Fission and cluster decay of the ^{76}Sr nucleus in the ground state and formed in heavy-ion reactions

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(Received 8 April 1997)

Calculations for fission and cluster decay of ^{76}Sr are presented for this nucleus to be in its ground state or formed as an excited compound system in heavy-ion reactions. The predicted mass distribution, for the dynamical collective mass transfer process assumed for fission of ^{76}Sr, is clearly asymmetric, favoring α nuclei. Cluster decay is studied within a preformed cluster model, both for ground-state to ground-state decays and from excited compound system to the ground state(s) or excited states(s) of the fragments. [S0556-2813(97)04211-8]

PACS number(s): 25.70.Jj, 23.70.+j, 24.60.Dr, 27.50.+e

$^{76}_{38}$Sr is a superdeformed nucleus with an estimated quadrupole deformation $\beta_2=0.44$ (see Fig. 1 in [1]). From the point of view of known *spherical* shell closures at $Z=N=40$, such a large ground-state deformation for ^{76}Sr means the natural breaking of these spherical shells and hence nuclear instability against both fission and exotic cluster decay processes. However, we shall see in the following that, like the other superdeformed nuclei in this mass region [1], although this nucleus is naturally stable (negative Q value) against only light clusters with masses $A_2<12$, the calculated cluster decay half-lives for $A_2\geqslant 12$ are also large enough ($T_{1/2}>10^{80}$ s) to term this nucleus as a stable nucleus against all cluster decays. This kind of stability could apparently be due to stable *deformed* shell closures at $Z=N=38$, predicted earlier in many other calculations [2,3]. Alternatively, if these nuclei are prepared in heavy-ion collisions, then, depending on the excitation energy of the compound nucleus formed, both fission (also called fusion-fission) and cluster decay are the viable processes. The present day experiments are directed at these studies (see, e.g., [4–7] and earlier references therein).

It now seems accepted that compound systems with $A\leqslant 42$ are characterized by nuclear orbiting phenomenon (the deep inelastic process), although a considerable amount of yield due to fusion-fission could not be ruled here too [8,9]. On the other hand, the systems with $A\approx 47-60$ are strongly the cases of fusion-fission processes (fully-energy-damped fragments) since for all cases studied so far the observed yields are independent of nuclei in the entrance channel and no strong peaking of yields is observed near the target and projectile masses [4–7]. In all these cases, asymmetric mass splitting is favored and hence lie far below the Businaro-Gallone transition point [10] [the fissility parameter x ($=Z^2/50A$) is less than the $x_{\rm BG}=0.396$ for $l=0$ and this value decreases as the l value increases]. For nuclei with $A\sim 80$, the situation is not so clear. Only three experiments are made [11,12] that form the compound systems $^{78}_{38}$Sr, $^{80}_{40}$Zr, and $^{83}_{36}$Kr, and one calculation is available for ^{80}Zr [13]. Notice that fissility $x=0.370$ and 0.312 ($<x_{\rm BG}$), respectively, for ^{78}Sr and ^{83}Kr, but $x=0.40$ ($>x_{\rm BG}$) for ^{80}Zr. Also, at least ^{78}Sr and ^{80}Zr are superdeformed in their respective ground states. The interesting result is, whereas the measured mass spectra of ^{83}Kr [11] and ^{80}Zr [12] are clearly asymmetric and symmetric, as expected, respectively, that of ^{78}Sr [12] is more asymmetric than symmetric. The last experiment on ^{28}Si+^{50}Cr forming the compound system ^{78}Sr* is made only at one energy ($E_{\rm lab}=150$ MeV) and at one angle ($\theta_{\rm lab}=30°$). In view of this result, we have chosen the ^{76}Sr nucleus with x ($=0.38$) as well as deformation β larger than that for ^{78}Sr (estimated $\beta_2=0.41$ for ^{78}Sr). Such a study has not yet been taken up either experimentally or theoretically. Our calculations in the following show a clear asymmetric mass distribution, as expected from the point of view of Businaro-Gallone transition [10]. This result suggests that a properly-angle-intergrated mass distribution for ^{78}Sr (not yet measured) should also be clearly asymmetric since fissility x for ^{78}Sr is smaller than that for ^{76}Sr.

