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FISSION MASS YIELDS OF EXCITED MEDIUM HEAVY NUCLEI

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1. INTRODUCTION

The distribution yields of mass and charge in fission can be quite naturally explained in the framework of the fragmentation theory /1-4/. In this theory the mass and charge asymmetries are treated as collective variables beside the relative coordinate and further deformation coordinates describing the nuclear shape. The coordinates of the mass and charge asymmetries for two-body fragmentations are given as

$$\eta = \frac{A_1 - A_2}{A_1 + A_2}, \qquad \eta_z = \frac{Z_1 - Z_2}{Z_1 + Z_2}, \tag{1}$$

which are discrete coordinates for separate nuclei and continuous ones for overlapping fragments. The central point of the fragmentation theory is the quantum mechanical treatment of the mass and charge asymmetry coordinates. The wave function, depending on η and η_z, allows one to predict probabilities, i.e., mass and charge yields, for the outcome of fission reactions. Since a quantum mechanical description presumes a coherent collective motion, the theory is restricted to fission at low excitation energies, unless the collective degrees of freedom are consistently coupled to the statistically unordered intrinsic motion of the nucleons. The latter extension of the theory becomes necessary for a realistic description of deep inelastic collisions and can be carried out by opening the dynamical system described by the collective coordinates.

The fragmentation theory has been quite successfully used for the description of mass and charge distributions in fission, quasi-fission and deep-inelastic collisions, for predicting the maximum of the fusion cross sections for compound systems obtained by different target-projectile combinations, for explaining the asymmetry in the mass transfer in heavy-ion collisions and for the evaluation of lifetimes for alpha and heavy cluster decay of actinide nuclei. Reviews about the status of the fragmentation theory have been given by Gupta /5/, Maruhn et al. /6/ and Sandulescu et al. /7,8/. This theory shows two distinguishable structure effects in the fission mass distributions of actinide nuclei:

i) The maximum fission mass yields are concentrated around the symmetric mass fission ($\eta = 0$) since the liquid drop potential energy surface has a strong minimum for the symmetric fragmentation. Double- and triple-humped fission mass distributions arise due to shell effects in the potential energy surface (closed shells $Z = 50$, $N = 82$) and are in agreement with those observed in experiment.

ii) In addition the fission mass yields reveal maxima in the shoulders which lead to highly asymmetric fission or, in other terms, heavy cluster emission.

We should like to mention that this new decay mode of heavy nuclei, intermediate between nuclear fission and alpha decay, has been recognized in 1977 by Sandulescu and Greiner[9], who have shown, that very asymmetric fission can proceed through deep valleys in the fragmentation potential which are generated by shell effects of one of the fragments close to the double magic nucleus ^{208}Pb. These predictions[9,7,10] and the calculations of lifetimes for heavy cluster emission[8,11,12] are confirmed in the meantime by experiments. Rose and Jones[15] Aleksandrov et al.[14] and Gales et al.[15] discovered the ^{14}Ca radioactivity of ^{223}Ra, giving the first evidence for such a new type of decay mode. Also the emission of the ^{14}C cluster was observed for the neighbouring isotopes ^{222}Ra and ^{224}Ra by Price et al.[16] and theoretically also interpreted by Shi and Swiatecki[17]. Very recently the first experimental results concerning a new type of decay of ^{231}Pa by Ne emission are reported[18].

In contrast to the spontaneous fission mass yields of the actinide nuclei, where the strong asymmetric peaks are many orders of magnitudes smaller than the main peaks close to symmetric fragmentation, we expect for the fission of excited medium heavy nuclei that the mass distributions show much larger asymmetric peaks. The following reasons support this assumption. The liquid drop potential as function of η varies only a few MeV for $|\eta| < 0.8$ and, therefore, shell effects due to the magic proton and neutron numbers $Z = 20, 28, 50$ and $N = 20, 28, 50, 82$ should lead to various valleys in the potential energy surface and, consequently, to a larger variety of structures in the mass yields over the entire range of the mass asymmetry. In this connection we like to mention the situation in the case of lighter compound nuclei. Betts[19] has measured the mass distribution of ^{56}Ni after the reaction ^{16}O + ^{40}Ca at 75 MeV and found maxima at all fragmentations with α-particle structure: ^{28}Si + ^{28}Si, ^{32}S + ^{24}Mg, ^{36}Ar + ^{20}Ne, ^{40}Ca + ^{16}O. This experiment demonstrates that one can obtain very structured mass distributions in the fission of excited medium heavy nuclei. A first calculation of this mass distribution has been carried out by Malhotra et al.[20] in the framework of the fragmentation theory.

