CASCADE

A Nuclear Evaporation Code

Written by F. Puhlhofer (version and report dated 1979)
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- Introduction

The program CASCADE was written by F. Puhlhofer to perform evaporation calculations based upon the statistical theory of compound nucleus reactions [see F. Puhlhofer, Nucl.Phys.A280(1977)267]. The program was originally written for an IBM computer but was modified to run on the VAX by Garman and Zwarts. E.F. Garman modified the original version to include electric dipole gamma decay properly by introducing the giant dipole resonance (GDR) strength function and including gamma decay from the compound nucleus (not calculated at all in puehlhofer original version of CASCADE) according to recommendations by Puhlhofer. F. Zwarts then included parity in a simplified way to be able to perform calculations for special states of good spin and parity. Major changes were introduced by M.N. Harakeh to include isospin and parity properly in the statistical decay as well as electric quadrupole decay by including the quadrupole strength function for the isoscalar and isovector giant quadrupole resonances (GQR). These changes are documented in another report. Here only the description of the input cards is documented. There are two versions of the program CASCADE available now: one version CASCIP that treats isospin and parity exactly and therefore is large and slow; another version CASCN which treats parity approximately and thus is about a factor four faster than CASCIP. Unless there is justification to use program CASCIP e.g. for light nuclei where isospin plays an important role in determining the branching ratios of proton, neutron, alpha and gamma decay, one should use the smaller and faster program CASCN. Before running either version of the program CASCADE one should make sure that a table of binding energies (EBTABLE.DAT) of different nuclei and an appropriate table of transmission coefficients (TLCALC.DAT) are present. If not, then the programs EBTABLE and TL should be run. The input cards of these programs along with those of CASCADE are described below. All formats are free formats except where indicated. For the cards with free format the program expects a value to be entered for each parameter specified in the read statement. The cards for the programs CASCN and CASCIP are compatible although CASCN does not necessarily use some of the information that is inputted. However, it is important that all parameters described below for the cards pertinent to the program CASCADE should be entered for both versions CASCN and CASCIP. Where appropriate, it is indicated which parameters are irrelevant for the program CASCN.

- INPUT CARDS FOR PROGRAM TL

CARD 1 Transmission coefficients parameters

1. IZMIN
   Minimum charge of the decaying nucleus for which transmission coefficients are to be calculated.
2. IZMAX
   Maximum charge of the decaying nucleus for which transmission coefficients are to be calculated (charge of the compound nucleus).
3. KOUTP
   = 0 Do not print parameters.
   .NE.0 Print optical model potential parameters (i.e. IZ,IACN, IZF,IEKIN,ECM,U,RR,ALR,WS,WD,RI,ALI,US,RS,AS,RC,LMAX).
4. KOUTTL
   = 0 Do not print transmission coefficients.
   = 1 Print transmission coefficients in F-format.
   = 2 Print transmission coefficients in E-format.
5. KSTORE
   = 0 Do not store transmission coefficients on disk.
   .NE.0 Store transmission coefficients on disk for later use by CASCADE.
6. ESTEP
   Energy step with which to calculate transmission coefficients (default value: 1.0 MeV).

CARD 2 Fourth particle parameters

1. IZE(4)
   Charge of the fourth particle to be included in the evaporation calculation in addition to the proton, neutron and alpha.
2. IAE(4)
   = 0 No fourth particle.
   = A Mass of the fourth particle.
3. EBE4 Total binding energy of the fourth particle (e.g. EBE for an alpha particle is 28.297 MeV)
4. CNZ
   Constant for calculating neutron excess (N-Z = CNZ*Z**2 + 0.5). (default value: 0.004).