Theoretically, both the quantum mechanical fragmentation process [13–16] as well as the statistical models [8,11,17–19] have been used to explain the measured mass distributions in these reactions. The statistical or compound nucleus model calculations, assuming fusion-fission processes, are made for three possible cases of (i) two spheres separated by a fixed distance $d=2$ fm [11], (ii) saddle point shapes, called the transition state model [8], and (iii) scission point shapes with d taken as a variable [17–19]. In this last case, the Hauser-Feshbach formalism [20] is extended to include the decay fragments heavier than the α particle. Perhaps, the preformation factor for different fragments should also be added to this extended Hauser-Feshbach method (EHFM). In a statistical model all open decay channels are taken to be equally populated. This is true as long as one is talking of γ decay and the light particle evaporation of n, p, and α particles. However, once the heavy fragments are also included, the α particle is known to compete with some heavy fragments (the exotic cluster decays) and, hence, a preformation probability factor between α and the other heavy fragments should come in.

In this paper, we use quantum mechanical fragmentation theory (QMFT) [13–16] and the cluster decay model [1,21,22] based on QMFT. According to QMFT, the binary fragmentation is a collective mass transfer process where

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both light and heavy fragments (including the light particles) are produced with different quantum mechanical probabilities. Applications of both the fragmentation and cluster decay processes are made in only a few cases for the light systems [13–16], and in fact it was on the basis of this theory that fusion-fission was first proposed by Gupta and collaborators in 1984 as the possible explanation of the observed data on fragmentation of light systems.

In QMFT, a dynamical collective coordinate of mass (and charge) asymmetry $\eta=(A_1-A_2)/(A_1+A_2)$ [and $\eta_Z=(Z_1-Z_2)/(Z_1+Z_2)$] is introduced whose limiting values are 0 and 1, i.e., $0\leqslant\eta\leqslant 1$ [14,23–27]. Since the potentials $V(R,\eta)$ and $V(R,\eta_Z)$, calculated within the Strutinsky renormalization procedure ($V=V_{\rm LDM}+\delta U$) by using the appropriate liquid drop model (for $V_{\rm LDM}$) and the asymmetric two-center shell model (for δU), are nearly independent of the relative separation coordinate R, R can be taken as a time-independent parameter and hence solve the stationary (instead of time-dependent) Schrödinger equation in η:

$$\left\{-\frac{\hbar^2}{2\sqrt{B}_{\eta\eta}}\frac{\partial}{\partial\eta}\frac{1}{\sqrt{B}_{\eta\eta}}\frac{\partial}{\partial\eta}+V_R(\eta)\right\}\psi_R^{(\nu)}(\eta)=E_R^{(\nu)}\psi_R^{(\nu)}(\eta). \tag{1}$$

The R value for light nuclei is fixed at the touching configuration of two nuclei [13–16]:

$$R=C_1+C_2, \tag{2a}$$

with the Süsmann central radii

$$C_i=R_i-\frac{1}{R_i}, \tag{2b}$$

$$R_i=1.28A_i^{1/3}-0.76+0.8A_i^{-1/3}. \tag{2c}$$

In this approximation, the fragmentation potential

$$V(\eta)=-B_1(A_1,Z_1)-B_2(A_2,Z_2)+E_c+V_P, \tag{3}$$

where $B_i(A_i,Z_i)$ are the experimental binding energies [28], $E_c=Z_1Z_2e^2/R$ and V_P is the additional attraction due to nuclear proximity potential, given by the well-known pocket formula of Blocki *et al.* [29]. The charges Z_i in Eq. (3) are fixed by minimizing $V(\eta_Z)$, defined by Eq. (3) without V_P, in η_Z coordinate. The rotational energy due to angular momentum (V_l) is not added here since its contribution to the structure of yields is shown to be small for lighter systems [15]. Of course, V_l should be added for a comparison of the relative yields. It may be mentioned here that in a more realistic calculation, the two-center nuclear shape should be used, instead of Eq. (2). One can then trace the actual nuclear shapes involved. For a more quantitative comparison, perhaps $R=C_1+C_2+d$ ($\leqslant$2 fm) would be a better choice because then one is closer to the saddle shape.

