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A MODEL FOR STATISTICAL MULTISTEP REACTIONS
(CODE EXIFON)

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A Model for Statistical Multistep Reactions (code EXIFON)

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A model for statistical multistep direct and multistep compound reactions is presented. It predicts emission spectra for neutrons, protons, alphas, and photons including equilibrium, preequilibrium, direct (collective and non-collective) as well as multiple particle emission processes. The range of validity: mass numbers $A \geq 27$, bombarding energies below 30 MeV. All calculations are performed *without* any free parameter.

1. Introduction

A unique description of (a,xb) emission spectra where a,b = n,p,α, and γ (neutron, proton, alpha, and γ-ray) as well as excitation functions (activation cross sections) is proposed within a pure statistical multistep approach /1-4/. This approach is based on random matrix physics /5,6/ and was derived from Green's function formalism /7/. In this model the total emission spectrum of the process (a,xb) is divided in three main parts,

$$\frac{d\sigma_{a,xb}(E_a)}{dE_b} = \frac{d\sigma^{SMD}_{a,b}(E_a)}{dE_b} + \frac{d\sigma^{SMC}_{a,b}(E_a)}{dE_b} + \frac{d\sigma^{MPE}_{a,xb}(E_a)}{dE_b} \quad . \tag{1}$$

The first term denotes the statistical multistep direct (SMD) part and contains one- and two-step contributions. The second term symbolizes the statistical multistep compound (SMC) emission. Both terms together represent the so-called *first-chance* emission process. Otherwise, the multiple particle emission (MPE) reactions which include the *second-chance*, *third-chance* emissions, etc. are summarized in the last term, i.e.,

$$\frac{d\sigma^{MPE}_{a,xb}(E_a)}{dE_b} = \sum_c \frac{d\sigma_{a,cb}}{dE_b} + \sum_{c,d} \frac{d\sigma_{a,cdb}}{dE_b} + \ldots \quad . \tag{2}$$

The following (model-independent) relations between the optical-model (OM) reaction cross section and the integral partial cross sections should be satisfied (at incident energy E_a)

$$\sigma^{OM}_a = \sum_b \sigma_{a,b} \quad , \tag{3a}$$

$$\sigma_{a,b} = \sum_c \sigma_{a,bc} \quad \text{and} \quad \sigma_{a,bc} = \sum_d \sigma_{a,bcd} \quad , \quad \text{etc.,} \tag{3b}$$

with $\sigma_{a,b} = \sigma^{SMD}_{a,b} + \sigma^{SMC}_{a,b}$ as the total first-chance emission cross section. In this context, activation cross sections are given by

$$\sigma_{a,b\gamma} = \sigma_{a,b} - \sum_{c\neq\gamma} \sigma_{a,bc} \quad , \tag{4a}$$

$$\sigma_{a,cb\gamma} = \sigma_{a,cb} - \sum_{d\neq\gamma} \sigma_{a,cbd} \quad , \tag{4b}$$

where b,c,d $\neq \gamma$. More explicitly, the (n,p)-, (n,α)-, and (n,2n)-excitation functions have the form

$$\sigma_{n,p\gamma} = \sigma_{n,p} - \sigma_{n,pn} - \sigma_{n,2p} - \sigma_{n,p\alpha} \quad , \tag{5a}$$

$$\sigma_{n,\alpha\gamma} = \sigma_{n,\alpha} - \sigma_{n,\alpha n} - \sigma_{n,\alpha p} - \sigma_{n,2\alpha} \quad , \tag{5b}$$

$$\sigma_{n,2n\gamma} = \sigma_{n,2n} - \sigma_{n,3n} - \sigma_{n,2np} - \sigma_{n,2n\alpha} \tag{5c}$$