CARD 3 Optical model potential options

1. KPOTN
   Option for neutron potential (default value: 1).
   = 1 From Rapaport et al., Nucl.Phys. A330(1979)15 [Set B].
   = 2 From Wilmore and Hodgson, Nucl.Phys. 55(1964)673. Not recommended.
   For E > 60 MeV KPOTN = 1 is used.
2. KPOTP
   Option for proton potential (default value: 1).
   = 1 From Becchetti and Greenlees, Phys.Rev. 182(1969)1190.
   = 2 From Perey, Phys.Rev. 131(1963)745. Not recommended. For E > 60 MeV KPOTP = 1 is used.
3. KPOTA
   Option for alpha potential (default value: 1).
   = 1 From Satchler, Nucl.Phys. 70 (1965) 177.
   = 2 From McFadden and Satchler, Nucl.Phys. 84 (1966) 177. For E > 100 MeV KPOTA = 1 is used.
   = 3 From Huizenga and Igo, Nucl.Phys. 29 (1962) 462. Not recommended. For E > 60 MeV KPOTA = 1 is used.
4. KPOT4
   Option for 4th particle potential (default value: 1). All possible 4th particles have only one potential option except for deuteron :
   = 1 From Perrin et al., Nucl.Phys. A282 (1977) 221.
   = 2 From Hinterberger et al., Nucl.Phys. A111 (1968) 265.
   = 3 From Daehnick et al., Phys.Rev. C21 (1980) 2253.
   = 4 From Lohr and Haeberli, Nucl.Phys. A232 (1974) 381.
   and 12C and 16O :
   = 1 A general heavy ion potential (for A.LE.20) obtained from Voos et al., Nucl.Phys. A135(1969)207.
   = 2 For 12C+12C from Gobbi et al. ANL report 7837 (1971). For 16O a general potential extracted from Perey and Perey.
   = 3 For 12C from Perey and Perey from 12C+28Si at 84 MeV.

- INPUT CARDS FOR PROGRAM EBTABLE

CARD 1 Binding energies control parameters

1. KOPT
   = 1 Theoretical masses for all particle-stable nuclei from the Myers-Swiatecki mass formula.
   = 2 Theoretical masses calculated using the droplet model mass formula by Hilf et al. Nucl.Phys. A203 (1973) 627.
   = 3 No option.
   = 4 Read in masses (measured and extrapolated) from KVI masstable MASSTABLE.SRT.
   = 5 Comparison of theoretical (Myers-Swiatecki) and measured masses (only lineprinter output).
   = 6 Same as 5 with Hilf masses with the Lysekil constants [Arkiv for Fysik 36 (1966) 343].

2. KPRINT
   = 0 Do not print binding energies.
   .NE.0 Print binding energies for all nuclei
3. KDISC
   = 0 Do not store binding energies on disk.
   .NE.0 Store binding energies on disk for later usage by CASCADE.

- INPUT CARDS FOR PROGRAM CASCADE (CASCN & CASCIP)

CARD 1 Title

1. TITLE Any alphanumeric title of 80 or less characters.

CARD 2 Entrance channel

1. IZP
   Atomic number of projectile.
2. IAP
   Mass number of projectile.
3. IZT
   Atomic number of target nucleus.
4. IAT
   Mass number of target nucleus.
5. ELAB
   Beam energy in MeV. This is interpreted as the excitation energy of the compound nucleus EXCN if JCN.GE.0 (see card 3) and if IAP = 0.

CARD 3 Spins, parity and isospin in entrance channel

1. JP
   Spin of projectile (twice the value for an odd nucleus).
2. JT
   Spin of target (twice the value for an odd nucleus).
3. IP12
   Product of intrinsic parities of target and projectile.
   = 0 For even parity in the entrance channel.
   = 1 For odd parity in the entrance channel.
   = 2 For identical 0+ nuclei.
   < 0 For unknown parity in the entrance channel.
4. JCN
   < 0 Usual. The population in the CN is then calculated according to parameters of card 6.
   .GE.0 The CN population is assumed to be in one spin JCN with a population cross section of 1000 mb. The spin is JCN+1/2 for odd mass. The excitation energy EXCN = ELAB (card 2) if IAP = 0. This option is used for example, if one wants to study the influence of the angular momentum in the CN on the decay mode. The parameters on card 6 are then irrelevant but should be entered nevertheless.
   = 999 Then the CN population is read as a function of angular momentum, parity and isospin. Card 6 is skipped in this case and instead of it a number of cards are read. See further card 6.
5. ITZT
   = 1 For a T< state of the compound nucleus if JCN.GE.0.
   = 2 For a T> state of the compound nucleus if JCN.GE.0.
   This is irrelevant if JCN < 0.
   This is irrelevant for program CASCN.
6. INDPAR
   = 0 Do not use option for different level densities of positive and negative parities in even-even nuclei. Note that for nuclei other than even-even the density of negative parity states as compared to positive parity ones depends strongly on the mass region under consideration.
   = 1 Use.
   This is irrelevant for program CASCN.
7. INDIS
   = 0 Do not print either Clebsch-Gordon coefficients for gamma and particle decay or level densities.
   = 1 Print Clebsch-Gordon coefficients for gamma and particle decay for all steps of the cascade.
   = 2 Print total and cumulative level densities as function of excitation energy.
   = 3 Print level densities as function of excitation energy, spin, parity and isospin.
   = 9 Print all of the above (i.e. options 1, 2 and 3).
   In program CASCN only option 1 is irrelevant, however option 3 in this case means print level densities as function of excitation energy and spin.
8. AMIX
   Parameter for isospin mixing, where isospin mixing is assumed to take the simple form of linear dependence as a function of excitation energy, i.e. isospin mixing = AMIX + BMIX*EX.
   This is irrelevant for program CASCN.
9. BMIX
   Parameter for isospin mixing. See note above concerning AMIX. This is irrelevant for program CASCN.