The numerical solution of Eq. (1), on proper scaling, gives the fractional mass distribution yields for each fragment as

$$Y(A_i)=|\psi_R(\eta(A_i))|^2\sqrt{B_{\eta\eta}}\,\frac{2}{A} \tag{4}$$

($i=1$ or 2). For the mass parameters $B_{\eta\eta}$ we use the classical hydrodynamical model of Kröger and Scheid [30]. For two touching spheres, this model gives a simple analytical expression

$$B_{\eta\eta}=\frac{AmR_t^2}{4}\left(\frac{v_t(1+\beta)}{v_c}-1\right), \tag{5a}$$

with

$$\beta=\frac{R_c}{4R_t}\left(2-\frac{R_c}{R_1}-\frac{R_c}{R_2}\right), \tag{5b}$$

$$v_c=\pi R_c^2R_t,\quad R_c=0.4R_2, \tag{5c}$$

and $v_t=v_1+v_2$, the total conserved volume. Also, $R_2\ll R_1$ and R_c ($\neq 0$) is the radius of a cylinder of length R_t, whose existence allows a homogeneous, radial flow of mass between the two fragments. Here m is the nucleon mass.

The nuclear temperature effects in Eq. (4) are also included through a Boltzmann-like function

$$|\psi_R|^2=\sum_{\nu=0}^{\infty}|\psi_R^{(\nu)}|^2\exp(-E_R^{(\nu)}/\theta), \tag{6}$$

with θ the nuclear temperature in MeV, related to the excitation energy as

$$E^*=\tfrac{1}{9}A\theta^2-\theta. \tag{7}$$

Furthermore, in some of the calculations here, temperature effects are taken to act also on the shell effects as follows [31]:

$$V=-\sum_{i=1}^{2}\left[V_{\rm LDM}(A_i,Z_i)+\delta U_i\exp(-\theta^2/2.25)\right]+E_c+V_P. \tag{8}$$

Similarly, mass parameters should also vary with temperature, but no usable prescription is available to date. A constant average mass is taken to mean a complete washing of shell effects in it.

For cluster-decay calculations, we use the preformed cluster model (PCM) of Malik and Gupta [21,22]. This model, based on QMFT, also uses the decoupled approximation to R and η motions and defines the decay half-life $T_{1/2}$ or the decay constant λ as

$$\lambda=\frac{\ln 2}{T_{1/2}}=P_0\nu P. \tag{9}$$

Here P_0 is the cluster preformation probability at a fixed R, given by the solution of the stationary Schrödinger equation (1). At $R=C_1+C_2$, $P_0=Y(A_2)$, given by Eqs. (4) and (6). For ground-state to ground-state decay, $\nu=0$. In the following, we choose $R=C_1+C_2$ [instead of $R=R_0$, the compound nucleus radius, where $V(R_0)=Q$ value] since this assimilates the effects of both deformations of the two fragments and neck formation between them [32].

P is the tunneling probability, which can be obtained by solving the corresponding stationary Schrödinger equation in

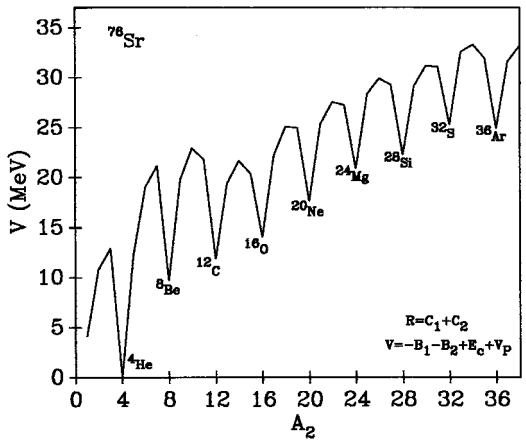

FIG. 1. Mass fragmentation potential for ^{76}Sr, calculated by using the experimental binding energies. Only the light fragments A_2 are shown along the x axis. The other fragment $A_1=A-A_2$.

R. Instead, Malik and Gupta calculated it as the WKB penetrability which for the tunneling path shown in Fig. 1 of [22] is given by

$$P=P_iP_b, \tag{10a}$$

with

$$P_i=\exp\left(-\frac{2}{\hbar}\int_{C_1+C_2}^{R_i}\{2\mu[V(R)-V(R_i)]\}^{1/2}dR\right), \tag{10b}$$

$$P_b=\exp\left(-\frac{2}{\hbar}\int_{R_i}^{R_b}\{2\mu[V(R)-Q]\}^{1/2}dR\right). \tag{10c}$$

This means that tunneling begins at $R=C_1+C_2$ and terminates at $R=R_b$ with $V(R_b)=Q$. The deexcitation probability between P_i and P_b is taken to be unity here. Both Eqs. (10b) and (10c) are solved analytically [21,22]. Apparently, we are considering here the decay from the ground state of the parent nucleus to the ground states of the decay products. On the other hand, if the compound system is excited or the system ends in the excited state of one or both the decay products, the Q value has to be adjusted accordingly (as discussed in the following).

