accelerator of the Flerov Laboratory in Dubna using the extracted beam. A layer of ^{248}Cm, 170 μg/cm^2 in thickness, was put on a carbon backing and used as a target. Fission fragments coincident in time were registered by a two-arm time-of-flight spectrometer CORSET [18], each arm of which consisted of a start detector composed of microchannel plates with an electrostatic mirror and two position-sensitive (x,y-sensitive) stop detectors, also of microchannel plates of 6×4 cm^2 each. The start detectors were located at a distance of 3 cm from the target. The minimal start-stop flight path was 12 cm. Thus, the spectrometer consisted of two start and four stop detectors and registered events within a solid angle of 360 msr. The position resolution of the stop detectors was $\pm0.1°$. The mass resolution was estimated as 3–5 amu. Figure 1 presents the mass yields and TKE measured by us immediately before the experiment for the spontaneous fission of ^{252}Cf in relation to the mass of the heavy fission fragment. For comparison we also show here the results from the classical work by Schmitt *et al.* [19], in which the MED of the ^{252}Cf fission fragments was studied with the help of semiconductor surface barrier detectors (SSBD's). The data from [19] are shown by the dotted and solid curves corresponding to the MED after neutron emission and the MED corrected to the neutron emission. The width of our mass distributions of ^{252}Cf fission fragments we measured is somewhat wider than that in [19]. However, we attribute it to inhomogeneities in the ^{252}Cf spontaneous fission source. On the whole, all the mass distributions obtained by us repeat the structural peculiarities of the MED from [19], the peak/valley ratio being >20. Thus, we established that the mass and energy resolution of our spectrometer is not lower than that of the SSBD's.

In the experiments with the ^{22}Ne ion beam, the arms of the spectrometer were positioned so that registration of the fission fragment mass and energy was possible up to the ratio $M_H/M_L=5$. The edge of the spectrometer could ''see'' some small part of the time-coincident correlated spontaneous fission fragments from the ^{248}Cm target. However, as a result of the high position resolution of the stop detectors, these events were unambiguously separated from the events of the ^{270}Sg compound nucleus fission.

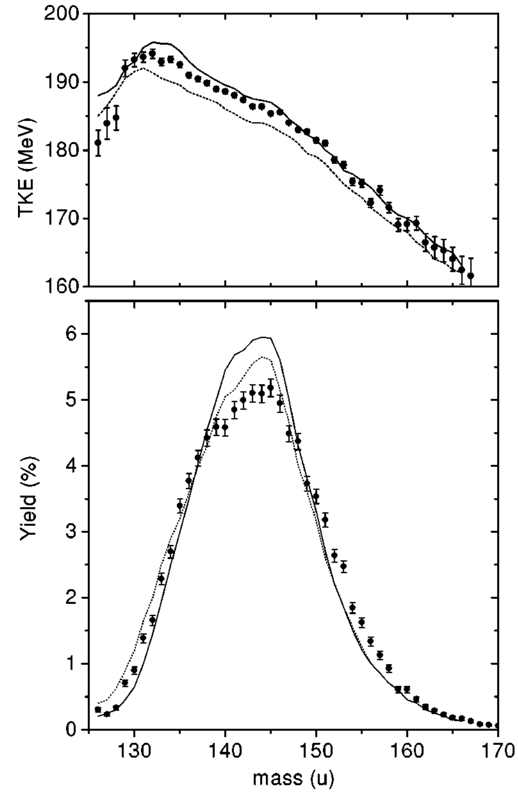

FIG. 1. Mass yields and average TKE in relation to the mass of the heavy fission fragment for the spontaneous fission of ^{252}Cf, measured on the CORSET spectrometer. The results from the work by Schmitt *et al.* [19] are shown by dotted and solid curves corresponding to the final and corrected to the neutron emission MED.