In this paper we study the fission of excited medium heavy nuclei choosing the ^{172}Yb compound nucleus as an example. The fission yield of this system is expected to have structures arising from the closed shells with $Z = 20, 28, 50$ protons and $N = 20, 28, 50, 82$ neutrons. For example the decays ${}^{172}_{70}\mathrm{Yb}^*_{102} \to {}^{132}_{50}\mathrm{Sn}_{82} + {}^{40}_{20}\mathrm{Ca}_{20}$ or $\to {}^{124}_{50}\mathrm{Sn}_{74} + {}^{48}_{20}\mathrm{Ca}_{28}$ or $\to {}^{86}_{36}\mathrm{Kr}_{50} + {}^{86}_{34}\mathrm{Se}_{52}$ lead to nuclei with 4, 3 and 1 closed proton and neutron shells, respectively. Experimentally, the excited ^{172}Yb compound nucleus can be produced in reactions with protons, neutrons and α-particles and also by fusion reactions with light ions as, for example, ^{18}O + ^{154}Sm and ^{22}Ne + ^{150}Nd. In the first of the latter reactions the reaction barrier has a height of about $E_{lab} = 71$ MeV and the ^{172}Yb compound nucleus is obtained with a minimal excitation energy of 50 MeV. The corresponding numbers for the second reaction are given by 87 MeV and 53 MeV.

In Sect. 2 we apply the fragmentation theory to the ^{172}Yb compound system. We present the potential energy surface as function of the mass asymmetry and the length of the fissioning nucleus and the calculation of the fission yield of ^{172}Yb. In Sect. 3 we draw conclusions from the predicted fission yields for future experimental studies of the fission yields of excited medium heavy nuclei.

2. POTENTIAL ENERGY SURFACE AND FISSION YIELDS FOR ^{172}Yb

In the calculation of the potential energy surface the following coordinates for the parametrization of the nuclear shape as shown in Fig. 1 are used: The separation of the fragments is measured by a length parameter ℓ, which is the length of the system along the symmetry axis. Under the assumption of a homogeneous mass and charge density and of a constant ratio of the mass density to the charge density (i.e., $\eta = \eta_z$), the asymmetry coordinates η and η_z are reduced to a single volume asymmetry coordinate $\xi = (V_1 - V_2)/(V_1 + V_2)$, where the volumes V_1 and V_2 are defined with a plane through the neck of the fissioning nuclear system. The rotationally symmetric deformed shapes of the fragments are described with the quadrupole deformation parameters $\beta_i = a_i/b_i$ $(i = 1,2)$. The neck parameter ϵ is defined by the ratio of barrier heights of the asymmetric two-center potential ($\epsilon = E_0/E'$, see fig. 1). With these coordinates the potential energy is a function of ℓ, ξ, β_1, β_2 and ϵ. In addition we assume a dependence of the potential on the temperature T. The potential is calculated as the sum of three terms, namely the energy V_{LDM} of the liquid drop model of Meyers and Swiatecki[21,22] with a modified surface asymmetry constant and the energies δU and δP for the shell and pairing corrections:

$$V(\ell, \xi, \beta_1, \beta_2, \epsilon, T) = V_{LDM} + (\delta U + \delta P)\exp(-T^2/T_0^2). \qquad (2)$$

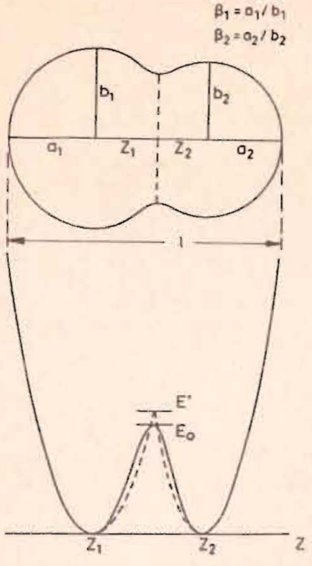

Fig. 1. Definition of the parameters of the nuclear shape and the corresponding two-center shell model potential along the axis connecting the nuclear centers. The neck parameter is defined by the ratio of barrier heights $\epsilon = E_0/E'$ as indicated in the lower half of the figure.