In Eq. (9), ν is the assault frequency, given simply as

$$\nu=\frac{\text{velocity}}{R_0}=(2E_2/\mu)^{1/2}/R_0, \tag{11}$$

where $E_2=(A_1/A)Q$ is the kinetic energy, taken as the Q value shared between two fragments, and $\mu=m(A_1A_2/A)$ is the reduced mass.

Figure 1 shows the fragmentation potential for ^{76}Sr, plotted as a function of the light fragment mass A_2. Calculations are made in steps of one nucleon transfer. We notice in Fig. 1 that potential energy minima lie only at $N=Z$, $A=4n$ nuclei, showing the strong shell effects of α nuclei. It is important to realize here that this fragmentation potential is independent of the nuclei in the entrance channel and the light (A_2) and heavy ($A_1=A-A_2$) fragments occur in coincidence.

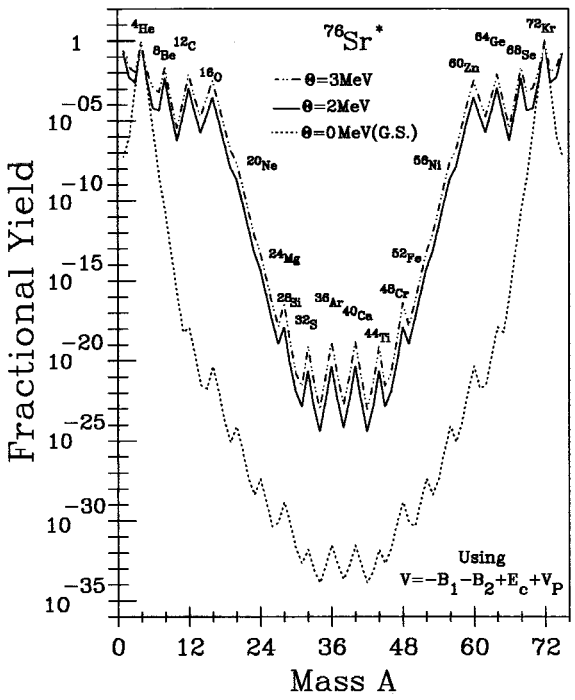

FIG. 2. Calculated mass distribution yields for the fission of ^{76}Sr from the ground state ($\nu=0$) and at temperatures $\theta=2$ and 3 MeV ($E^*=32$ and 73 MeV). The range of fragment masses is $1\leqslant A_i\leqslant 75$, and the yields are normalized to unity for both the light (A_2) and heavy (A_1) fragments.

The calculated fractional yields are shown in Fig. 2 for the fission of ^{76} Sr from the ground state ($\nu=0$) and at two arbitrary excitation energies ($\theta=2$ and 3 MeV). We notice that in the ground state almost all the yield is taken away by the α particle alone, but as the compound system is heated up, other fragments also show up. The interesting results are (i) the yields are largest for α nuclei and (ii) the mass distribution is strongly asymmetric. Also, the role of temperature in increasing the yields, more so for the symmetric and nearly symmetric fragments, is shown in Fig. 2.

We have also analyzed the role of temperature on shell effects δU. For this purpose, we have redone our calculations by using the theoretical binding energies [33] where $V_{\rm LDM}$ and δU contributions are tabulated separately. The calculated fragmentation potentials at different temperatures and the resulting yields are shown, respectively, in Figs. 3 and 4. We notice that temperature effects on the fragmentation potential as well as on the yields are large, but the general character of the mass distribution (positions of maxima and minima) remains unaffected. At very high temperature, the asymmetric structure of yields becomes weaker due to the washing away of shell effects, as expected from fission studies [14,26,27] also. Furthermore, our earlier calculations [15,16] show that the contribution of shell effects in mass parameters $B_{\eta\eta}$ are also of similar orders and act in the same way, i.e., without disturbing the general character of the mass distribution. This latter result could be used to assimilate the small entrance channel effects of the observed mass distributions by fitting $B_{\eta\eta}(\eta)$ empirically [16].

