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International Nuclear Model and Code Comparison on Pre-Equilibrium Effects

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I. Introduction

This paper gives the specification of an intercomparison of statistical nuclear models and codes with emphasis on pre-equilibrium effects. It is partly based upon the conclusions of a meeting of an ad-hoc working group on this subject (see document NEANDC-A-137), on some criticism by Prof. M. Blann, communicated to the NEA Data Bank by Dr. M. Uhl, and on some suggestions of the present authors. We are very grateful to Drs. Betak, Blann, Fu, Gardner, Gmuca, Gupta, Herman, Mann, Ribansky, Seeliger, Garg, Uhl and Young for their comments on the draft version of this document. Most of the remarks have been included in the updated specifications given in this paper. The present proposal deviates from the previous one mainly in the choice of a somewhat heavier nucleus : ^{93}Nb instead of ^{59}Co. Using ^{93}Nb has several advantages:

1. The pre-compound part of the neutron emission spectrum is more pronounced than that of ^{59}Co.

2. This nucleus is quite well studied with respect to pre-equilibrium aspects, both experimentally and theoretically; it is often used as a "sample problem" in nuclear model calculations to illustrate pre-equilibrium effects.

3. There are experimental data for neutron emission spectra and angular distributions not only at 14.6 MeV, but also at 25.7 MeV(1). Furthermore, there are experimental data for σ_{n2n} and σ_{n3n} from 14.6 to 24 MeV(2). Proton-emission data including angular distributions are also available at 15 MeV (13, 14).

It is realised that the previous nucleus ^{59}Co is well studied in the statistical-model exercise and that it requires some additional effort by the participants to change to another nucleus. However, we think that the above-mentioned arguments are convincing, in particular point 3.

The character of this exercise differs from the equilibrium exercise in that the pre-equilibrium models currently in use are quite different. Therefore it is more correct to speak about a model intercomparison rather than a code intercomparison. Since the models differ in the modelling of pre-equilibrium aspects, we cannot specify all the parameters.

Therefore we restrict these to:

1. Masses, Q-values,
2. Level-scheme data (discrete levels),
3. Optical-model parameters (global spherical potential),
4. γ-ray competition parameters,
5. total level-density specification.

The parameters, specific for the precompound emission are not prescribed. Instead it is required to fit the 14.6 MeV total neutron emission spectrum $\frac{d\sigma}{d\epsilon}$ at ϵ = 6 to 9 MeV, where precompound emission dominates. The participants should therefore specify their model and the parameters used. To facilitate this task, a questionnaire has been included (Appendix A).

The main quantity to be calculated is the total neutron emission spectrum $\frac{d\sigma}{d\epsilon}$ as a function of incoming energy E and outgoing energy ϵ. These angle-integrated spectra should be calculated at E = 10, 14.6, 20 and 25.7 MeV. Comparison with experimental data will be performed at the NEA Data Bank. If possible, also the reduced Legendre coefficients of the angular distributions should be calculated. Other important quantities to be calculated are: $\sigma_{nn'\gamma}$, σ_{n2n}, $\sigma_{np\gamma}$, $\sigma_{n\alpha\gamma}$ and their energy spectra (angle-integrated).

Finally, for the more sophisticated model codes, it is requested to calculate the total energy-integrated particle-production cross sections, the isomeric state population from the (n,n') and (n,2n) reactions and the total photon production cross section (at 14.6 MeV).

It is not necessary to include width-fluctuation corrections in the calculations. There is also no need to calculate $\sigma_{n\gamma}$ in this exercise. However, γ-ray competition should be included (if possible) to calculate the multi-particle emission cross sections (and isomeric-state populations).

2. Masses, Q-values, etc.

The masses and Q-values should be taken from a recent nuclear mass table. Some values are provided in Table 3a(18).

3. Level scheme data (discrete levels)

The level schemes of most of the residual nuclei are specified in Table 1. These data are usually based upon recent issues of the Nuclear Data Sheets. The first energy of the continuum calculation, E_c, is indicated in Table 3a.