Finally, the double-differential emission cross-section is defined by

$$\frac{d^2\sigma_{a,xb}(E_a)}{dE_b d\Omega_b} = \frac{d\sigma^{SMD}_{a,b}(E_a)}{dE_b} \sum_{L=0}^{4} \frac{2L+1}{4\pi} a_L(E_b) P_L(\cos\theta) + \frac{1}{4\pi}\left[\frac{d\sigma^{SMC}_{a,b}(E_a)}{dE_b} + \frac{d\sigma^{MPE}_{a,xb}(E_a)}{dE_b}\right] \tag{6a}$$

$$= \frac{d\sigma_{a,xb}(E_a)}{dE_b} \sum_{L=0}^{4} \frac{2L+1}{4\pi} f_L^{(a,xb)}(E_a,E_b)\, P_L(\cos\theta) \tag{6b}$$

with

$$f_L^{(a,xb)}(E_a,E_b) = \left[\frac{d\sigma^{SMD}_{ab}(E_a)}{dE_b} \Big/ \frac{d\sigma_{a,xb}(E_a)}{dE_b}\right] a_L(E_b) \ . \tag{6c}$$

Here, the angular distribution of SMC and MPE emissions is assumed to be isotropic, while for SMD processes the empirical systematics $a_L(E_b)$ of Kalbach and Mann /8/ are adopted ($L \leq 4$).

The following abbreviations are used: $E=E_a+B_a$ and $U=E_a+B_a-B_b-E_b$ are the excitation energies of the composite and residual systems; B_c and $E_c=\hbar^2k_c^2/2\mu_c$ are the binding and kinetic energies.

2. Residual Interaction

The simplest effective (two-body) interaction which predicts collective and non-collective phenomena is the surface-delta interaction firstly proposed by Green and Moszkowski in /9/,

$$I(\vec{r}_1,\vec{r}_2) = -4\pi \frac{F_o}{A} [\chi_{nl}(R)]^{-4} \delta(r_1-R)\, \delta(r_2-R) \sum_{\lambda\mu} Y^*_{\lambda\mu}(\hat{r}_1) Y_{\lambda\mu}(\hat{r}_2) \quad (7)$$

The strength parameter F_o= 27.5 MeV was obtained from nuclear structure considerations in /10/. This strength parameter will be used in this nuclear reaction model too. Due-to the factor $[\chi_{nl}(R)]^{-4}$ this force is state-independent.

The effective interaction leads to the following mean squared matrix elements (see Ref./4/)

$$\overline{I^2} = \frac{1}{4} (k_F R)^{-2} A^{-1/3} (F_o/A)^2 = 137\, r_o^{-2} A^{-3} \quad (\text{in MeV}^2) \quad (8)$$

for the bound-bound transition I_{BB}. For all other bound/unbound types of matrix elements (I_{BU}, I_{UB}, I_U) we have the parameterization,

$$\overline{I^2_a}(E_a) = \frac{2}{3} \frac{\rho(E_a)}{4\pi} \frac{E_F}{E_a} \overline{I^2} \quad ; \quad \overline{I^2_b}(E_b) = \overline{I^2}\, (2s_b+1) \frac{2}{3} \rho(E_b) \; ; \quad (9)$$

$$\overline{I^2_{ab}}(E_a,E_b) = \frac{2}{3} \frac{\rho(E_a)}{4\pi} \frac{E_F}{E_a} \overline{I^2} \frac{2}{3} \rho(E_b) \; . \quad (10)$$

Here, the single-particle state density of particle c = n,p,α with mass μ_c is given by

$$\rho(E_c) = \frac{4\pi\, \mathcal{V}\, \mu_c k_c}{(2\pi)^3 \hbar^2} = \frac{r_o^3\, A\, E_c^{1/2}}{893} \quad (\text{in MeV}^{-1}) \quad (11)$$

where $\mathcal{V} = 4\pi R^3/3$ is the nuclear volume and $R=r_o A^{1/3}$ is the nuclear radius (in fm). At Fermi energy E_F= 40 MeV we obtain for r_o= 1.40 fm the well-known value

$$g = 2\,(2s+1)\, \rho(E_F) = A/13 \quad (\text{in MeV}^{-1}) \quad (12)$$

The factor 2 in (12) represents the isospin degeneracy. For the calculations we use the following (renormalized) radius parameter

$$r_o(A) = r_{WS}\, [\, 1 + (\pi a/R)^2 \,]^{1/3} \quad (13)$$

where r_{WS} is the radius parameter of the global OM Woods-Saxon potential of Wilmore-Hodgson /11/ and a is its diffuseness. For A≃50 we have $r_o(A) \simeq 1.40$ fm.