The shell corrections δU are calculated with the single-particle energies $E_\nu(\ell, \xi, \beta_1, \beta_2, \epsilon)$ of the asymmetric two-center shell model$^{/23/}$ in the framework of the renormalization procedure of Strutinsky$^{/24/}$. The shell and pairing correction energies are multiplied by a phenomenological temperature-dependent factor which effectively describes the vanishing of these correction energies for temperatures larger than a limiting temperature T_0 assumed as $T_0 = 1.5$ MeV in the following calculations. The corresponding intrinsic excitation energy above the potential energy surface is related to the temperature T of the compound system by

$$E^* = \frac{A}{10\ \text{MeV}} T^2. \qquad (3)$$

According to this formula the shell effects of ^{172}Yb are diminished above an excitation energy of $E^* = 38.7$ MeV, if we set $T_0 = 1.5$ MeV. In order to simplify the dependence of the potential on the five geometrical variables, we assume that the fission process, described by the coordinates ℓ and ξ, is adiabatically slow in comparison with the time evolution of the deformation and neck degrees of freedom. Therefore, it is justified to minimize the potential (2) with respect to the deformation parameters β_1 and β_2 of the fragments and the neck parameter for fixed values of ℓ and ξ. In the following calculations the parameters β_1, β_2 and ϵ are obtained by minimizing the total potential energy $V(\ell, \xi, \beta_1, \beta_2, \epsilon, T = 0)$ or the LDM energy $V_{LDM}(\ell, \xi, \beta_1, \beta_2, \epsilon)$ for given values of ℓ and ξ. The first minimization procedure is the most adequate one for the fission problem, but very time consuming because of the repeated calculation of the two-center shell model energies. The minimization of V_{LDM} is a useful approximation for the full minimization in the case, that the potential depends more sensitively on the deformation than on the shell structures.

Figure 2 shows the calculated potentials for zero temperature as functions of $\eta \sim \xi$ for $\ell = 21$ fm (β_1, β_2, ϵ from

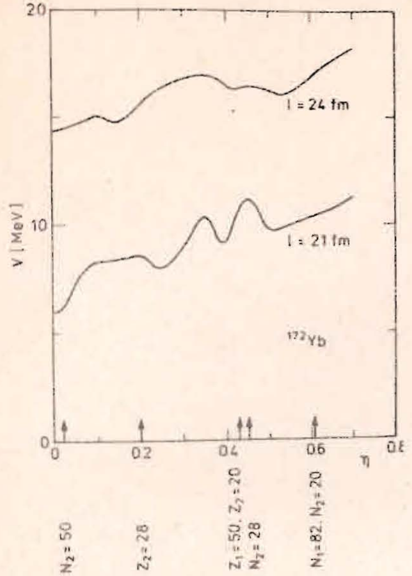

Fig. 2. The fission potential of ^{172}Yb for lengths $\ell = 21$ and 24 fm and zero temperature as function of the asymmetry coordinate η. The potential for $\ell = 21$ fm (lower curve) is calculated with parameters β_1, β_1 and ϵ obtained by minimizing V_{LDM}, the potential for $\ell = 24$ fm (upper curve) by minimizing V. Fragmentations with closed shells are indicated by arrows and the corresponding proton and neutron numbers are written at the η-axis.