Our calculated decay half-lives for the decay of ^{76}Sr from its ground state to the ground states of all α-nuclei clusters

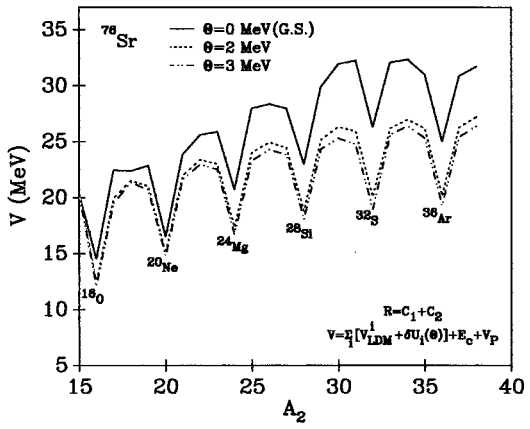

FIG. 3. Same as for Fig. 1, but by using the theoretical binding energies and for the mass range $15 \leqslant A_i \leqslant 61$ only. Also, the temperature effects on shell corrections δU are shown for $\theta = 2$ and 3 MeV. All the three potentials are normalized to the experimental data in Fig. 1 at $A_2 = 15$.

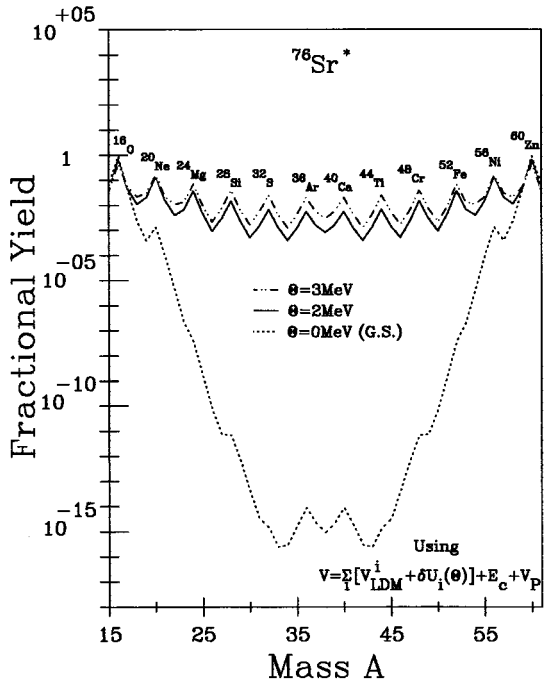

FIG. 4. Same as for Fig. 2, but by using the potentials of Fig. 3.

with positive Q values are given in Table I. Of course, the decay could also occur in the excited states of the daughter and/or cluster nuclei. This would mean decreasing the Q value to $Q - E_i$, where, say, E_i is the energy of first excited state of the daughter nucleus. This type of decay is studied in the following paragraph (Table II). Apparently, all the predicted decay half-lives (in both the tables) are very large and could not be measured in the near future. However, the numbers presented in Table I (and Table II) are still of interest for the discussion of other physical results in the following. First, the ^{76}Sr nucleus can be said to be stable against all possible cluster decays. Another interesting point to note is that the daughter nuclei for ^{20}Ne and ^{36}Ar decays are the doubly magic $N = Z$ nuclei. Hence, in view of the so-far observed cluster decays [34], these two decays should be the most probable decays. But the preformation factors P_0 for both ^{20}Ne and ^{36}Ar clusters are very small, though the decrease of P_0 with the increase of cluster size is very much in agreement with the situation known for observed decays (see, e.g., Fig. 13 in the review [34]). Also, the penetrabilities P are very small. This is particularly so for ^{12}C decay since its Q value is very small.

The role of excitation energy E^* of the compound system is presented in Table II. Once again, the cluster decays could end into the ground states or excited states E_i of the fragments. It may be reminded here that the other competing decay channels are the γ decay and the n, p, and α particles (as already noted at the beginning of the paper). Whereas the light-particle decays can, in principle, be treated within QMFT (like in Fig. 1 for the compound nucleus in the ground state), γ decay leads the compound system to its ground state whose cluster decay is already studied in the last paragraph above. Thus, for the decay of the excited compound nucleus into the ground state(s) of the fragment(s), the effective Q value (Q_{eff}) will become $Q + E^*$, but if it goes into an excited state E_1 of one fragment, $Q_{\text{eff}} = Q + E^* - E_1$. Both the cases are studied in Table II for some arbitrary value of $E^* = 10$ MeV and the observed first excited states of the daughter fragments A_1. Interesting enough, the decay constant λ increases (or $T_{1/2}$ decreases) considerably, particularly for the lighter clusters. Such calculations for light nuclei are made for the first time and have become relevant because it is now possible to study experimentally [35] the

TABLE I. Calculated cluster decay constants [λ (s^{-1})] and decay half-lives [$T_{1/2}$ (s)], along with other characteristic quantities, for the decay of ^{76}Sr from its ground state to the ground states of daughter nuclei and/or clusters. The penetrabilities P and the preformation factors P_0 are calculated at $R = C_1 + C_2$ for use of experimental binding energies in the scattering and fragmentation potentials.