Notes: 1. For codes that calculate only continuum emission, these data are not relevant.
2. For other residual nuclei, the participants should perform a continuum calculation only, assuming E_c= 0.1 MeV.
3. For ^{92}Nb and ^{93}Nb γ-ray branchings are given for discrete levels.

4. Optical model

In this exercise, a spherical optical model is used, of which the definition of the parameters is given in Table 2a. The selected global optical-model parameters are given in Table 2b.

For neutrons and protons, parametrisation close to those of F.G. Perey (e.g. (3)) have been selected. These parametrisations should work well at energies from 0.9 to 22 MeV. Please indicate when the channel-spin dependence of the transmission coefficients has been neglected (T_l instead of T_{lj}).

For neutrons, we have checked that the potential is in reasonably good agreement with available experimental ^{93}Nb data for σ_t and σ_{el} from 1 to 15 MeV.

For α-particles, the potential of Igo and Huizenga(4) has been selected.

5. Gamma-ray parameters

For the calculation of γ-ray competition the Brink-Axel giant-dipole model should be used to describe E1 transitions. For all residual nuclides, the same data are prescribed, i.e.

$$E_r = 16.5 \text{ MeV},$$
$$\Gamma_r = 5.0 \text{ MeV},$$
$$\sigma_r = 0.162 \text{ b}.$$

Using these parameters, the following value of the total s-wave radiation width is obtained for the reaction ^{93}Nb(n,γ) ^{94}Nb at the neutron binding energy:

$$\langle\Gamma_\gamma(l=0)\rangle = 165 \text{ meV}.$$

The value $\langle\Gamma_\gamma\rangle$/Dobs amounts to 0.166 x 10^{-4}. If necessary, a normalisation constant in the Brink-Axel formula should be used to obtain this value (the same normalisation constant should be used in each residual nucleus). The authors should specify their formalism used.

Note: If no γ-ray competition is used, the participants should clearly indicate this.

For γ-ray cascade calculations (isomeric state population), the M1 and E2 electromagnetic transitions should be allowed with the strengths of M1 and E2 set to: strength (E1/M1) = strength (M1/E2) = .10, relative to the total E_1 radiation width for s-wave resonances of the reaction ^{93}Nb(n,γ)^{94}Nb at the neutron binding energy ($\Gamma\gamma$= 165 meV) (the same normalisation constants should be used for each residual nucleus). For the energy dependences of the M1 and E2 transitions the Weisskopf formula should be used.

The branching ratios for ^{92}Nb and ^{93}Nb levels are given in Table 1. Use theory to obtain branchings for other residual nuclides (only needed for calculation of total photon production).

The participant should specify the Yrast line used in the calculation of the gamma-ray emission data.

6. Total level-density parameters

For the calculation of the equilibrium part - or in the unified codes, the combined pre-equilibrium and equilibrium parts - it is requested to fit the total level density (i.e. summed over all possible particle-hole combinations) at two energies, so that:

1. the total number of levels equals N_c at $E=E_c$;

2. the level spacing of s-wave levels equals Dobs at the neutron binding energy B.

With these conditions, the participant should preferably use the composite Gilbert-Cameron formula(5). When this formula is not programmed, the Fermi-gas formula of Dilg et al(6) or another representation could be used (other formulas could be important in unified models, where it is required that the sum of all particle-hole components equals the total level density).

