DYNAMIC EFFECTS IN SEQUENTIAL DECAY GEMINI CODE WITH TIME SCALES AND COULOMB TRAJECTORIES*

W. Gawlikowicz

M. Smoluchowski Institute of Physics
Jagellonian University
Reymonta 4, 30-059 Cracow, Poland

(Received February 24, 1997)

A new version of the GEMINI code, including time scales and calculation of Coulomb trajectories of sequentially emitted particles, is presented. Energy spectra of charged particles and reduced velocity correlations have been calculated using the no-time-scale, and the time-scale version of the GEMINI code, to elucidate importance of the sequential decay dynamics. The reduced velocity correlations predicted by the time-scale version of the GEMINI code are in good agreement with experimental data.

PACS numbers: 24.10. Lx, 24.60. Dr

Deexcitation of hot nuclei by particle evaporation and/or fission is described by different sequential codes [1, 2] which mostly do not include information on time distances along the decay chain (chains). Since in a comparison with experimental data the exclusive observables, based on velocity or energy measurements, are frequently used to study different reaction mechanisms, the applied codes should contain at least some elements of the decay dynamics.

Most of the sequential decay codes are based on the assumption, that consecutive decays are properly separated in time, and therefore statistically independent. With an increase of the excitation energy the time scale for emission is reduced so that the above assumption may break down in two ways: *(i)* the parent nucleus may not have time to equilibrate between successive emissions; *(ii)* emitted particles may not have time to leave the vicinity of the parent and consequently the presence of previously emitted fragments may influence the decay process.

* This work was supported by the Polish-French (IN2P3) agreement and the Committee of Scientific Research of Poland (KBN Grant No. PB 719/P3/93/04).

Here we present a modified version of the GEMINI code [1], which may overcome, at least partly, difficulties of type *(ii)*. This new version contains time scales and a calculation of Coulomb trajectories of sequentially emitted particles. The GEMINI is a popular, frequently used code of Charity *et al.* [1]. It describes multiparticle, sequential decay of hot nuclear systems, where all binary divisions from light-particle evaporation to symmetric fission are considered. Using a Monte–Carlo technique GEMINI follows the decay chain until all particles became "cold".

For emission of light fragments ($Z \leq 2$) the decay widths are calculated using the Hauser–Feschbach formalism [3]. In this case the decay width for emission of a light particle (Z_1, A_1) having spin J_1, from a system (Z_0, A_0) with excitation energy E^* and spin J_0, leaving the residual system (Z_2, A_2) is:

$$\Gamma_{\mathrm{light}} = \frac{2J_1+1}{2\pi\rho_0} \sum_{J_2} \sum_{l=|J_0-J_2|}^{J_0+J_2} \int\limits_0^{E^*-B-E_{\mathrm{rot}}(J_2)} T_l(\varepsilon)\rho_2(U_2, J_2)d\varepsilon\,, \tag{1}$$

where J_2 is the spin of residual system, and l is the orbital angular momentum. ε denotes the kinetic energy of emitted particle, and U_2 the thermal excitation energy of residual system. ρ_0 and $\rho_2(U_2, J_2)$ are the level densities of initial and residual system, and $T_l(\varepsilon)$ is the transmission coefficient. B denotes the binding energy, and $E_{\mathrm{rot}}(J_2)$ is the rotation plus deformation energy of the residual system.

For emission of intermediate-mass fragments, IMFs ($Z > 2$) the transition state formalism [4, 5] is used. The corresponding decay widths are calculated as:

$$\Gamma_{\mathrm{imf}} = \frac{1}{2\pi\rho_0} \int\limits_0^{E^*-E_{\mathrm{sad}}(J_0)} \rho_{\mathrm{sad}}(U_{\mathrm{sad}}, J_0)d\epsilon\,, \tag{2}$$

where U_{sad} and ρ_{sad} denotes the thermal excitation energy and level density of conditional saddle-point configuration, respectively. $E_{\mathrm{sad}}(J_0)$ is the deformation plus rotation energy at the saddle-point. Here ϵ is the kinetic energy of the transitional degree of freedom.