The processing of the data was performed in a standard way [20,21] due to the two-body nature of the process. Special attention was paid to the angular folding correlations in the plane of the reaction as well as outside. Only those of the registered events were chosen and analyzed which corresponded to the two-body nature of the process with complete impulse transfer. Fission events from the incomplete fusion—sequential fission—were rejected. The fission fragment energy losses in the target layer, backing, and emitter of the start detectors were taken into account when processing the data. Since the geometrical dimensions of the spectrometer did not allow registration of the whole set of the fission fragment energy and mass ratios with an equal probability, some corrections to the geometrical efficiency of the spectrometer were introduced by us. These corrections were small and did not exceed 5%.

The measured MED's of ^{270}Sg fission fragments are shown in Fig. 2 for two energies of the ^{22}Ne projectiles. At 127 MeV, 9.2×10^5 fission events were registered and 1.2×10^4 events at 102 MeV. Two-dimensional matrices of the fission fragments (mass, TKE) are shown in Figs. 2(a) and 2(b). At high energies [Fig. 2(b)], we observe a triangular distribution with rounded slopes typical for rather strongly heated nuclei. This distribution is close in its properties to the predictions of the liquid drop model [22] or the diffusion model [23]. For 102 MeV [Fig. 2(a)], E^* is equal to 28