Parent nucleus	Cluster+ daughter	Q value (MeV)	Preformation probability P_0	Penetrability P	Decay constant λ (s^{-1})	Decay half-life $\log_{10}T_{1/2}$ (s)	Remarks
$^{76}_{38}$Sr	^{12}C+^{64}Ge	0.035	5.529×10^{-18}	1.26×10^{-1319}	1.08×10^{-1316}	1315.81	Most stable
	^{16}O+^{60}Zn	4.53	2.128×10^{-20}	1.52×10^{-89}	4.91×10^{-88}	87.15	Stable
	^{20}Ne+^{56}Ni	6.55	3.704×10^{-24}	6.44×10^{-86}	3.91×10^{-88}	87.25	Stable
	^{24}Mg+^{52}Fe	7.87	1.962×10^{-27}	2.04×10^{-91}	6.55×10^{-97}	96.02	Stable
	^{28}Si+^{48}Cr	9.92	7.149×10^{-29}	1.38×10^{-81}	1.68×10^{-88}	87.62	Stable
	^{32}S+^{44}Ti	9.18	7.771×10^{-32}	9.95×10^{-98}	1.19×10^{-107}	106.77	Very stable
	^{36}Ar+^{40}Ca	10.69	1.392×10^{-31}	3.43×10^{-87}	7.44×10^{-97}	95.97	Stable

TABLE II. Same as for Table I, but for the decay of excited compound system ^{76}Sr* to the ground states (g.s.) of daughter and cluster nuclei (case I) and also to the first excited states of the daughter nuclei (case II). The effective Q value (Q_{eff}) for case I is $Q+E^*$ and that for case II is $Q+E^*-E_1$. The excitation energy of the compound system is arbitrarily taken as $E^*=10$ MeV.

Parent nucleus	Cluster A_2	Daughter A_1	Q value (MeV)	g.s. or E_1 of A_1 (MeV)	Q_{eff}	Penetrability P	Decay constant λ (s^{-1})	Decay half-life $\log_{10}T_{1/2}$ (s)
$^{76}_{38}$Sr	^{12}C	^{64}Ge	0.035	g.s.	10.035	2.17×10^{-27}	1.85×10^{-24}	23.57
				0.902	9.133	1.97×10^{-29}	1.68×10^{-26}	25.62
	^{16}O	^{60}Zn	4.53	g.s.	14.53	6.13×10^{-26}	1.99×10^{-24}	23.54
				1.004	13.526	5.15×10^{-28}	1.67×10^{-26}	25.62
	^{20}Ne	^{56}Ni	6.55	g.s.	16.55	3.13×10^{-29}	1.90×10^{-31}	30.56
				2.701	13.849	8.25×10^{-37}	5.01×10^{-39}	38.14
	^{24}Mg	^{52}Fe	7.87	g.s.	17.87	1.15×10^{-33}	3.69×10^{-39}	38.27
				0.84	17.03	5.30×10^{-36}	1.71×10^{-41}	40.61
	^{28}Si	^{48}Cr	9.92	g.s.	19.92	1.97×10^{-33}	2.41×10^{-40}	39.46
				0.752	19.168	2.10×10^{-35}	2.55×10^{-42}	41.43
	^{32}S	^{44}Ti	9.18	g.s.	19.18	1.41×10^{-39}	1.68×10^{-49}	48.62
				1.083	18.097	4.62×10^{-43}	5.50×10^{-53}	52.10
	^{36}Ar	^{40}Ca	10.69	g.s.	20.69	2.37×10^{-37}	5.16×10^{-47}	46.13
				3.352	17.338	3.24×10^{-48}	7.04×10^{-58}	56.99

above-mentioned fine structure effects of decay into the excited states of fission fragments. If data become available for some system(s), it will help in deciding between the fission and cluster decays of these light nuclear systems.