3. SMD Cross Section

For the incident-energy range below 30 MeV we restrict ourselves to one- and two-step contributions since the SMD process terminates after few collisions. According to the distinction between non-collective particle-hole excitations [ex] and collective vibrational states [vib] the SMD cross section becomes a sum of 2 one-step and 4 two-step contributions (b = n,p),

$$\frac{d\sigma_{ab}^{SMD}(E_a)}{dE_b} = \frac{\mu_a \mu_b \mathcal{V}^2}{(2\pi\hbar^2)^2} \frac{4\pi}{(k_a R)^2} \frac{k_b}{k_a} \mathcal{P}_a(E_a)\, \mathcal{P}_b(E_b) \sum_{[y]} [\ y\ ] \qquad (14)$$

where [y] symbolizes the individual contributions denoted according to the sequence of exciton and phonon excitations,

$$[ex] = \frac{1}{2}(1+\delta_{ab}) \left[\frac{2}{3} F_o A^{-4/3} g/2 \right]^2 U \ , \qquad (15a)$$

$$[vib] = \delta_{ab} \sum_{\lambda} \frac{1}{2} \left[\frac{2}{3} V_o \right]^2 \frac{1}{4\pi} \beta_\lambda^2\, \delta(U-\omega_\lambda) \ , \qquad (15b)$$

$$[2ex] = (1+\delta_{ab}) \left[\frac{2}{3} F_o A^{-4/3} g/2 \right]^2 q\, \frac{U^3}{6} \ , \qquad (15c)$$

$$[ex,vib] = (1+\delta_{ab}) \left[\frac{2}{3} F_o A^{-4/3} g/2 \right]^2 q \sum_{\lambda} \frac{1}{2} \left[\frac{2}{3} V_o \right]^2 \frac{1}{4\pi} \beta_\lambda^2\, \delta(U-\omega_\lambda)$$

$$[vib,ex] = \delta_{ab}\ [ex,vib] \ , \qquad (15e)$$

$$[2vib] = \delta_{ab} \sum_{\lambda\lambda'} \left[\frac{1}{2} \left[\frac{2}{3} V_o \right]^2 \frac{1}{4\pi} \right]^2 \beta_\lambda^2\, \beta_{\lambda'}^2\, q\, \delta(U-\omega_\lambda-\omega_{\lambda'}) \ . \qquad (15f)$$

The real OM potential depth is taken as V_o = 48 MeV. Otherwise, the quantities ω_λ and β_λ denote the energy and deformation parameters of a phonon with multipolarity λ. Here, we restrict ourselves to two low-lying vibrational states of multipolarity $\lambda^\pi = 2^+$ and 3^- taken from nuclear tables /12,13/. For odd-mass nuclei the weak coupling model /14/ was adopted. All delta functions are replaced by Gaussians of width 0.7 MeV simulating both the limited (exit channel) energy resolution in experiments and the spreading of spectroscopic strength. Further, $q = (\pi/2)(\rho(E)/kR)^2 = 4.12\ 10^{-5}\ r_o^4 A^{4/3}\ \mathrm{MeV}^{-2}$. Pairing corrections are included by modification of U.

In (p,n)-reactions isobaric-symmetry effects should be considered /15/. Therefore, the transition rate, $\bar{I}_{ab}^2 (g/2)^2 U$, has to be diminished by a factor 1/2 (since the 1p1h-excitation of a proton and a neutron hole in the residual nucleus has isospin T=0 or 1 but only one of them is preferred).