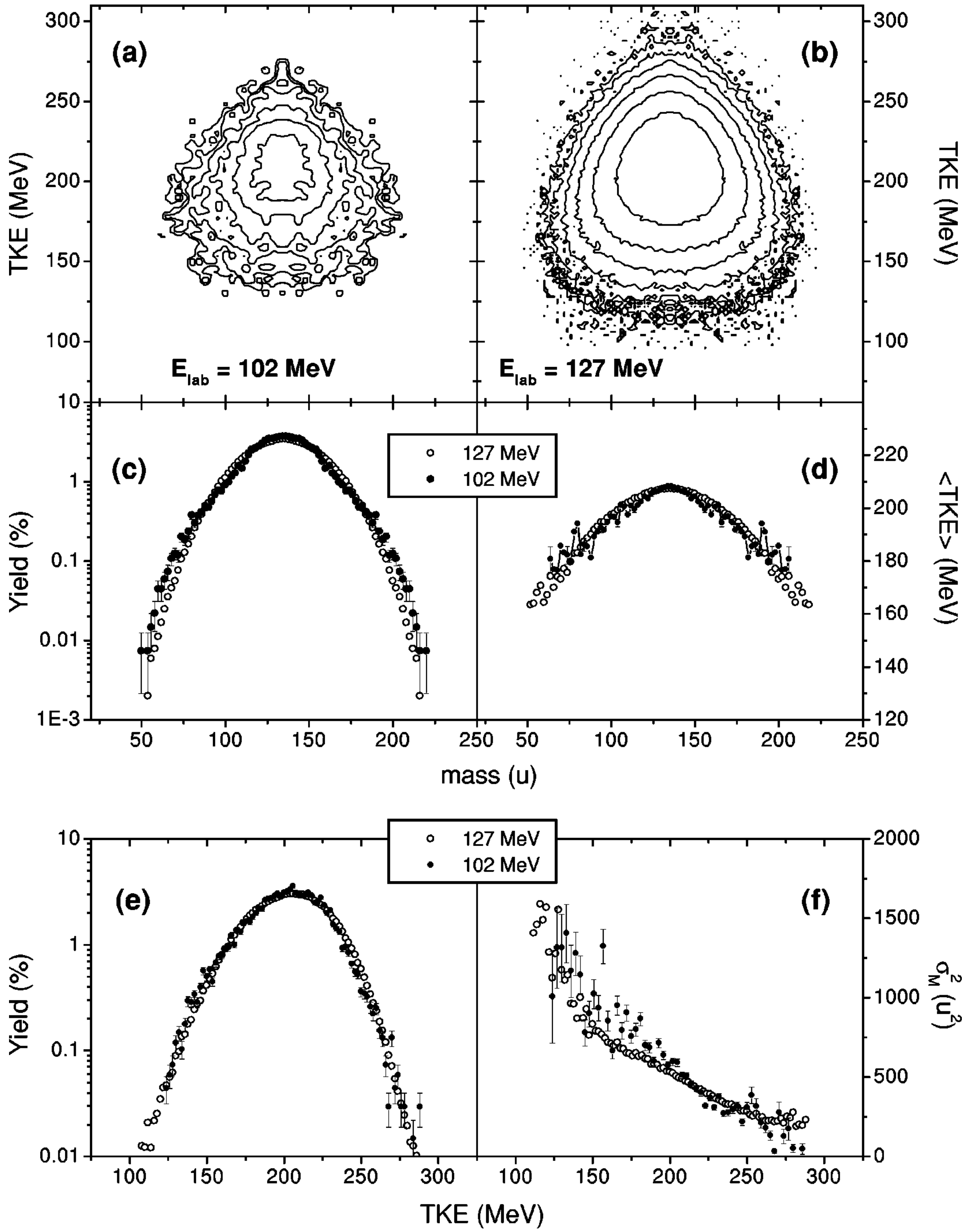

FIG. 2. Mass-energy distributions of ^{270}Sg ($Z=106$) fission fragments for the ^{22}Ne projectiles energies of 102 and 127 MeV.

MeV, and the two-dimensional matrix differs from that described above in its shape, having a sharp peak and extensions in the direction of the higher TKE. Figure 2(c) compares the fission fragment mass distributions (the yield is normalized to 200%) for the two energies. It is clearly seen that at the lower energy, as distinguished from the higher energy, the mass distribution does not have a Gaussian shape and can be interpreted as a manifestation of different fission modes. One mode is rather narrow, near $A_{CN}/2$, the other one rather wide, for the asymmetric masses. The latter is so wide that the mass yields at its slopes turn out to be higher than those for the high excitation energy. It is only possible if in the nuclear cooling process the shell effects manifest themselves in the region of the fission fragment masses 200–210, i.e., near the mass of the doubly magic lead 208. The interpretation of this phenomenon can be twofold. First: the latest theoretical calculations of the potential energy surface for the lighter ^{252}Cf predict the existence of the ''lead'' fission valley [24] located high in energy. It cannot be observed experimentally in the spontaneous fission of ^{252}Cf due to this. It is also predicted for the heavy nuclei with $Z=114$ and 120 [25]. The existence of the valley for ^{270}Sg is quite probable since the light fragment becomes closer to the magic one with $Z=28$.

For a noticeable population of the valley, the nucleus should be sufficiently excited, however not so strongly as to make the shell effects disappear as is the case at $E_{lab}=127$ MeV. A similar effect was observed for the other fission modes in work [15] in which ^{256}Fm(s,f) and ^{255}Fm(n_{th},f) were used as examples, or ^{213}At in [1].

Another interpretation of the increased yield in the region of the fission fragment masses $A=200$ for the low excitation energy may be connected with manifestation of the quasifission component, which seems to be more probable from our point of view. Quasifission characteristics have been studied in works [21,26] and discussed in [27]. It has been shown in [26], employing the reaction ^{238}U+^{27}Al, that when the U projectile energies are close to the Coulomb barrier some ''shoulders'' appear at the slopes of the prevailing symmetric fission, which corresponds to the increased yield of the reaction products in the mass region 200–210, i.e., the region of the magic lead. They are connected with the nonequilibrium quasifission component and can be clearly distinguished in the mass-angle correlations. An investigation of angular distributions was not the aim of the present work, and our spectrometer did not accept a very wide range of angles. Thus we cannot interpret with much certainty the increased yield of fission fragments in this region of masses. The TKE(M) distributions shown in Fig. 2(d) do not clarify the situation. For the mass region of ~ 200, although the measurement errors are quite serious, the TKE is higher for the lower energy than for the higher energy. However, this effect can be explained by the manifestation of the lead fission mode, since for the fragments in the region of spherical closed shells the TKE must be higher. The higher TKE is also characteristic of quasifission [24]. That is why the question concerning the character of this component's formation—equilibrium or nonequilibrium—is still open. Some more experiments are in order at even lower projectile energies as well as measurements of the mass-angular correlations.