In Table 3a, the values of the parameters required to calculate N_c and Dobs are specified. When the Gilbert-Cameron formula is used, the pairing energies P of ref. (5) are also prescribed (see Table 3a). Table 3b gives the parameters a, U_x and Δ for three possible representations:

1. Gilbert-Cameron formula with improved definition of the spin cut-off parameter(7):

$$\sigma^2 = 0.146 \sqrt{aU}\, A^{2/3}.$$

2. Gilbert-Cameron formula with original definition of the spin cut-off parameter(5):

$$\sigma^2 = 0.0888 \sqrt{aU}\, A^{2/3}.$$

3. Back-shifted Fermi gas model(6) with:

$$I_{eff} = I_{rigid}.$$

The parameter a follows from the quantity a by means of the relation:

$$a = \frac{\pi^2}{6} g.$$

Notes:

1. The participant should clearly specify the formula used. The preferred representation is formula 1.

2. At low energies the definition of σ^2 is not clear in the case of Gilbert-Cameron. It is suggested to use a linear interpolation between σ^2_{exp} at $E = E_c$ and $\sigma^2(E_x)$ at the dividing energy $E_x = U_x+P$. The value of σ^2_{exp} is given in Table 3a.

3. From some preliminary calculations with the Gilbert-Cameron formula and the back-shifted Fermi gas formula, it follows that the differences in the cross sections due to the use of different level density formulas cannot be neglected, particularly at energies above 10 MeV. This has to be regretted, but it is a basic uncertainty in our model calculations, as long as these simple level-density formulas are used. In some codes, different level-density formulas could be used. The participants are invited to use these options to study the effect of the different approaches. Our preference for the Gilbert-Cameron formula is only based upon the fact that this formula is probably the most widely used.

7. Particle-hole state density

In most cases it is expected that the particle-hole state densities are based upon the expression of Williams(8), possibly with corrections. The exact formula used should be specified, both for the initial and final state densities. When the calculations of precompound parts and compound parts are unified, the sum over all particle-hole level densities should satisfy the conditions given in the previous section. When the precompound calculation is used as a correction to the compound model, one could use the same parameters as used in the equilibrium calculation, including energy shifts or pairing energy corrections. This would facilitate the intercomparison of the results. however, as it is noticed that another parametrisation could be more realistic for pre-equilibrium calculations, deviations are allowed, provided that they are indicated clearly. In many codes only the option $g = A/13$ MeV^{-1} and P=0 is allowed. This should be specified.

When angular momentum is conserved in the calculation, the adopted expression for the p-h spin cut-off parameter should be specified.

8. Precompound parameters

In some codes there are some "free" parameters to fit the emission spectra, such as K occurring in the expression for the average transition matrix elements, e.g.

$$\left| M^2 \right| = \frac{K}{A^3 E}.$$

This, or a similar expression, should be indicated, together with the value of the parameter(s). The value(s) of the free parameter(s) should be adjusted in order to obtain agreement with the (angle-integrated) total neutron emission spectrum at E = 14.6 MeV and ϵ = 6 to 9 MeV:

$$\frac{d\sigma}{d\epsilon}\ (6\text{-}7\ \text{MeV}) = 56.0 \pm 6\ \text{mb/MeV},$$

$$\frac{d\sigma}{d\epsilon}\ (7\text{-}8\ \text{MeV}) = 46.9 \pm 5\ \text{mb/MeV},$$

$$\frac{d\sigma}{d\epsilon}\ (8\text{-}9\ \text{MeV}) = 36.5 \pm 4\ \text{mb/MeV}.$$

These data are obtained from an analysis of the experimental data of Hermsdorf et al(9), performed at ECN, Petten*. At ϵ = 6-9 MeV, most of the emission is due to pre-equilibrium; at higher energies the experimental data are quite uncertain due to direct effects or uncertaintities in the subtraction of the elastic scattering peak.

Other parameters, such as R or Q factors(10,15) should also be specified. Gadioli et al.(11) have proposed $R = \frac{n \pm 1}{n}$, where the "+" and "-" signs refer to neutron and proton emission, respectively, to account for charge conservation. For "unified" models it is desired that these parameters approach unity at equilibrium.

The treatment of the α-channel has also to be described, e.g. according to ref. (12). When fit-parameters are used, such as form-factors, they should be specified.

Parameters for the description of angular distribution are not prescribed. The user should specify the formalism used.