Coulomb effects are considered by the phenomenological penetration factor,

$$\mathcal{P}_c(E_c) = \sigma_c^{OM}(E_c)/\sigma_n^{OM}(E_c) \quad , \tag{16}$$

which influences the ingoing and outgoing channels in (13). $\sigma_c^{OM}(E_c)$ is the OM reaction cross section for particle type c = n, p, α taken from /16/. This factor is 1 for neutrons.

The SMD-process for γ-emission is treated as a two-step process: formation of a 1p1h-doorway state and its decay. (This phenomenological descriprion will be improved in future.)

4. SMC Cross Section

The SMC cross section has the familiar form (b = n,p,α,γ)

$$\frac{d\sigma_{ab}^{SMC}(E_a)}{dE_b} = \sigma_a^{SMC}(E_a) \sum_{N=N_0}^{N'} \frac{\tau_N(E)}{\hbar} \Gamma_{Nb}(E,E_b)\uparrow \quad . \tag{17}$$

where $\tau_N(E)$ satisfies the time-integrated master equation,

$$-\hbar\, \delta_{NN_0} = \Gamma_{N-2}^{(+)}(E)\downarrow \tau_{N-2}(E) + \Gamma_{N+2}^{(-)}(E)\downarrow \tau_{N+2}(E) - \Gamma_N(E)\tau_N(E) \quad , \tag{18}$$

for each exciton number $N=N_p+N_h$. The sum in Eq.(17) runs from N_0 up to a reliable maximum $N' = (2gE)^{1/2}$ which includes the so-called "equilibrium stage" $\bar{N} \simeq (1.4gE)^{1/2}$. The initial exciton number is N_0= 2, 3, or 6 for photon-, nucleon-, or α-induced reactions.

Here, the damping widths are given by /17/

$$\Gamma_N^{(+)}(E)\downarrow = 2\pi\overline{I^2}\ (N_h/N)\ g^2\ E\ (U/E)^N \tag{19a}$$

$$\Gamma_N^{(-)}(E)\downarrow = 2\pi\overline{I^2}\ \tfrac{1}{2}\ g\ N_p N_h (N-2) \quad . \tag{19b}$$

The total widths is defined by

$$\Gamma_N(E) = \Gamma_N^{(+)}(E)\downarrow + \Gamma_N^{(-)}(E)\downarrow + \sum_b \sum_{\Delta N} \int dE_b\ \Gamma_{Nb}^{(\Delta N)}(E,E_b)\uparrow \quad , \tag{20}$$

where the sum runs over all particle-types b = n,p,α, and γ. Here, the partial escape widths for b = n, p, and α are given by

$$\Gamma_{Nb}^{(\Delta N)}(E,E_b)\uparrow = 2\pi\ \overline{I_b^2}(E)\ \rho_{N-N_b}^{(\Delta N)}(E-B_b^{eff}-E_b)\ \mathcal{P}_b(E_b) \tag{21}$$

with three modes of the final state density (ΔN = 2,0,-2),

$$\rho^{(+)}_{N-1}(U) = (N_h/N)\ g^2\ E\ (U/E)^N\ , \tag{22a}$$

$$\rho^{(0)}_{N-1}(U) = N_p(N_h + \frac{N_p-1}{2})\ g\ (U/E)^{N-2}\ \left[\ (N-1)-(N-2)(U/E)\ \right]\ , \tag{22b}$$

$$\rho^{(-)}_{N-1}(U) = \frac{N_p(N_p-1)N_h}{4E}\ \frac{(N-1)!}{(N-4)!}\ (U/E)^{N-4}\ \left[\ 1-\ (U/E)\ \right]^2\ . \tag{22c}$$

which are firsty proposed in /18/. Note, however, the factor N_h/N in (22a) which excludes pair-creation by *particle*-scattering. For α-particles (b=α) the partial escape widths has to be multiplied by the preformation factor /19/

$$F_{13}(E_\alpha) = 0.28144 - 0.01113\ E_\alpha + 1.34\ 10^{-4}\ E_\alpha^2\ , \tag{23}$$

which plays the dominant role for emission energies below 20 MeV. Additionally, a factor of 2 (spin-degeneracy of the active nucleon in the formation mode [1,3] of the α-particle) is considered.