The above discussion concerns very heavy masses $m \approx 200–210$ and their complementary masses. However, the break in the mass distributions [see Fig. 2(c)], connected with the transition from the narrow to the wide distribution, takes place near the heavy fragment mass $m \approx 160$ and cannot be explained either by the lead valley or quasifission. Some other fission modes are ushered in here. In our opinion, the narrow symmetric component is connected with the manifestation of the spherical neutron shell with $N=82$ in both fragments. Spontaneously fissioning heavy nuclei never have as many as 164 neutrons in the nucleus, and upon approaching this number, starting from $N=157–158$ in the Fm nuclei, some drastic changes occur in the mass-energy yields, and the high-energy narrow supershort mode appears as a result [8,14]. It also occurs with the Rf nuclei, though not so distinctly, at the neutron number transition from 156 to 158, but the contribution of the supershort mode into the total distribution turns out to be less than in the case of ^{258}Fm. It is explained by the nonmagic nature of the proton composition of ^{262}Rf fission fragments in strictly symmetric fission.

In the case of ^{270}Sg, a strong manifestation of the high-energy mode can hardly be expected due to excitation of the nucleus up to 28 MeV. However, one should not forget that according to estimations from different systematics [27–29], 0.5–0.7 prescission neutrons ν_{pre} can be emitted before fission, and the real excitation energy in the scission point is 4–6 MeV lower than in the case without neutron emission.

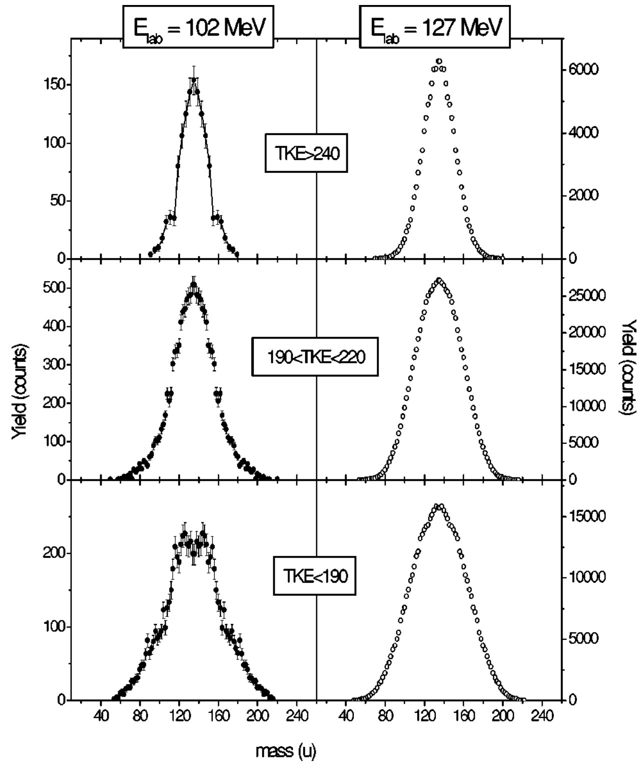

FIG. 3. ^{270}Sg ($Z=106$) fission fragment mass distributions for specific TKE ranges.

The remaining excitation of the fissioning nucleus turns out to be insufficient to cause the shell effects to disappear.

Comparison of the ^{270}Sg fission fragments characteristics for two excitation energies shows that the average TKE hardly changes; however, the form of the TKE(M) dependence does change. In Fig. 2(d) it is illustrated by a more sloping curve for symmetric masses. In Fig. 2(e) where the Y(TKE) yields are compared one can very well see that at lower excitation energies in the TKE range of 220–240 MeV the yields are lower and the distribution is narrower than those for the high excitation. In the TKE range of >250 MeV the open circles practically coincide with the solid ones, thus creating a high-energy ''shoulder'' on the yield slope. We estimate the average TKE for the high-energy mode as ~ 240 MeV which is in good agreement with other data [8,14].