9. Requested calculations

The incident energies for the calculations are E=10, 14.6, 20 and 25.7 MeV. For the outgoing centre-of-mass energies ϵ the energy mesh should be appropriate to describe the data (indicate when the spectra are stored in a histogram form). It is suggested to use at least 1 MeV bins up to 14 MeV, if possible smaller bins up to 2 MeV and 2 MeV bins above 16 MeV. The following quantities need to be calculated.

9.1 Integrated cross sections at 5 incident energies:

a) σ_t, σ_{el}, σ_r (composite-formation cross section),

b) σ_{nnx}, σ_{npx}, $\sigma_{n\alpha x}$ (first emission of n, p, and α respectively),

c) $\sigma_{nn'}$ (inelastic scattering cross section), σ_{n2n}, σ_{n3n}, σ_{nnp}, σ_{np}, σ_{npn}, $\sigma_{n\alpha n}$ (other cross sections are relatively small),

d) total particle (and gas-) production cross sections σ_{nnem}, σ_{npem}, $\sigma_{n\alpha em}$.

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* This analysis was performed by fitting the coefficients of the function $A_o+A_1P_1(\cos\theta)+A_2P_2(\cos\theta)$ through the original data of Hermsdorf et al. (9). The results are in agreement with a similar analysis of Kammerdiener's data (16) and those of Salnikov et al. (17).

Notes: 1) In cases b) to d) it is of interest to indicate the equilibrium component separately; also the full equilibrium calculation (with pre-equilibrium turned off) should be performed (specify equilibrium definition).

2) As intermediate results the transmission coefficients T_l (averaged over j) and/or the inverse reaction cross sections should be given at each incident energy and for each outgoing particle.

9.2 Angle-integrated spectra at 14.6 and 25.7 meV

a) $\frac{d\sigma_{nnx}}{d\epsilon}$, $\frac{d\sigma_{npx}}{d\epsilon}$, $\frac{d\sigma_{n\alpha x}}{d\epsilon}$ (first emission of n, p and α, respectively).

b) Total neutron emission spectra (excluding elastic scattering) $\frac{d\sigma_{nnem}}{d\epsilon}$ (summed over all outgoing neutrons).

9.3 Angular distributions of (total) neutron emission spectra at 14.6 and 25.7 MeV

The preferred representation is given by reduced centre-of-mass Legendre coefficients f_l (l=1, 2, 3) where

$$\frac{d^2\sigma}{d\epsilon d\Omega} = \frac{1}{4\pi}\frac{d\sigma}{d\epsilon}\sum_l (2l+1)\, f_l\, P_l\, (\cos\theta);$$

f_l should be tabulated as a function of ϵ (in c.o.m.).

9.4 γ-ray emission at 14.6 MeV

a) Reaction cross section for the population of the isomeric states ^{93m}Nb and ^{92m}Nb.

b) Total photon-production cross section.

c) γ-ray emission spectrum $\frac{d\sigma}{d\epsilon}$.

The participants are kindly asked to send all information on their codes and to answer the questions in the questionnaire (Appendix A).

Please send your contribution and direct any questions of interpretation related to the specifications, to :

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91191 Gif-sur-Yvette CEDEX
France

The deadline for the solutions to reach the above address is 1st November 1983.

10. References

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Table 1

Level scheme data

LEVELS FOR 86RB

1	0.0	-2.0
2	0.4881	+1.0
3	0.5560	-6.0
4	0.5569	-3.0
5	0.7795	-7.0
6	0.8732	-3.0
7	0.9785	-4.0
8	1.0271	+1.0
9	1.0327	-3.0
10	1.0925	-4.0
11	1.1059	+2.0
12	1.1220	+1.0
13	1.1560	+0.0
14	1.1962	-3.0
15	1.2472	-4.0
16	1.3050	+3.0

LEVELS FOR 89SR

1	0.0	+2.5
2	1.0320	+0.5
3	1.4734	+3.5
4	1.9402	+2.5
5	2.0076	+1.5
6	2.0574	-1.5
7	2.0613	+4.5
8	2.0790	-5.5
9	2.2801	+0.5
10	2.4516	+1.5
11	2.5701	-1.5
12	2.6710	+3.5