Summarizing, we have presented our calculations for fission and cluster decays of ^{76}Sr. Both the cases of ^{76}Sr in the ground state and produced as an excited compound system in heavy-ion reactions are studied. Here fission is treated as a collective mass transfer process and cluster decay studies are based on a model allowing preformation of clusters. Calculations show that, in a clear asymmetric mass distribution, ^{76}Sr nucleus allows preferential α-nuclei transfer resonances as well as decays. The only experimental study available on this system is 1α and 2α transfer products from ^{36}Ar on ^{40}Ca at an energy near the Coulomb barrier ($V_c=53.6$ MeV) [36]. Our calculations suggest that for obtaining complete fission products, one has perhaps to go to at least double the Coulomb barrier energies. Also, following Sobotka *et al.* [11], use of inverse kinematics (projectile heavier than the target) may be an additional help. This provides a large center-of-mass velocity which facilitates the verification of full momentum transfer and easy identification of the fragment's atomic number at higher incident energies. Also, the high-energy solution at forward angles should enhance the observation of compound-nucleus decay and virtually eliminate any possible deep inelastic contribution.

One of us (R.K.G.) would like to express his thanks to Professor Dr. Bernard Haas, CRN, Strasbourg, and his colleagues for the nice hospitality of the Institute extended to him for a month during the autumn of 1996 when this work was completed. Brief reports of this work were contributed earlier at the Second International Conference on Atomic and Nuclear Clusters 1993, Santorini (Greece), and at Cluster 94: Clusters in Nuclear Structure and Dynamics, Strasbourg (France), 1994.

[1] R. K. Gupta, W. Scheid, and W. Greiner, J. Phys. G **17**, 1731 (1991).

[2] P. Möller and J. R. Nix, Nucl. Phys. **A361**, 117 (1981); At. Data Nucl. Data Tables **26**, 165 (1981).

[3] R. Bengtsson, P. Möller, J. R. Nix, and J.-Y. Zhang, Phys. Scr. **29**, 402 (1984).

[4] C. Beck, D. Mahboub, R. Nouicer, T. Matsuse, B. Djerroud, R. M. Freeman, F. Haas, A. Hachem, A. Morsad, M. Youlal, S. J. Sanders, R. Dayras, J. P. Wieleczko, E. Berthoumieux, R. Legrain, E. Pollacco, Sl. Cavallaro, E. De Filippo, G. Lanzano, A. Pagano, and M. L. Sperduto, Phys. Rev. C **54**, 227 (1996).

[5] K. A. Farrar, S. J. Sanders, A. K. Dummer, A. T. Hasan, F. W. Prosser, B. B. Back, I. G. Bearden, R. R. Betts, M. P. Carpenter, B. Crowell, M. Freer, D. J. Henderson, R. V. F. Janssens, C. Beck, R. M. Freeman, Sl. Cavallaro, and A. Szanto de Toledo, Phys. Rev. C **54**, 1249 (1996).

[6] S. J. Sanders, A. Hasan, F. W. Proser, B. B. Back, R. R. Betts, M. P. Carpenter, D. J. Henderson, R. V. F. Janssens, T. L. Khoo, E. F. Moore, P. R. Wilt, F. L. H. Wolfs, A. H. Wuosmaa, K. B. Beard, and Ph. Benet, Phys. Rev. C **49**, 1016 (1994).

[7] Sl. Cavallaro, C. Beck, E. Berthoumieux, R. Dayras, E. De Filippo, G. Di Natale, B. Djerroud, R. M. Freeman, A. Hachem, F. Haas, B. Heusch, G. Lanzano, R. Legrain, D. Mahboub, A. Morsad, A. Pagano, E. Pollacco, S. J. Sanders, and M. L. Sperduto, Nucl. Phys. **A583**, 161 (1995).

[8] S. J. Sanders, Phys. Rev. C **44**, 2676 (1991).

[9] N. Aissaoui, F. Haas, R. M. Freeman, C. Beck, M. Morsad, B.