The escape width for γ-emission (b=γ) has the form ($U=E-E_\gamma$),

$$\Gamma_{N\gamma}(E,E_\gamma)\hat{\uparrow} = 2\pi\ D^2(E)\ 2\ \rho(E_\gamma) \sum_{\Delta N} \rho_N^{(\Delta N)}(E-E_\gamma)\ , \tag{24}$$

where the sum runs over two escape-modes (ΔN = 0,-2) defined by

$$\rho_N^{(0)}(U) = Ng\ \left(\frac{U}{E}\right)^{N-1}\ ;\ \rho_N^{(-)}(U) = N_pN_h(N-1)(N-2)\left(\frac{E_\gamma}{E^2}\right)\left(\frac{U}{E}\right)^{N-3}. \tag{25}$$

To obtain the electro-magnetic interaction $D^2(E)$ the γ-emission is assumed as pure dipole emission. Adopting the Brink hypothesis /20/ it can be deduced from the formation cross section of a 1p1h-doorway state,

$$\sigma_\gamma^{GDR}(E_\gamma) = \sigma^{1p1h}(E_\gamma) = \frac{2\pi\mathcal{V}}{\hbar c}\ \overline{D^2}(E)\ g^2E_\gamma\ . \tag{26}$$

For σ_γ^{GDR} the Lorentzian form of Ref.21 was used. Similar to (11) the photon state density in (24) is given by

$$\rho(E_\gamma) = \frac{4\pi\ \mathcal{V}\ k_\gamma}{(2\pi)^3 c\hbar} = 2.76\ 10^{-8}\ r_o^3\ A\ E_\gamma^2 \quad \text{in MeV}^{-1}\ . \tag{27}$$

The SMC-formation cross section in (17) is defined by

$$\sigma_a^{SMC}(E_a) \equiv \frac{(2\pi)^4}{k_a^2}\ \mathcal{P}_a(E_a)\ \overline{I_a^2}(E_a)\ g^3E^2/4 = \frac{2\pi\mathcal{V}}{\hbar v_a}\ \mathcal{P}_a(E_a)\ \overline{I^2}\ g^3E^2/4\ . \tag{28}$$

However, for incident energies below 3 MeV and above ≃18 MeV this simple formula overpredicts the cross section. Therefore, we replace it by

$$\sigma_a^{SMC}(E_a) = \sigma_a^{OM}(E_a) - \sum_b \sigma_{a,b}^{SMD}(E_a) \quad . \tag{29}$$

which holds in the whole energy range. Eq.(29) is taken from probability conservation.

The following nuclear structure effects are included in the SMC description:

(i) *Pairing effects*. For a system of A=N+Z nucleons the effective neutron (proton) binding energy is defined by

$$B_{n(p)}^{eff} = \begin{cases} B_{n(p)}+\Delta & \text{for odd} \\ B_{n(p)}-\Delta & \text{even} \end{cases} \quad N\ (\ Z\ )\ , \tag{30}$$

where $B_{n(p)}$ is the neutron (proton) binding energy, and $\Delta = 12\ A^{-1/2}$ MeV. For α- and γ-emissions we use $B_\alpha^{eff} = B_\alpha$ and $B_\gamma^{eff} = 0$. The effective binding energy is used in (21) as well as for the definition of the (effective) excitation energy, $E=E_a+B_a^{eff}$.

(ii) *Pauli blocking effects*. The excitation energies E and U are replaced by $E-A_{ph}$, $U-A_{p-1,h}$ (for particle emission), and $U-A_{ph}$ (for γ-emission). The energy shift is defined by $A_{ph} = (N_p^2+N_p+N_h^2-3N_h)/4g$.