LEVELS FOR 93ZR

1	0.0	+2.5
2	0.2669	+1.5
3	0.9471	+0.5
4	1.018	+0.5
5	1.151	+0.5
6	1.222	+0.5
7	1.4255	+1.5
8	1.4356	+0.5
9	1.4504	+1.5
10	1.4702	+2.5
11	1.477	+3.5
12	1.597	+2.5
13	1.648	+1.5

LEVELS FOR 90Y

1	0.0	-2.0
2	0.2025	-3.0
3	0.6820	+7.0
4	0.7768	+2.0
5	0.9537	+3.0
6	1.0474	+5.0
7	1.1895	+4.0
8	1.2147	-0.0
9	1.2982	+6.0
10	1.3710	-1.0

LEVELS FOR 92Y

1	0.0	-2.0
2	0.2415	+0.0
3	0.3100	-2.0
4	0.4306	+1.0
5	0.4403	-3.0
6	0.7801	-0.0
7	0.8924	+1.0
8	0.9534	-4.0

LEVELS FOR 92ZR

1	0.0	+0.0
2	0.9345	+2.0
3	1.3828	+0.0
4	1.4954	+4.0
5	1.8473	+2.0
6	2.0667	+2.0
7	2.1500	+4.0
8	2.3397	-3.0
9	2.3983	+4.0

LEVELS FOR 89Y

1	0.0	-0.5
2	0.9092	+4.5
3	1.5074	-1.5

LEVELS FOR 91NB

1	0.0	+4.5
2	0.1045	-0.5
3	1.1868	-2.5
4	1.3126	-1.5
5	1.5810	+3.5
6	1.6125	-1.5
7	1.6370	+4.5
8	1.7904	-4.5
9	1.8448	-2.5
10	1.8850	+0.5
11	1.9631	+2.5
12	1.9844	-6.5
13	2.0345	-8.5

LEVELS FOR 94NB

1	0.0	+6.0
2	0.0410	+3.0
3	0.0587	+4.0
4	0.0787	+7.0
5	0.1184	+5.0
6	0.1404	-2.0
7	0.3119	+5.0
8	0.3342	+2.0

LEVELS FOR 92NB

1	0.0	+7.0
2	0.1355	+2.0
3	0.2259	-2.0
4	0.2856	+3.0
5	0.3574	+5.0
6	0.3898	-3.0
7	0.4802	+4.0

γ-RAY BRANCHINGS

GAMMA: TO LEVEL	2	(1.0)
	2	(1.0)
	1	(1.0)
	2	(0.03)
	3	(0.96)
	4	(0.01)
	4	(0.76)
	5	(0.24)

LEVELS FOR 93NB
(updated)

1	0.0	+4.5
2	0.0304	-0.5
3	0.686	-1.5
4	0.7440	+3.5
5	0.8087	+2.5
6	0.8101	-1.5
7	0.9499	+6.5
8	0.9791	+5.5
9	1.0826	+4.5
10	1.127	+2.5
11	1.29	-1.5
12	1.2974	+4.5
13	1.3156	-1.5
14	1.3351	+8.5

γ-RAY BRANCHINGS

GAMMA: TO LEVEL	2	(1.0)
	1	(1.0)
	1	(0.9877)
	4	(0.0123)
	2	(1.0)
	2	(1.0)
	1	(1.0)
	1	(0.265)
	4	(0.663)
	8	(0.072)
	5	(1.0)
	3	(1.0) ?
	1	(0.53)
	4	(0.3)
	8	(0.17)
	4	(1.0)
	7	(1.0)