Figure 2(f) shows dependence of the fission fragment mass dispersion σ_M^2 on the TKE. For the lower energy, the decrease in the value of this characteristic with increasing TKE is sharp, approaching zero at the highest TKE, which suggests very narrow fission fragment mass distributions for this TKE range.

Figure 3 shows fission fragment mass distributions for specific TKE ranges. For $E_{lab}=102$ MeV and TKE >240 MeV, the sum of the two fission modes, the sharply narrow and the wide ones, is clearly seen.

We have discussed the nature of the high-energy component; now let us dwell on the wide mode. Evidently its properties are close to those of standard II, but at the same time it has its own specific features. As mentioned earlier, this mode is connected with the manifestation of the deformed shell with $Z=56$. Then in the case of Sg fission the light fragment will have $Z=50$, i.e., the magic proton number. Suppose that

N and Z in the fission fragments are distributed in proportion to their masses; then the light fragment with $Z=50$ will have $N=77$ and mass $M=127$. Shown in Fig. 3 (lower panel) for $E_{lab}=102$ MeV and TKE$<$190 MeV, at the top of the distribution curve there appears a two-hump formation, and the light fragment peak corresponds to the mass $M=126$. We must admit though that the statistics are not sufficient and errors are large, but what we observe may be a manifestation of this mode.

In the same figure, at TKE$<$190 MeV there is also a wide low-energy pediment that is most probably connected with the fission mode characteristic of the heated nucleus and its properties resemble the liquid drop model.

All the above-mentioned conclusions certainly require further careful analysis since on the whole the observed phenomena are not very distinct and they only start to manifest themselves at lower excitation energies.

Thus, it has been experimentally shown that at medium excitation energies the MED of ^{270}Sg ($Z=106$) fission fragments is of multimodal character. In the total distribution of the fission fragment masses at $E_{lab}(^{22}\text{Ne})=102$ MeV, a narrow symmetric mode has been found that is connected with the manifestation of the magic neutron number $N=82$. The wide structure of the distribution pediment is possibly also bimodal. We can state that the investigation of fission of superheavy nuclei, deep under the Coulomb barrier at very low excitation energies, provides abundant information on the properties of the fission process.

[1] M. G. Itkis, V. N. Okolovich, A. Ya. Rusanov, and G. N. Smirenkin, Z. Phys. A **320**, 433 (1985); Sov. J. Part. Nucl. **19**, 301 (1988); Nucl. Phys. **A502**, 243c (1989).

[2] H. C. Britt, H. E. Wegner, and J. C. Gursky, Phys. Rev. **129**, 2239 (1963); H. J. Specht, Nukleonika **20**, 717 (1975); Rev. Mod. Phys. **46**, 733 (1974); E. Konechy and H. W. Schmitt, Phys. Rev. **172**, 1213 (1968).

[3] M. G. Itkis, Yu. Ts. Oganessian, G. G. Chubarian, V. S. Salamatin, A. Ya. Rusanov, and V. N. Okolovich, in *Proceedings of the XV EPS Conference LEND-95*, St. Petersburg, Russia, 1995, edited by Yu. Ts. Oganessian (World Scientific, Singapore, 1995), p. 177; Nucl. Phys. A (to be published).

[4] K.-H. Schmidt *et al.*, Nucl. Phys. **A630**, 208c (1998).

[5] R. Vandenbosch and J. R. Huizenga, *Nuclear Fission* (Academic Press, New York, 1973).

[6] F. Gonnenwein, in *Nuclear Fission Process*, edited by C. Wagemans (CRC Press, Boca Raton, 1991), p. 287.

[7] D. Hoffman, in *Proceedings of the 4th International Symposium on Phys. Chem. Fission*, Julich, Germany, 1979 (IAEA, Vienna, 1980), Vol. 2, p. 275.

[8] E. K. Hulet *et al.*, Phys. Rev. Lett. **56**, 313 (1986); Phys. Rev. C **40**, 770 (1989).