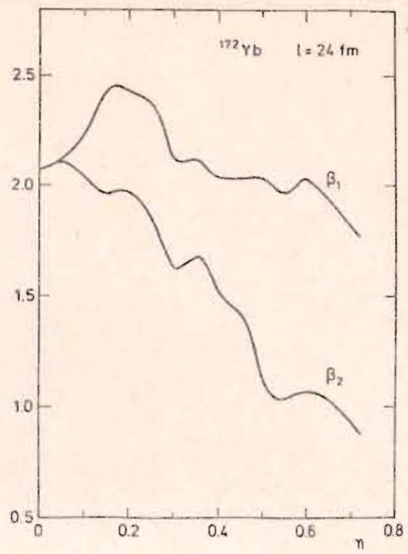

Fig. 3. The deformation parameters β_1 and β_2 of the fragments as function of η for $\ell = 24$ fm obtained by minimizing V with respect to β_1, β_2 and ϵ for fixed ℓ and η and zero temperature.

min V_{IDM}) and $\ell = 24$ fm (min $V(\ell, \xi, \beta_1, \beta_2, \epsilon, T = 0)$). The energy values are referred to the liquid drop model energy of the spherical compound nucleus, which is set at zero. One recognizes a smooth average rise of the potentials of 3-4 MeV between $\eta = 0$ and $\eta = 0.7$, which is due to the liquid-drop model energy. The oscillating behaviour of the curves is generated by the shell and pairing corrections. At the η-axis in Fig. 2 we indicate the magic neutron and proton numbers of the fragments occurring at these η values. The magic numbers $Z = 20, 50$, $N = 28$ and $N = 20, 82$ are found at $\eta = 0.43, 0.45$

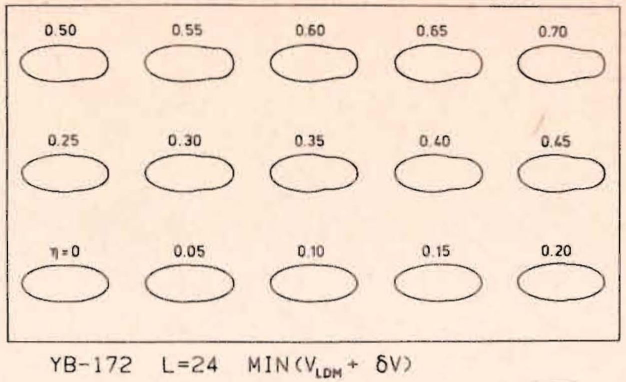

Fig. 4. The nuclear shapes of the fissioning ^{172}Yb *nucleus for* ℓ *= 24 fm and various values of the mass asymmetry coordinate. The corresponding deformation parameters are given in Fig. 3.*

and 0.61, respectively. The various minima in the potentials can partly be associated with these magic numbers, but the shapes of the fragments are deformed. Figure 3 gives the ratios $a_i/b_i = \beta_i$ of the axes of the fragments for $\ell = 24$; and Fig. 4, the corresponding fission shapes. As we have proven by calculations, the sudden scission of the neck will set in at lengths around $\ell = 25$ fm, where the energy of the separated fragments becomes lower than the energy of the fission shapes shown in Fig. 4. The potential energy surface is applied in the calculation of the mass distribution. For simplicity we decouple the η-motion from the ℓ- (or relative) motion of the fragments. In that case the wave functions for the mass asymmetry degree of freedom are determined by the following eigenvalue equation ($\xi = \eta$):

$$\left(-\frac{h^2}{2\sqrt{B_{\eta\eta}}}\frac{\partial}{\partial\eta}\frac{1}{\sqrt{B_{\eta\eta}}}\frac{\partial}{\partial\eta} + V(\ell,\eta,T)\right)\psi_k(\eta,\ell,T)) = E_k\psi_k(\eta,\ell,T). \tag{4}$$

The mass coefficient $B_{\eta\eta}$ is set as a constant averaged value. It is computed within a consistent method by applying the cranking model including residual interactions of BCS-pairing type with the same single-particle states of the asymmetric two-center model as used in the calculation of the shell corrections. For a temperature T of the fissioning compound system we can assume that the eigenstates of (4) are occupied with a Boltzmann distribution function. Then the probability density of the mass asymmetry is obtained as

$$w(\eta,\ell,T) = \sum_k \exp(-E_k/T)\,|\psi_k(\eta,\ell,T)|^2 \Big/ \sum_k \exp(-E_k/T), \tag{5}$$