Table 2a

Definition of Optical Potential

(according to Becchetti and Greenlees, Phys. Rev. 182, 1190 (1969)

	expression	validity range	explanation
$U_{opt}(r)$ =	$-V_R f_R$		central real
	$+(\frac{\hbar}{m_\pi c})^2 \frac{V_{so}}{r}(\frac{d}{dr} f_{so})$ $\vec{l}\cdot\vec{\sigma}$		spin orbit
	$+\begin{cases}\frac{Zze^2}{2R_c}[3-(\frac{r}{R_c})^2] \\ \frac{Zze^2}{r}\end{cases}$	for $r \leqslant R_c$ for $r \geqslant R_c$	Coulomb
	$- iW_v f_I$		imaginary volume
	$+ i4a_I W_{SF}(\frac{d}{dr} f_I)$		imaginary surface

where $f_x = f(r,R_x,a_x) = [1+\exp(r-R_x)/a_x]^{-1}$

$Rx = r_x A^{1/3}$

$R_x = r'_x A^{1/3} + r''$ for heavier projectiles (such as alphas)

r_c = Coloumb Radius

Note: Whenever a parameter is omitted, it is assumed that the corresponding potential is not considered.

Table 2b

Optical Model Parameters

Neutron Parameters

$V_R = 48.0 - 0.293E$ (E in MeV-Lab)

$r_R = 1.27$ fm $\quad a_R = 0.66$ fm

$W_{SF} = 9.6$ MeV

$r_I = 1.27$ fm $\quad a_I = 0.47$ fm

$V_{SO} = 7.2$ MeV

$r_{SO} = 1.27$ fm $\quad a_{SO} = 0.66$ fm

Proton Parameters (ref. 3)

$V_R = 53.3 - 0.55E + 0.4\ Z/A^{1/3} + 27.0\ (N-Z)/A$ (E in MeV-Lab)

$r_R = 1.25$ fm $\quad a_R = 0.65$ fm

$W_{SF} = 13.5$ MeV

$r_I = 1.25$ fm $\quad a_I = 0.47$ fm

$V_{SO} = 7.50$ MeV

$r_{SO} = 1.25$ fm $\quad a_{SO} = 0.65$ fm

r_c (coulomb radius) $= 1.25$ fm

Alpha Parameters (ref. 4)

$V_R = 50.0$ MeV

$r_R' = 1.17$ fm $\quad a_R = 0.576$ fm $\quad r_R'' = 1.77$ fm

$W_V = 13.74$ MeV

$r_I' = 1.17$ fm $\quad a_I = 0.576$ fm $\quad r_I'' = 1.77$ fm

$r_c = 1.17$ fm

Note: If the code does not allow for the second form of the radius expression in Table 2a, an effective radius parameter has to be calculated for each mass number (i.e. $r_x = 1.56$ for A = 93).

Table 3a

Calculation of level-density parameters[a)]

Nucleus (compo-site nucleus)	Mass (amu)	B (MeV)	J^π (target)	σ^2_{exp} [b)]	pc) (MeV)	E_c [d)] (MeV)	N_c [e)]	Dobs (eV)
86Rb	85.911	8.650	5/2-	7.24	0	1.309	15.5	201.4
89Sr	88.907	6.364	0+	5.31	1.24	2.707	11.5	37438
89Y	88.906	11.469	4-	6.42	0.93	1.745	2.5	140.0
90Y	89.907	6.857	1/2-	9.49	0	1.417	9.5	4414
92Y	91.909	6.544	1/2-	3.12	0	1.030	7.5	869.5
92Zr	91.905	8.635	5/2+	6.12	1.92	2.486	8.5	336.6
93Zr	92.907	6.732	0+	2.46	1.20	1.735	12.5	3678
91Nb	90.907	12.055	8+	9.36	0.93	2.065	12.5	51.2
92Nb	91.907	7.883	9/2+	11.6	0	0.501	6.5	267.3
93Nb	92.906	8.832	7+	6.70	0.72	1.364	13.5	41.5
94Nb	93.907	7.230	9/2+	12.0	0	0.396	7.5	99.6

a) The level density is characterised by the total number of levels N_c at energy E_c and the s-wave level spacing Dobs at the neutron binding energy B.

b) Spin cut-off parameter σ^2, derived from experimental spin distribution of levels up to $E=E_c$.

c) Pairing energy correction for Gilbert-Cameron formula, from (5).

d) E_c = first energy of continuum calculation.

e) "Average" number of levels at energy E_c.