CARD 4 Structure of the decay cascade

This card specifies the structure of the so-called decay cascade, which contains all nuclei considered as possible decay products and defines their sequence in the various decay chains. The parameters are usually computed internally if all values are entered as zeros.

1. KOPTK
   Number of decay steps (for any combination of decays).
   = 0 Internal computation (= EXCN/12, but .GE.3).
   .GE.1 Internal computation with number of steps given. (check cross sections "last step above threshold").
   =99 The cascade structure is read in (between cards 13 and 14, check subroutine KASKAD).
2. IPS1
   Number of decaying nuclei (only for KOPTK = 99).
3. IPSMAX
   Number of nuclei in the cascade (.LE.500) (only for KOPTK = 99).
4. NNX
   Maximum excess of neutron minus proton emissions.
5. NPX
   Same for proton emission.
6. NAX
   Maximum number of alpha emissions.

   The last three parameters may be used to trim the wings of the decay cascade in case of high excitation.

CARD 5 4th particle decay mode, fission

1. IZE(4)
   Atomic number of the 4th particle to be taken into account in addition to n-, p- and alpha emission. Make sure that the corresponding transmission coefficients are available. No additional decay mode if entered zero.
2. IAE(4)
   Mass number of the 4th particle.
3. JE(4)
   Spin of the 4th particle (twice the value for odd mass).

4. IPE(4)
   Parity of the 4th particle.
   = 0 even.
   = 1 odd.
   Else unknown.
5. EXC4
   Excitation energy of 4th decay particle (since 4th decay particle may come out in an excited state). In this case, JE(4) and IPE(4) are the spin and parity of the excited state of the 4th decay particle.
6. IZFF
   = 0 No fission competition.
   .NE.0 With fission competition.
7. DAF
   af = A/DAF = level density parameter at the saddle point (default value: DALDM).
8. FFB
   Fraction of the liquid-drop fission barrier (default value: 1.0).

CARD 6 Angular momentum distribution in the compound nucleus

CARD 6a Read only if JCN.NE.999

1. CL0
   Maximum angular momentum (a very approximate value is calculated internally if entered zero).
2. DIFF
   Diffuseness (default value: 2 hbar).
3. NOTE:
   The transmission coefficient is given by the expression

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  TL = 1/[1+Exp{(L-CL0)/DIFF}]
and the total fusion cross section by
  SIGMCN = Sum over L of SIGML
where
  SIGML = (2L+1)*TL.
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4. SIGMCN Instead of CL0 the total fusion cross section (in mb) may be inserted.

CARDS 6b Format(2A,I3,F8.0). Read only if JCN.EQ.999

1. IP
   Parity of the CN populated levels.
   = + Positive parity.
   = - Negative parity.
   = E Skip to CARD 7.
   Any other character will stop the program with an error message. This is irrelevant for program CASCN.
2. IL
   Isospin of the CN populated levels.
   = < Lower isospin T<.
   = > Upper isospin T>.
   Any other character will stop the program with an error message. This is irrelevant for program CASCN.
3. J_TEMP
   Angular momentum of the CN populated levels (twice the value for an odd compound nucleus).
4. WT_TEMP
   Cross section of the CN populated levels (in mb).
5. NOTE:
   a maximum of L_DIM cards in CASCN and 4*L_DIM cards in CASCIP in an arbitrary order are allowed. If more cards are given they are ignored. If two or more cards give the population cross section for the same angular momentum, parity and isospin, the population cross sections are added. These cards are terminated by a card with E in the first column.

CARD 7 Level density parameters at low excitation (EX.LE.UTR)

1. FTHETA
   Fraction of the rigid-sphere moment of inertia used as effective value for calculating the yrast line at low excitation energy, (default value: 0.85).
2. KOPTLD
   Option for the level density parameters DA, DELTA (and CK).
   = 0 Interpolation of values of Dilg et al., Nucl.Phys.A217, for the mass range A < 45.
   = 2 Same for A > 45.