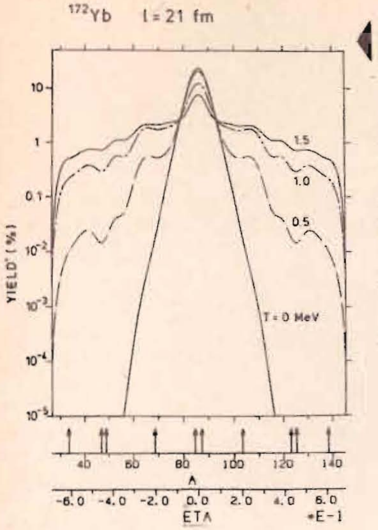

Fig. 5. The fission mass yield in percent for ^{172}Yb *as function of the nucleon number of the fission fragment or the mass asymmetry coordinate* η*. The curves are calculated with the potential for* ℓ *= 21 fm shown in Fig. 2 and for the temperatures T = 0 (——), 0.5 (–·–), 1.0 (—–) and 1.5 (——) MeV. The arrows indicate the position of fission fragments with closed proton or neutron shells.*

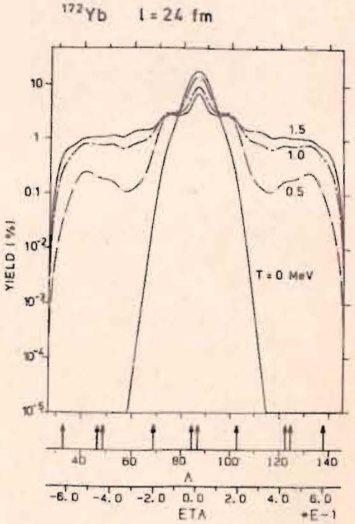

Fig. 6. The fission mass yield in percent for ^{172}Yb *calculated with the potential for* ℓ *= 24 fm shown in Fig. 2. For the further explanation see the figure caption of Fig. 5.*

where w is normalized in the interval $-1 \leq \eta \leq 1$ with the volume element $\sqrt{B_{\eta\eta}}\,d\eta$. The fission mass yield, normalized to 200%, is given by the expression

$$Y(A_1) = w(\eta,\ell,T)\sqrt{B_{\eta\eta}}\,\frac{400}{A}. \tag{6}$$

Figures 5 and 6 show the fission mass yields of ^{172}Yb calculated for fixed lengths $\ell = 21$ fm, respectively, and temperatures T = 0, 0.5, 1.0 and 1.5 MeV. The corresponding excitation energies of the ^{172}Yb compound nucleus above the fission potential can be evaluated according to Eq.(3). For T = 1 MeV we obtain E* = 17.2 MeV. The calculated fission mass distributions reflect the structures of the potentials $V(\ell,\eta,T)$. With increasing excitation energy of the fissioning compound system higher eigenstates of the mass asymmetry degree of freedom contribute in

Eq.(5) to the probability density and, consequently, the shoulders of the mass distributions become structured due to the minima in the potential at larger values of η.