Table 3b

Level-density parameters[a)]

Nucleus	Gilbert-Cameron 1 [b)]		Gilbert-Cameron 2 [c)]		Dilg et al.[d)]	
	a (MeV^{-1})	U_x (MeV)	a (MeV^{-1})	U_x (MeV)	a (MeV^{-1})	Δ(MeV)
86Rb	10.01	4.998	9.278	5.060	9.214	-1.069
89Sr	9.501	3.477	8.375	3.883	8.924	0.4802
89Y	8.600	2.213	8.112	1.537	8.460	0.3116
90Y	9.318	3.792	8.390	4.066	8.914	-0.7409
92Y	12.10	2.628	11.02	2.705	11.30	-0.5117
92Zr	11.83	4.047	10.92	3.995	10.43	0.7695
93Zr	12.69	4.607	11.46	4.774	10.63	-0.1563
91Nb	9.400	5.132	9.415	4.407	8.725	-0.2954
92Nb	10.30	6.400	9.762	6.259	8.923	-1.747
93Nb	12.58	4.678	12.39	4.270	11.24	-0.4636
94Nb	12.51	5.707	11.86	5.603	10.65	-1.553

a) Level-density parameters calculated from the data given in Table 3a.

b) Improved Gilbert-Cameron formula, with $\sigma^2 = 0.146 \sqrt{aU}\, A^{2/3}$ (5).

c) Original Gilbert-Cameron formula, with $\sigma^2 = 0.0888 \sqrt{aU}\, A^{2/3}$ (7).

d) Back-shifted Fermi gas formula of Dilg et al.(6).

Appendix A

Questionnaire on Pre-equilibrium/Equilibrium Model Codes

1. Participant

2. Code name and references, availability (give date):

3. Equilibrium-model part

- ☐ 3.1 Weisskopf-Ewing type (no conservation of angular momentum; no discrete levels)
- ☐ 3.2 Hauser-Feshbach (H.F.) type
- ☐ 3.3 Else, or comment:

4. Pre-equilibrium-model part

☐ 4.1 Full master equation approach (n_o=3) ☐ with or ☐ without quantum mechanical conservation of angular momentum (and parity).

☐ 4.2 Never-come back assumption (only λ^+-transitions starting from n_o=3)

☐ 4.3 (Geometry-dependent) hybrid-model, indicate n_o= ☐

☐ 4.4 Two-component model (protons and neutrons are explicitly distinguished as in Ref (11)).

☐ 4.5 Else, or comment:

5. Relation of equilibrium to pre-equilibrium parts

☐ 5.1 Unified model of pre-equilibrium and equilibrium emission with conservation of angular momentum and ☐ with or ☐ without treatment of discrete levels.

☐ 5.2 Pre-equilibrium is treated as a correction to the statistical model (indicate relation below)

☐ 5.3 Else, or comment (give definition of equilibrium and/or pre-equilibrium, if this is useful):

6. Options

☐ 6.1 Cross sections (angle and energy integrated).

☐ 6.2 Particle spectra (angle—integrated).

☐ 6.3 Angular distributions.

☐ 6.4 Multi-particle emission up to ☐ outgoing particles with ☐ or without ☐ multiple precompound decay treatment.

☐ 6.5 Else, or comment:

7. Total level density in equilibrium part

☐ 7.1 Gilbert-Cameron(1) $\begin{cases}\sigma^2=0.0888\sqrt{aU}\,A^{2/3} & \square\ ). \\ \sigma^2=0.146\sqrt{aU}\,A^{2/3} & \square\ ).\end{cases}$

☐ 7.2 Back-shifted Fermi-gas model of Dilg et al.(2).