CARD 8 Level density parameters at high excitation (liquid drop region, EX.GE.ULDM)

1. DALDM
   Level density parameter constant for ALDM = A/DALDM (1/MeV), (default value: 8 MeV)
2. UTR
   Interpolation range between the low-energy region (.LE.UTR) and the
3. ULDM
   liquid-drop region (.GE.ULDM). Valid for DA and DELTA,
   (default values: 60/A**(1/3) MeV and 120/A**(1/3) MeV, respectively).
4. UJTR
   Same for the moment of inertia,
5. UJLDM
   (default values: UTR and ULDM, respectively).
6. KOPTLQ
   Level density parameter option.
   = 0 DALDM as above, DELTALDM corresponding to the liquid-drop g.s.
   = 1 Same parameters DA and DELTA as at low excitation.
7. KOPTEB
   Option for liquid-drop mass formula.
   = 0 Myers-Swiatecki Lysekil.
   = 1 Myers, droplet model (recommended).
   = 2 Same with Wigner term.
   = 3 Groote, Hilf, Takahashi.
   = 4 Same with Wigner term
   = 5 Seeger.
   = 6 Same with Wigner term.

CARD 9 Yrast line

1. R0LDM
   Radius parameter (in fm) for calculating the moment of inertia and the spin cutoff parameter (default value: rms-radius from Myers, Nucl.Phys. A204(1973)465).
2. DEF
   Constants used for parameterizing the yrast line of a rotating liquid
3. DEFS
   drop: EROT = I(I+1)*hbar**2/(2J), J = J0(1+DEF*L**2+DEFS*L**4), (default values are calculated internally to fit the Cohen, Plasil, Swiatecki results).

CARD 10 Gamma-decay widths

1. XYE1
   E1 gamma-width in Weisskopf units (default value: .0001).

2. NOTE:
   if entered negative an extra card 10a is read for GDR parameters.
3. XYM1
   M1 gamma-width in Weisskopf units (default value: .03).
4. XYE2
   E2 gamma-width in Weisskopf units (default value: 5).
5. NOTE:
   If entered negative an extra card 10b is read for GQR parameters. In this case, however, ABS(XYE2)/EX is taken to be the E2 strength up to 1/3 of the isoscalar GQR energy, after which the E2 strength is determined by the parameters of the isoscalar and isovector GQR's.
6. CJG1
   Lower edge for spin transition range for E2 enhancement.
7. CJG2
   Upper edge for spin transition range for E2 enhancement.
8. XYENH
   Enhanced E2 strength in W.u. above CJG2.
9. GMIN
   Minimum gamma-decay, GMIN*(XYE1+XYM1+XYE2). This is important only for the lower edge of the population matrix and determines how much goes into isomer population. (default value: 1.E-6).

CARD 10a GDR parameters (read in only if XYE1 < 0)

1. FGDR1
   Fraction of Classical E1 EWSR in relative units for the first lorentzian.
2. EGDR1
   Excitation energy of the first lorentzian in MeV.
3. GGDR1
   Width of the first lorentzian in MeV.
4. FGDR2
   Fraction of Classical E1 EWSR in relative units for the second lorentzian.
5. EGDR2
   Excitation energy of the second lorentzian in MeV.
6. GGDR2
   Width of the second lorentzian in MeV.

CARD 10b GQR parameters (read in only if XYE2 < 0)

1. FISQR
   Fraction of the isoscalar E2 EWSR in relative units for the isoscalar GQR.
2. EISQR
   Excitation energy of the isoscalar GQR in MeV.
3. GISQR
   Width of the isoscalar GQR in MeV.
4. FIVQR
   Fraction of the isovector E2 EWSR in relative units for the isovector GQR.
5. EIVQR
   Excitation energy of the isovector GQR in MeV.
6. GIVQR
   Width of the isovector GQR in MeV.

CARD 11 Cut-offs

1. WGR
   Populations below the given value in any decaying nucleus are ignored, (default value: 0.003 mb/MeV.hbar). Check lost cross sections.
2. CGR
   Cutoff for the decay intensity of a (1*ESTEP)MeV.1hbar population element in a specific channel (default value: 0.25*WGR).
   The following four parameters are used to control the upper energy limit of the (L_EX_DIM*ESTEP).L_DIM MeV.hbar population matrices.
3. CVCBE
   Fraction of the Coulomb barrier of an emitted charged particle assumed as minimum kinetic energy (default value: 0.30, if EXCN < 60 then 0.1).
4. CVCB
   Relative strength of the quadratic term (default value: 0.04).
5. VK
   Minimum kinetic energy above Coulomb barrier (default value: EXCN/100).
6. CVK
   Quadratic term (default value 0.05).