The conditional barriers for neutrons, protons and alphas are taken from the systematics of McMahan and Alexander [6] , and Dostrovsky *et al.* [7]. For particles heavier than alphas and lighter than mass 100 the barriers were obtained from the two-spheroid finite-range program written by Sierk [8]. Barriers for $100 < A < 190$ are extrapolated from calculations of Sierk using larger number of shape parameters.

The emission lifetime is given by the total decay width as:

$$\tau = \frac{\hbar}{\Gamma^{\mathrm{tot}}_{\mathrm{light}} + \Gamma^{\mathrm{tot}}_{\mathrm{imf}}}\,, \tag{3}$$

where $\Gamma^{\rm tot}_{\rm light}$ and $\Gamma^{\rm tot}_{imf}$ is the total width for emission of light particles and IMFs, respectively (all possible decay channels are taken into account). One should note that $\Gamma^{\rm tot}_{\rm light}$ represents the majority of the total decay width, defining the emission lifetimes. While the total decay width gives the emission lifetime, the partial decay widths (for each possible channel of decay) give the branching ratios, *i.e.* charge (mass) spectrum.

Theoretical and experimental estimations [9] predict that the lifetime of nuclei (for the emission of the first neutron) changes from about 10^{-18} s, to about 10^{-23} s, for temperatures increasing from 1 to 10 MeV, respectively. The dependence upon the mass of the decaying nucleus is not a strong one. These predictions agree with the earlier estimation of the hot nucleus lifetime, obtained from the statistical theory ($A = 142$, $T = 4.4$ MeV) which properly reproduces the observed small-angle charged particle correlations in the reaction 680 MeV ^{40}Ar + Ag [12]. Hot nuclei deexcite emitting light particles, intermediate mass fragments (IMFs), and fission fragments. Fission and IMF emission can be treated as the two extremes of a single mode of decay, connected by the mass asymmetry degree of freedom [5]. Recent measurements of pre-scission neutron multiplicities suggest for a symmetric fission after fusion, decay times in the range $3.5 \pm 1.5 \times 10^{-20}$ s, over a large set of projectile-target combinations [13]. For increasing mass-asymmetry of the fission fragments the decay-time is reduced [13] showing a smooth transition to values characteristic for the neutron evaporation. The IMF emission times do not change to much in the collision energy range $18 \div 84$ MeV/nucleon [13, 14].

Basing on the above evidence, the lifetime for emission of nucleons, and for emission of IMFs can be simply parameterized [15]:

$$\tau = 2e^{13/T}e^{A/8} \quad [\mathrm{fm/c}] \ , \tag{4}$$

where T [MeV] is the nuclear temperature, and A is the mass of the emitted fragment.

Since in formula (4) there is no dependence on the mass of the emission source it gives the same lifetimes for all nuclei at a given temperature. On the other hand as shown in [9] the heavier is the decaying system the longer is its lifetime. However, the differences are rather small.

In Fig. 1 we present the emission lifetimes calculated from the decay widths of eq.(3) as well as from parameterization (4). Fig. 1 indicates that lifetimes of nuclei increase with cooling of the system, especially below $T = 2$ MeV where potential barriers become effective. It means that the decay probabilities may be significantly influenced by the proximity (in space as well as in time) of other particles only in the very early stage of deexcitation.

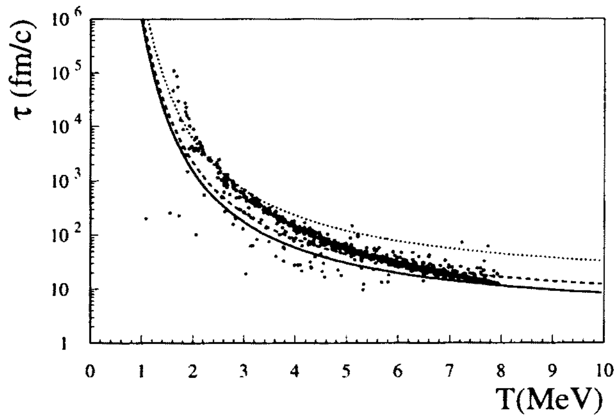

Fig. 1. The emission lifetimes as a function of temperature of a decaying system. Calculations were performed for the ^{70}Se nucleus excited to 520 MeV. Points from GEMINI decay widths (Eq. (3)) for all possible deexcitation chains. Lines from (Eq. (4)), for protons, alphas and carbons (starting from bottom,respectively).