(iii) *Shell-structure effects*. The constant single-particle state density g in (12) will be multiplied by an energy-dependent factor which leads to /22/,

$$g(\mathcal{E}) = g\ (\ 1 + \frac{\delta W}{\mathcal{E}}\ (1-\exp(-0.05/\mathcal{E})))\quad , \tag{31}$$

with δW as the shell correction energy taken from tables /23/. The quantity $\mathcal{E}$ = E or U denotes here the excitation energy of the composite or residual systems.

(iv) *Low energy behaviour*. The penetrability through the nuclear barrier is considered by the additional factor /14/

$$\mathcal{P}_c'(E_c) = 4k_cK\ (K+k_c)^{-2} \tag{32}$$

in the ingoing and outgoing channels. $K = [2\mu(E+E_F)]^{1/2}/\hbar$ is the wave number inside the nucleus.

5. Multiple Particle Emission (MPE)

The MPE is treated as a pure SMC approach. Thus, for second-chance processes (a,cb) with $c \neq \gamma$, we write

$$\frac{d\sigma_{a,cb}(E_a)}{dE_b} = \int dE_c \, \frac{d\sigma_{a,c}(E_a)}{dE_c} \, \mathcal{N}_{a,cb}(E_1,E_b) \quad , \tag{33}$$

with $E_1 = E - B_c^{eff} - E_c$ as the intermediate energy. Here, the emission probability is given by

$$\mathcal{N}_{a,cb}(E_1,E_b) \equiv \sum_{N=N_0}^{N'} \frac{\tau_{N-1}(E_1)}{\hbar} \, \Gamma_{N-1,b}(E_1,E_b)\hat{\Gamma} \quad , \tag{34}$$

which is normalized according to

$$\sum_b \int dE_b \, \mathcal{N}_{a,cb}(E_1,E_b) = 1 \quad . \tag{35}$$

The escape widths in (34) are calculated by Eqs.(21) and (24) using the residual excitation energy

$$U_{ph} = E_1 - A_{ph} - E_b - B_b^{eff} - k\Delta \tag{36}$$

with k = 1. (In general, e.g., if we consider magic-number nuclei, we have k = -1, 0, or 1 depending on the reaction channel.)

The above MPE-formalism is more general than the MPE-expressions reported earlier in /1,2/. As obvious from (33) and (34) the master equation (18) should be solved for each intermediate energy E_1. An extension of this formalism to higher-chance emission processes like (a,cdb), etc. is straightforward.

In total γ-emission spectra (a,xγ) the full cascade deexcitation (for example (a,c$\gamma\gamma$), (a,c$\gamma\gamma\gamma$), etc.) is not taken into account so far.

6. CODE EXIFON (VERSION 1.0)

Range of applicability:	mass number A > 25
	incident energy E_a < 30 MeV
incomming/outgoing particles:	neutron, proton, alpha, photon

Computer:	PC/AT
Language:	FORTRAN 77
Memory size:	175 kByte
Lines:	ca. 960
Number of subroutines:	10
Running time:	ca. 40 s at $E_a \simeq$ 14 MeV
Input-data file:	for each nucleus 0.6 kByte (including binding energies, shell-correction energies, phonon parameters)

Input:

1. Target nucleus (A,Z)
2. Incident particle-type a
3. Incident energy E_a

(4. only for excitation functions: Number and bin of incident energies)

5. *standard* or *modified* describtion

Options for modified description:

1. gamma emission:	0	-	no
	1	-	yes ←
2. proton global OM potential:	0	-	Perey ←
	1	-	Becchetti-Greenlees
	2	-	Menet et al.
3. strength parameter of the residual interaction (F_o=25.7 MeV)			
4. 1-step direct (exchange) process:	0	-	no
	1	-	yes ←
5. 2-step direct (exchange) process:	0	-	no
	1	-	yes ←

(The arrow indicates the *standard* description)

Output:

1. Emission spectra for all (a,xb)-channels
2. Angular distributions of neutrons and protons in form of Legendre-coefficients (L ≤ 4)

(emission energy-bin: ΔE_b= 0.2 MeV)