Djerroud, R. Caplar, and A. Hachem, Phys. Rev. C **55**, 516 (1997).
[10] U. L. Businaro and S. Gallone, Nuovo Cimento **1**, 629 (1955); **1**, 1277 (1955).
[11] L. G. Sobotka, M. A. McMahan, R. J. McDonald, C. Signarbieux, G. J. Wozniak, M. L. Padgett, J. H. Gu, Z. H. Liu, Z. Q. Yao, and L. G. Moretto, Phys. Rev. Lett. **53**, 2004 (1984).
[12] P. M. Evans, A. E. Smith, C. N. Pass, L. Stuttge, B. B. Back, R. R. Betts, B. K. Dichter, D. J. Henderson, S. J. Sanders, F. Videback, and B. D. Wilkins, Phys. Lett. B **229**, 25 (1989); Nucl. Phys. **A526**, 365 (1991).
[13] R. K. Puri and R. K. Gupta, J. Phys. G **18**, 903 (1992); R. K. Puri, S. S. Malik, and R. K. Gupta, Europhys. Lett. **9**, 767 (1989).
[14] R. K. Gupta, D. R. Saroha, and N. Malhotra, J. Phys. (Paris) Colloq. **45**, C6-477 (1984).
[15] D. R. Saroha, N. Malhotra, and R. K. Gupta, J. Phys. G **11**, L27 (1985).
[16] S. S. Malik and R. K. Gupta, J. Phys. G **12**, L161 (1986).
[17] T. Matsuse, S. M. Lee, Y. H. Pu, K. Y. Nakagawa, C. Beck, and T. Nakagawa, in *Towards a Unified Picture of Nuclear Dynamics*, edited by Y. Abe, F. Sakata, and S. M. Lee, AIP Conf. Proc. No. 250 (AIP, New York, 1992), p. 112.
[18] R. Nouicer, C. Beck, D. Mahboub, T. Matsuse, B. Djerroud, R. M. Freeman, A. Hachem, Sl. Cavallaro, E. De Filippo, G. Lanzano, A. Pagano, R. Dayras, E. Berthoumieux, R. Legrain, and E. Pollacco, Z. Phys. A (to be published).
[19] T. Matsuse, C. Beck, R. Nouicer, and D. Mahboub (unpublished).
[20] W. Hauser and H. Feshbach, Phys. Rev. **87**, 366 (1952).
[21] R. K. Gupta, in *Proceedings of the 5th International Conference on Nuclear Reaction Mechanisms*, Varenna, 1988, edited by E. Gadioli (Ricerca Scientifica ed Educazione Permanente, 1988), p. 416
[22] S. S. Malik and R. K. Gupta, Phys. Rev. C **39**, 1992 (1989).
[23] H. J. Fink, W. Greiner, R. K. Gupta, S. Liran, H. J. Maruhn, W. Scheid, and O. Zohni, in *Proceedings of the International Conference on Reactions between Complex Nuclei*, Nashville, 1974, edited by R. L. Robinson, F. K. McGowan, J. B. Ball, and J. M. Hamilton (North-Holland, Amsterdam, 1974), Vol. 2, p. 21.
[24] J. Maruhn and W. Greiner, Phys. Rev. Lett. **32**, 548 (1974).
[25] R. K. Gupta, W. Scheid, and W. Greiner, Phys. Rev. Lett. **35**, 353 (1975).
[26] R. K. Gupta, Sov. J. Part. Nucl. **8**, 289 (1977).
[27] J. A. Maruhn, W. Greiner, and W. Scheid, in *Heavy Ion Collisions*, edited by R. Bock (North-Holland, Amsterdam, 1980), Vol. 2, Chap. 6.
[28] G. Audi and A. H. Wapstra, Nucl. Phys. **A595**, 409 (1995).
[29] J. Blocki, J. Randrup, W. J. Swiatecki, and C. F. Tsang, Ann. Phys. (N.Y.) **105**, 427 (1977).
[30] H. Köger and W. Scheid, J. Phys. G **6**, L85 (1980).
[31] A. S. Jensen and J. Damgaard, Nucl. Phys. **A203**, 578 (1973).
[32] S. Kumar and R. K. Gupta, Phys. Rev. C **55**, 218 (1997); R. K. Gupta, in *Frontier Topics in Nuclear Physics*, Predeal, Romania, 1993, Vol. 334 of *NATO Advanced Study Institute, Series B: Physics*, edited by W. Scheid and A. S̃andulescu (Plenum, New York, 1994), p. 129.
[33] P. Möller, J. R. Nix, W. D. Myers, and W. J. Swiatecki, At. Data Nucl. Data Tables **59**, 185 (1995).
[34] R. K. Gupta and W. Greiner, Int. J. Mod. Phys. E Suppl. **3**, 353 (1994).
[35] R. Nouicer (private communication).
[36] T. Kirchner, Ph.D. thesis, Freien Universität, Berlin, Germany, 1994.