[9] V. V. Pashkevich, Nucl. Phys. **A169**, 275 (1971); Itkis *et al.* [3], p. 161.

[10] V. V. Pashkevich, Nucl. Phys. **A477**, 1 (1988).

[11] P. Möller, J. R. Nix, and W. J. Swiatecki, Nucl. Phys. **A469**, 1 (1987); **A492**, 349 (1989).

[12] S. Cwiok, P. Rozmej, A. Sobiczewski, and Z. Patik, Nucl. Phys. **A491**, 281 (1989).

[13] U. Brosa, S. Grossmann, and A. Müller, Phys. Rep. **197**, 167 (1990).

[14] M. R. Lane *et al.*, Phys. Rev. C **53**, 2893 (1996).

[15] H. C. Britt, D. C. Hoffman, J. van der Plicht, J. B. Wilhelmy, E. Cheifetz, R. J. Dupzyk, and R. W. Lougheet, Phys. Rev. C **30**, 559 (1984).

[16] M. G. Itkis, S. M. Lukyanov, V. N. Okolovich, A. Ya. Rusanov, V. S. Salamatin, and G. G. Chubarian, Sov. J. Nucl. Phys. **52**, 15 (1990); R. Ferguson, F. Plasil, H. Freisleben, C. E. Bemis, and H. W. Schmitt, Phys. Rev. C **8**, 1104 (1973).

[17] R. Bass, Nucl. Phys. **A231**, 45 (1974).

[18] E. M. Kozulin, N. A. Kondratjev, and I. V. Pokrovski, ''Heavy Ion Physics,'' JINR FLNR Scientific Report, 1995–1996, p. 215; N. A. Kondratiev, E. M. Kozulin, I. V. Pokrovski, and E. V. Prokhorova, in *Proceedings of the Fourth International Conference on Dynamical Aspects of Nuclear Fission*, Časta-Papiernička, Slovak Republic, 1998 (World Scientific, Singapore, 1999).

[19] H. W. Schmitt, J. H. Neiler, and F. G. Walter, Phys. Rev. **141**, 1146 (1966).

[20] G. G. Chubaryan, M. G. Itkis, S. M. Lukyanov, V. N. Okolovich, Yu. E. Penionzhkevich, V. S. Salamatin, A. Ya. Rusanov, and G. N. Smirenkin, Phys. At. Nucl. **56**, 286 (1993).

[21] J. Töke *et al.*, Nucl. Phys. **A440**, 327 (1985).

[22] J. R. Nix and W. J. Swiatecki, Nucl. Phys. **71**, 1 (1965).

[23] G. D. Adeev, I. I. Gonchar, V. V. Pashkevich, N. I. Pischasov, and O. I. Serdyuk, Sov. J. Part. Nucl. **19**, 529 (1988); Nucl. Phys. **A502**, 405c (1989).

[24] Yu. V. Pyatkov, V. V. Pashkevich, Yu. E. Penionzhkevich, V. G. Tishchenko, A. V. Unzhakova, H.-G. Ortlepp, P. Gippner, C.-H. Herbach, and W. Wagner, Nucl. Phys. **A624**, 140 (1997).

[25] R. A. Cherghescu, D. N. Poenary, and W. Greiner, J. Phys. G **23**, 1715 (1997).

[26] W. Q. Shen *et al.*, Phys. Rev. C **36**, 115 (1987); B. B. Back, S. Bjørnholm, T. Døssing, W. Q. Shen, K. D. Hildenbrand, A. Gobbi, and S. P. Sørensen, *ibid.* **41**, 1495 (1990).

[27] M. G. Itkis and A. Ya. Rusanov, Phys. Part. Nuclei **29**, 160 (1998).

[28] E. M. Kozulin, A. Ya. Rusanov, and G. N. Smirenkin, Phys. At. Nucl. **56**, 166 (1993).

[29] D. Hilscher and H. Rossner, Ann. Phys. (Paris) **17**, 471 (1992).