The agreement between predictions of Eqs (3) and (4) is reasonable for $T > 2$ MeV. This region is of prime importance for thermodynamics of hot nuclear matter.

In this work probabilities of consecutive binary partitionings, as well as initial particle velocities are calculated using the standard GEMINI code [1]. The decay time-constants defined by Eq. (3) are used to calculate successive emissions along the disintegration path, between which trajectories of all particles moving in the mutual Coulomb field are computed, by numerical integration of the equations of motion.

In order to show how the implementation of time scales and Coulomb trajectories influences the behavior of observables, we have chosen a case of a relatively light ^{70}Se nucleus, with a zero angular momentum, excited to 520 MeV (7.4 MeV/nucleon). This choice is, in part, due to our present studies [10], but also because of the computation time necessary for solving the equations of motion (the calculation time increases rapidly with mass and excitation energy). Calculations presented here were performed with the standard version of GEMINI [1], and with the modified one (with time scales and Coulomb trajectories), described in this work.

Charge spectra obtained from decay of the excited ^{70}Se nucleus, predicted by the standard as well as by the modified version of GEMINI, are presented in Fig. 2. As the decay widths are the same for the standard and for the modified version of the GEMINI code, the charge (mass) spectrum is also the same.

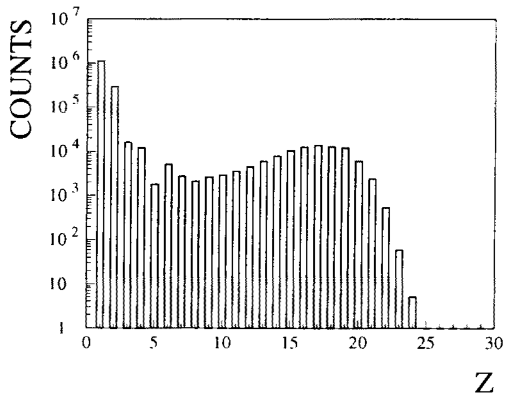

Fig. 2. Charge spectrum obtained from the decay of the ^{70}Se nucleus excited to 520 MeV. Sample of 100000 events generated by the GEMINI code.

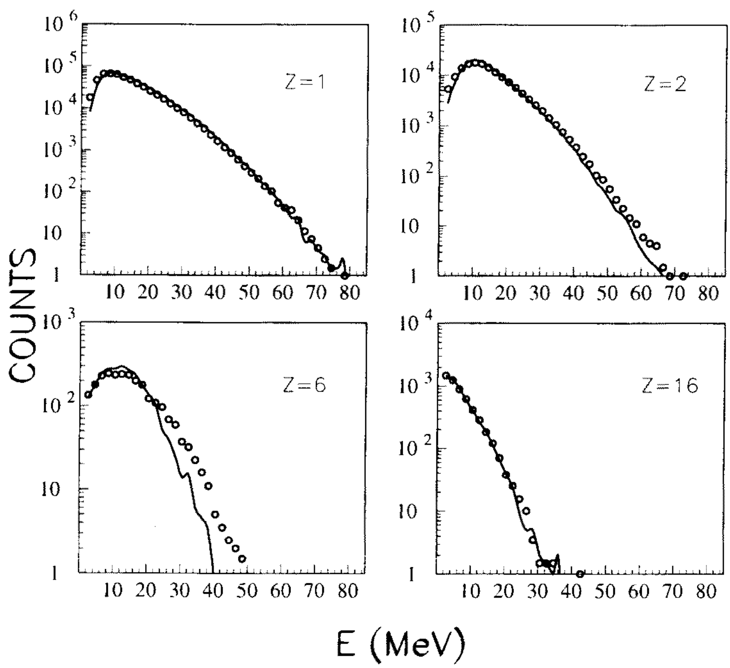

Fig. 3. Energy spectra of particles with $Z = 1, 2, 6$ and 16. Calculations were performed with the GEMINI code, with no-time-scales (open circles), and with time scales calculated from decay widths (solid line). The ^{70}Se nucleus was excited to 520 MeV. Sample of 100000 events.