☐ 7.3 Modifications or comments (e.g. σ^2 at low E):

8. Particle-hole level density

☐ 8.1 Williams state density(3) ☐ with or ☐ without an energy shift or pairing energy correction (if there is an n-dependent energy shift, indicate expression below).

☐ 8.2 $g = A/13$ MeV^{-1} and no pairing energy correction.

☐ 8.3 Williams' level density with n-dependent spin distribution, indicate σ_n^2 below.

☐ 8.4 Else, or comment:

9. Discrete levels

☐ 9.1 Included in equilibrium calculation only.

☐ 9.2 Not considered, E_c=0.1 MeV.

☐ 9.3 Else, or comment (e.g. when direct models are used or included in the model):

10. Internal transition rates

10.1 Average transition probability $\lambda^{\pm}=\frac{2\pi}{\hbar}\langle M^2\rangle\ \omega_f^{\pm}$ with $\omega_f^{\pm}$ according to:

- ☐ Williams(3)
- ☐ Oblozinsky et al.(4)
- ☐ else, or modifications:

and $\langle M^2\rangle$ according to

- ☐ $\langle M^2\rangle=cA^{-3}E^{-1}$ with c = ☐
- ☐ Kalbach(5), indicate fit parameters below.
- ☐ else, or comment:

☐ 10.2 Else, or comment:

11. Emission rates

11.1 Use of R- or Q-factors:

☐ Cline (without renormalisation to 1 at high values of n(6)).

☐ Kalbach's Q-factor, normalised to 1 at high values of n(7).

☐ Gadioli, et al.(8).

☐ Else, or comment:

11.2 Treatment of α-emission

☐ α-particle emission rate according to ref. (10).

☐ Form factor used $\gamma_\alpha =$ ☐.

☐ Else, or comment (give reference):

11.3 Transmission coefficients

☐ Inverse reaction cross sections used in precompound part.

☐ Transmission coefficients used in compound and precompound part, with ☐ or without ☐ j-dependence.

☐ Else, or comment:

12. Spectrum calculations

12.1 Complexity

☐ Only first-emitted particles calculated.

☐ Total particle production spectra calculated.

☐ Emission spectra are calculated for every reaction, and every outgoing particle (e.g. two spectra for n,2n).

☐ γ-ray cascade calculation possible.

☐ Else, or comment:

12.2 Representation

☐ Spectrum is represented in energy bins of ☐ equal or ☐ variable width.

☐ Spectrum is given by point data at ☐ equidistant or ☐ non-equidistant energies.

12.3 Else, or comment:

13. Angular distribution calculation

☐ 13.1 Only in H.F.-part, for (in)elastic neutron scattering to discrete levels.

☐ 13.2 Systematics of Kalbach and Mann for angular distributions in precompound part.

☐ 13.3 Model of Mantzouranis et al.(10), specify version below.

☐ 13.4 DWBA-type of calculation for emission from $n=n_0$ only.

☐ 13.5 Other model, specify below, give reference.

14. Gamma-Ray emission

☐ 14.1 No gamma-ray competition included.

☐ 14.2 No gamma-ray spectrum calculation or isomeric-state population calculation.

☐ 14.3 Specify Brink-Axel formula below.
E1-normalisation constant used for all nuclei = .

☐ 14.4 Specify Weisskopf formula for M1 and E2 below.
M1 - normalisation constant used for all nuclei = .
E2 - normalisation constant used for all nuclei = .

☐ 14.5 Specify expression for Yrast line below,

e.g. $\hbar^2 J^2_{max} = 2 I (E-\delta) \geqslant \hbar^2 J^2_{min.}$ (12)

or the Augustyniak et al.(13) prescription.

15. Additional comments:

References to Appendix

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(10) G. Mantzouranis et al., Phys. Lett., 57B (1975), 220.

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(12) D.G. Gardner, Proc. of NEANDC/NEACRP Specialists' meeting on fast neutron capture cross sections, Argonne, 1982; NEANDC(US)-214/L; ANL-83-4 (1983) p.67; UCRL-87438 (1982).

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