CARD 12 Cut-offs

1. EXR0
   EX-range of the population matrices in the first decay steps (default value: KIN_PAR*ESTEP MeV).
2. EXH
   Above this excitation energy a step size of 2 hbar in spin is used in the decaying nucleus, above 2*EXH 3 hbar steps are used (default value: 30 MeV, unless IP12 = 2 or INDPAR = 1 in CASCIP and IP12 = 2 in CASCN then EXCN + 1 MeV).
3. CJC
   Number of spin steps at the high-spin side of a population, where 1 hbar steps are used (default value: ACN/20, but .GE. 4). CAUTION: The spin region with strongly varying fission competition should be covered with 1 hbar steps.
4. LCO
   Angular momentum cutoff for all level densities (default value: CL0 + 2*DIFF).
5. ESTEP
   Energy step (in MeV) with which to perform the calculations (default value: 1.0 MeV).

CARD 13 Output control

1. KOUTW
   Lower cross section limit (in mb), above which population matrices are printed (default value: 100mb).
2. KOUTL
   Same for decay probabilities (default value: 1000 mb).
3. KEVAP
   Same for evaporation spectra (default value: 1000 mb).
4. KGAMMA
   = 0 Do not calculate gamma-decay below particle thresholds.
   .NE.0 Calculate gamma-decay below particle thresholds (important shape of gamma spectrum at low energies and for gamma multiplicities).
   = 2 Calculate only particle and gamma spectra and population matrices following an initial gamma decay in the compound nucleus.
   =-2 Calculate only particle and gamma spectra and population matrices following an initial 4th particle decay in the compound nucleus.

CARDS 13a Read in cascade structure (optional)

Only if KOPTK = 99 and IPS1, IPSMAX specified (see card 4). Input: IPSZO(IZF=1,4; IPS=1,IPS1) = assignment of numbers to the daughter nuclei produced by n-, p-, alpha- and 4th decay (IZF=1,4) of each decaying nucleus IPS = 1,IPS1 in the decay cascade. Defines length of decay chains and order of computation. Insert 0 if decay is to be neglected.

CARDS 14

Individual level density parameters for low excitation energy (optional; except for a card where IZ = 0)

1. IZ
   Atomic number Z.

2. IA
   Mass number A.
3. DA
   Constant for calculating the level density parameter a = A/DA, (DA ~ 8 MeV).
4. DELTA
   Zero of the thermal excitation energy for the g.s., U = EX - DELTA.
5. FTHETA
   = J/Jrigid (like on card 7).
6. CK
   Multiplicative constant in the level density (valid for the whole excitation energy range).
7. DELT
   Zero of the thermal excitation energy for the IAS. This is irrelevant for program CASCN.
   One card for each nucleus; arbitrary number of cards; arbitrary order. Overwrites internally calculated standard parameters. End defined by a card on which IZ = 0.
   This card is always necessary.

CARDS 15 Individual spectra (optional; except for a card where IZZ = 0, or an EOR card) For each nucleus, for which low-lying levels are to be read in:

- a) One card containing IZZ,IAA,EX
- b) Cards containing EXL,JL,PL,IL; format 7(F7.2,I2,2A).

End defined by a blank card, or an EOR card.
The input values are written, if they are needed, into a level table (for a maximum of 99 nuclei). If two spectra are supplied for the same or the mirror nucleus, the second overwrites the first one. A maximum of 50 levels can be given (with arbitrary order except for yrast levels or with interruption except for the first position on the card).

CARD a

1. IZZ
   Atomic number Z.
2. IAA
   Mass number A.
3. EX
   Excitation energy (in MeV) below which the analytical level density is erased and replaced by levels and above which the levels are interpreted as yrast levels (level density erased above the spin of the level). Yrast levels must be read in with increasing or constant spin at increasing excitation energy.

CARDS b Format(7(F7.2,I2,2A)

1. EXL
   Level excitation energy in MeV.
2. JL
   Level spin (twice for odd nuclei).
3. PL
   Level parity.
   = + Positive parity.
   = - Negative parity.
   = 0 Or blank start reading cards for another nucleus (see card a).
   Any other character => undefined parity.
4. IL
   Level isospin.
   = < Lower isospin T<.
   = > Upper isospin T>.
   Any other character will stop the program with an error message. This is irrelevant for program CASCN.