Fig. 3 shows energy spectra of light particles ($Z = 1$ and $Z = 2$), IMFs ($Z = 6$) and "heavy" particles ($Z = 16$) — see Fig. 2. As one can see, the GEMINI with time scales produces a narrower energy distribution of IMFs. It means, that in a sequential emission with a very short time scale (high excitation energy) the successive acts of emission are not independent and the daughter nuclei are influenced by other particles from a close vicinity. Such effect is not present for light particles, which move faster and, to a large extent, are emitted from cooler, secondary sources. It is also not observed for heavy ejectiles, having narrower energy distributions, originating from more chaotic, multiple "kicks" [16].

For evaluation of decay time scales, and also for studying interactions between emitted fragments one uses frequently a properly defined correlation function between pairs of charged fragments [11]. Such observable should be influenced by the Coulomb interaction between fragments and their emission times. Here we use the $1+R$ correlation as a function of the reduced velocity, $v_{\rm red}$, of pairs of fragments with a charge Z_i and Z_j, respectively :

$$1 + R = \frac{N_{ij}^{\rm true}(v_{\rm red})}{N_{ij}^{\rm mix}(v_{\rm red})}, \tag{5}$$

where

$$v_{\rm red} = \frac{v_{\rm rel}}{\sqrt{Z_i + Z_j}}. \tag{6}$$

Here $v_{\rm rel}$ denotes the relative velocity, $N_{ij}^{\rm true}$ is the true number of correlations between pairs of fragments, and $N_{ij}^{\rm mix}$ is the number of random correlations (here six subsequent events were mixed).

Fig. 4 presents the reduced velocity correlation function for particles with $2 \leq Z \leq 8$ calculated using the standard GEMINI [1], and with the modified one including time scales. They show a big difference for small values of $v_{\rm red}$, where the emitted fragments are expected to be closer in space and in time, interacting via the Coulomb forces. The reduction of the correlation function (the "Coulomb hole") for small values of the reduced velocity is not reproduced by the GEMINI code without time scales, where all subsequent decays are independent, and emitted fragments do not interact via the Coulomb forces.

In Fig. 5 we present a comparison between the reduced velocity correlation functions calculated by both, the standard and the new version of the GEMINI code, and the experimental one from Ref. [17], for the 35 MeV/nucleon Kr + Nb reaction. As in Ref. [17] we have selected particles with $3 \leq Z \leq 7$ detected at polar angles $7° \leq \theta_{\rm lab} \leq 35°$. The energy thresholds and the detection system granularity are taken into account. The linear momentum transfer (LMT) was taken to be 100%, and the impact param-

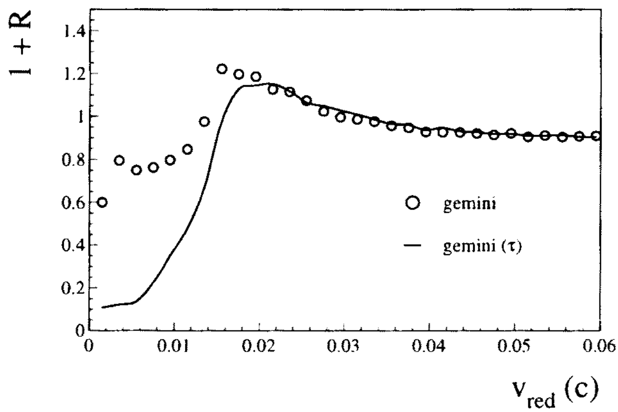

Fig. 4. Reduced velocity correlations for particles with $2 \leq Z \leq 8$. Calculations were performed with the GEMINI code, with no-time-scales (gemini), and with time scales calculated from decay widths (gemini(τ)). The ^{70}Se nucleus was excited to 520 MeV. Sample of 100000 events.