Differently to the fission mass distributions of the actinide nuclei the calculated distributions of the medium heavy ^{172}Yb compound system are extended to larger mass asymmetries with an appreciable higher mass yield. For example the distribution for ℓ = 24 fm and T = 0.5 MeV has dropped from $\eta = 0$ to $\eta = 0.5$ by two orders of magnitude only. Therefore, in medium heavy nuclei fission events with very asymmetric mass ratios should be experimentally more easily observable. The maximum at $\eta = 0$ in Figs.5 and 6 is generated due to the magic neutron numbers 50 in both fragments. In that case preferential decays into channels like $^{86}_{36}\mathrm{Kr}_{50} + ^{86}_{34}\mathrm{Se}_{52}$ or $^{92}_{42}\mathrm{Mb}_{50} + ^{80}_{28}\mathrm{Ni}_{52}$ are to be expected. The shell closures with $Z_1 = 50$, $Z_2 = 20$ and $N_2 = 28$ at $\eta \simeq 0.45$ lead to the structures around $\eta = 0.4$ and 0.5. In that range of the mass asymmetry coordinate the following fission channels with closed shell nuclei as products are possible: $^{124}_{50}\mathrm{Sn}_{74} + ^{48}_{20}\mathrm{Ca}_{28}$ ($\eta = 0.44$), $^{128}_{54}\mathrm{Xe}_{76} + ^{44}_{16}\mathrm{S}_{28}$ ($\eta = 0.49$) or $^{132}_{50}\mathrm{Sn}_{82} + ^{40}_{20}\mathrm{Ca}_{20}$ ($\eta = 0.53$). A more asymmetric fission process leading to nuclei with closed shells is the decay into $^{138}_{56}\mathrm{Ba}_{82} + ^{34}_{14}\mathrm{Si}_{30}$ ($\eta = 0.6$). For $\eta > 0.65$ one of the fragments is already a light nucleus with $A_2 \leq 30$. Fission processes with a light nucleus involved and denoted also as heavy cluster emission should lead to additional structures in the fission mass yields. But presently the very asymmetric part of the fission mass yield ($\eta > 0.7$) cannot be meaningfully calculated with the presently used asymmetric two-center shell model.

3. CONCLUSIONS

The important result for the fission of excited medium heavy nuclei is the expectance of broad and structured mass distributions. Differently to the actinide nuclei also the very asymmetric fragmentations should be more easily experimentally observable, because the very asymmetric yields are suppressed by only a few orders of magnitude in comparison to the yields of the symmetric fragmentations. The structures arise due to the various shell closures in the neutron and proton shells of the fragments.

In principle the fragmentation theory describes the fission of the compound system for all mass asymmetries. In the case of very asymmetric fragmentations ($A_1 \gg A_2$ with $A_2 < 30$) the fragmentation theory also treats the two-body break-up as a fission process described by the shape parameters of the nuclear system. This is in a certain contrast to the extreme picture of a cluster emission from heavy compound systems, where one assumes a preformation of the clusters (e.g., alpha-particles) inside the compound system. The terms "cluster emission" and "fission" amalgamate into the same meaning if we suppose that the compound system forms molecular-like cluster configurations which can separate with increasing relative distances. In the case of the fission description this process is described by collective shape coordinates and affected by shell effects in the potentials, whereas in the cluster description a microscopical treatment in the framework of the generator coordinate method can be considered. Both treatments should finally give the same mass and charge distributions.

It would be quite interesting to study the energy dependence of the fission yields of excited light and medium heavy nuclei as function of the excitation energy. Probably structures as function of the excitation energy may be observed for certain values of the mass asymmetry coordinate. Those structures can be thought as unique signatures for the formation of longer living nuclear molecular states. Therefore the investigations of mass and charge fission yields of light and medium heavy nuclei would be an excellent alternative experimental tool to learn more about the existence of nuclear molecules in heavier nuclear systems.

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Сэндулеску А. и др. E4-85-210
Распределение по массам при делении возбужденных средних масс ядер

Массовое распределение в делении возбужденных средних масс ядер было обсуждено на основе теории фрагментации. Показано, что очень асимметричные события ожидаются на несколько порядков меньше, чем для симметричного деления. Расчеты для массового распределения были сделаны для составного ядра ^{172}Yb как пример. Это массовое распределение показывает структуры для целой области массовой асимметрии, обоснованные долинами в потенциальной энергии с замкнутыми оболочками протонов или нейтронов.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

Сообщение Объединенного института ядерных исследований. Дубна 1985

Săndulescu A. et al. E4-85-210
Fission Mass Yields of Excited Medium Heavy Nuclei

The mass distributions resulting from the fission of excited medium heavy nuclei are discussed on the basis of the fragmentation theory. It is shown, that very asymmetric fission events can be expected with rates which are only a few orders of magnitude smaller than the rates for symmetric fission. As an example a calculation of the fission mass distribution of the excited ^{172}Yb compound nucleus is presented. This mass distribution reveals observable structures over the entire range of the mass asymmetry due to valleys in the potential energy surface for fission fragments with closed proton and neutron shells.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

Communication of the Joint Institute for Nuclear Research. Dubna 1985