3. Activation cross-sections (a,p, (a,α), (a,2n), (a,3n), etc.

Output-data prepared in files for:

- graphic software (e.g., PLOTCALL) [in subroutine PLOT]
- data libraries MF3 and MF6 in ENDF-6 format /24/ [in subroutine ENDF; to be published]

dimensionalities: energy - MeV (incident energy in LS, emission energy in CS)
length - fm
cross section - mb

Output-data files:

AXN.DAT	E_n , $d\sigma_{a,xn}/dE_n$, $d\sigma_{a,n}/dE_n$, $d\sigma^{SMC}_{a,n}/dE_n$, $d\sigma^{SMD}_{a,n}/dE_n$
AXP.DAT	E_p , $d\sigma_{a,xp}/dE_p$, $d\sigma_{a,p}/dE_p$, $d\sigma^{SMC}_{a,p}/dE_p$, $d\sigma^{SMD}_{a,p}/dE_p$
AXA.DAT	E_α , $d\sigma_{a,x\alpha}/dE_\alpha$, $d\sigma_{a,\alpha}/dE_\alpha$, $d\sigma^{SMC}_{a,\alpha}/dE_\alpha$
AXG.DAT	E_γ , $d\sigma_{a,x\gamma}/dE_\gamma$, $d\sigma_{a,2n\gamma}/dE_\gamma$, $d\sigma_{a,\gamma}/dE_\gamma$, $d\sigma^{SMD}_{a,\gamma}/dE_\gamma$
A2N.DAT	E_a , $\sigma_{a,2n\gamma}(E_a)$, $\sigma_{a,2n}(E_a)$, $\sigma_{a,3n}(E_a)$
AP .DAT	E_a , $\sigma_{a,p\gamma}(E_a)$, $\sigma_{a,p}(E_a)$
ALF.DAT	E_a , $\sigma_{a,\alpha\gamma}(E_a)$, $\sigma_{a,\alpha}(E_a)$

Definitions of emission spectra: $(a,c,b = n,p,\alpha,\gamma)$

partial *first*-chance emission: $(a,\underline{b}c)$
partial *second*-chance emission: $(a,c\underline{b})$
total first-chance emission: $(a,b) \equiv \sum_c (a,\underline{b}c)$
total emission: $(a,xb) \equiv (a,b) + \sum_c (a,c\underline{b}) + \ldots$
(approximation: $(a,\gamma b) \simeq 0$)

Arrays of emission spectra:

K = emission energy point (step = 0.2 MeV)
I = particle type 0 - n , 1 - p , 2 - α , 3 - γ

SMG(K,I,M) = SMG(0:200,0:3,2) M = 1 - (a,b)
= 2 - (a,xb)
SMD(K,I,N) = SMD(0:200,0:1,0:5) N = 0 - SMD part of (a,b)
(= [ex]+[vib]+[2ex]+[ex,vib]+[vib,ex]+[2vib])
= 1 - [ex]
= 2 - [vib]

= 3 - [2ex]
= 4 - [ex,vib] + [vib,ex]
= 5 - [2vib]

SMC(K,I,1) = SMC(0:200,0:2,1) - SMC part of (a,b)

SMC(K,I,IS) - partial second-chance emission:

	I = 0	1	2	3
IS = 2	(a,nn)	(a,np)	(a,nα)	(a,nγ)
3	(a,pn)	(a,pp)	(a,pα)	(a,αγ)
4	(a,αn)	(a,αp)	(a,αα)	(a,αγ)
5	(a,2nn)	(a,2np)	(a,2nα)	(a,2nγ)

SGA(K,I,M) - partial first-chance emission:

	I = 0	1	2
M = 0	(a,nn)	(a,pn)	(a,αn)
1	(a,np)	(a,pp)	(a,αp)
2	(a,nα)	(a,pα)	(a,αα)
3	(a,nγ)	(a,pγ)	(a,αγ)

FL(K,I,L) = FL(0:200,0:1,4) - Legendre coefficients $F_L^{(a,xb)}(E_a,E_b)$

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