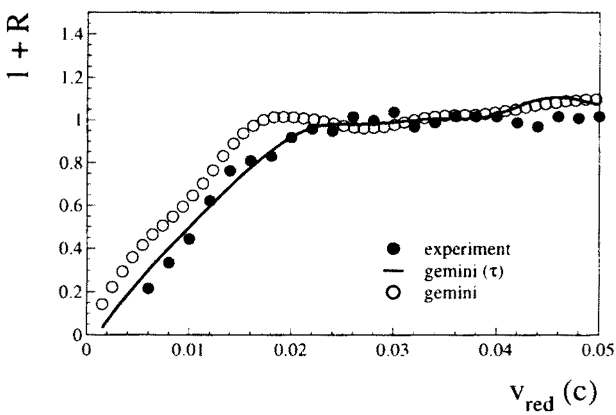

Fig. 5. Reduced velocity correlations for particles with $3 \leq Z \leq 7$, for 35 MeV/nucleon Kr + Nb reaction with LMT = 100%. $7° \leq \theta_{\rm lab} \leq 35°$. Experimental data (experiment), are compared with predictions of the GEMINI code with time scales (gemini(τ)), and with no-time-scales (gemini).

eter was taken from 0 to $0.3b_{\rm max}$, where $b_{\rm max}$ is the maximum estimated impact parameter [17]. As one can see the "Coulomb hole" for small reduced velocities is well reproduced by the new GEMINI code. It confirms the sequential decay scenario in this reaction [17]. The standard GEMINI code which does not include the dynamics nor the time scales reduces the size of the "Coulomb hole", and does not reproduce the experimental data.

In conclusion, the modified version of the GEMINI code with time scales and Coulomb trajectory calculations has been presented. This version of GEMINI produces narrower energy spectra of IMFs, suggesting that the successive acts of emission are not independent. Such effect is not present in the light particle and in the heavy particle energy spectra. The GEMINI code with time scales gives a strong reduction of the correlation function for small values of the reduced velocity, what finds confirmation in the experimental data. It is important for experimental evaluations of decay times.

I wish to thank dr Annick Lléres for her help during the preparation of the new version of the GEMINI code.

I appreciate the interesting and fruitful discussions with all my colleagues from the ISN Amphora Group, and particularly with drs. A. Chabane, A.J. Cole, P. Désesquelles, A. Giorni, D. Heuer, A. Lléres, J.B. Viano, and with drs. J. Brzychczyk, K. Grotowski, R. Płaneta, Z. Sosin, A. Wieloch from the M. Smoluchowski Institute of Physics.

REFERENCES

[1] R.J. Charity *et al.*, *Nucl. Phys.* **A483**, 391 (1988).

[2] *e.g.* T. Kozik *et al.*, *Z. Phys.* **A326**, 421 (1987); K. Grotowski *et al.*, *Phys. Lett.* **B223**, 287 (1989); A.J. Cole, *Phys. Rev.* **C40**, 1265 (1989).

[3] H. Hauser, H. Feshbach, *Phys. Rev.* **87**, 366 (1952).

[4] W.J. Świątecki, *Aust. J. Phys.* **36**, 641 (1983).

[5] L.G. Moretto, *Nucl. Phys.* **A247**, 211 (1975).

[6] M.A. McMahan, J.M. Alexander, *Phys. Rev.* **C21**, 1261 (1980).

[7] I. Dostrovsky, Z. Fraenkel, G. Freiedlander *Phys. Rev.* **116**, 683 (1959).

[8] H.J. Krappe, J.R. Nix, A.J. Sierk, *Phys. Rev.* **C20**, 992 (1979); P. Moller, J.R. Nix, *Nucl.Phys.* **A361**, 117 (1981); A.J. Sierk, *Phys.Rev.* **C33**, 2039 (1986); K.T. Davis, A.J. Sierk, *Phys. Rev.* **C31**, 915 (1985).

[9] B. Borderie, *Ann. Phys.(Paris)* **17**, 349 (1992).

[10] P. Pawłowski *et al.*, *Phys. Rev.* **C54**, R10 (1996).

[11] R. Bougault *et al.*, *Phys. Lett.* **B232**, 291 (1989); Y.D. Kim *et al.*, *Phys. Rev. Lett.* **67**, 14 (1991).

[12] A. Elmaani *et al.*, *Phys. Rev.* **C43**, 2474 (1991).

[13] D.J. Hinde *et al.*HMI , Rep. ANU-1094.

[14] F. Garcias *et al.*, *Phys.Lett.* **B255**, 311 (1991).

[15] W. Gawlikowicz, K. Grotowski, *Nucl. Phys.* **A551**, 73 (1993).

[16] A.J. Cole *et al.*. *Phys. Rev.* **C47**, 1251 (1993).

[17] E. Bauge *et al.*, *Phys. Rev. Lett.* **70**, 3705 (1993).