Precompound Cluster Decay in HMSAlice

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Abstract

Formulations empirically deduced to reproduce precompound cluster emission spectra in the Monte Carlo version of the ALICE nuclear reactions code (HMS-alice) are summarized. Clusters treated are ^2H,^3H,^3He and ^4He. Several comparisons of use of the derived algorithms with experimental data are presented.

1 Introduction

The Karlsruhe group added precompound cluster emission capabilities to the nuclear reactions code ALICE, along with other improvements, summarized in a report of May 2006 (1). The original author of the ALICE code had meanwhile been concentrating efforts on a Monte Carlo version of the code (2). In this report we summarize the algorithms used to add precompound cluster emission capabilities to a Monte Carlo version of the ALICE code, HMSAlice, inspired by the work of the Karlsruhe group (1). Precompound nucleon emission is treated by models having well defined, if semi-classical, physics concepts in formulation. In contrast, while physical justifications might one day be 'reverse engineered' for the present work, it evolved and is presented as no more than empirical formulas using physical quantities (excitations, binding energies, etc.). These were defined by fitting a body of high quality experimental data (3-8); the coding has been done to permit additional cluster channels to be added easily at a later time, if desired. At present we treat the precompound emission of^2H,^3H,^3He, and ^4He in addition to the usual n and p. All cascades are terminated in the Weisskopf- Ewing evaporation model for all emitted particles. While the formulation is empirical, we have tried to use physical concepts such as microscopic reversibility and spreading widths in hopes of approximating the thoughts of mother nature, and increasing the chances that formulas derived might have some degree of extrapolability.' Hope springs eternal..'.

2 Formulation

2.1 Partial widths for precompound clusters

We first formulate, for nucleon induced reactions, partial widths for emission of the 4 cluster types. We use both energy dependent and independent coefficients , coupled with functions dependent on available energy in the emission channels. We have, by fitting data, derived width multiplier constants as follows:

a^2H = 0.20
a^3H = 0.05
a^3He = 0.08
a^4He = 0.018(198/A)**0.5

where A is the parent nucleus mass number.

In the following we will designate cluster identities by " y", where y = $^2H,^3H,^3He,^4He$. For each cluster channel, we define at each emission stage (primary/first emission, secondary emission, etc.) the channel energy Ey available after decreasing the excitation by the cluster binding energy of the particular nuclide at the relevant stage of the emission cascade [be(z,a,y)], where z,a are the charge and mass numbers of the emitting nuclide, and by the excitation not available due to the Coulomb barriers (eoff(y)).Then, e.g. we would define a parameter a$E^4He = Eyfor^4$He emission, where Ein is the energy above the Fermi energy of a nucleon inducing the emission process as,

$$E^4He = Ein - be(z, a,^4 He) - eoff(^4He),$$

with similar formulas for the other clusters.Then for a particular step in the emission cascade, we estimate partial widths for the emission of the clusters;for alpha particles:

$$b^4He = a^4He * (200./Ein),$$

but if Ein.lt.40.,

$b^4He = a^4He * 5.,$

$w^4He = b^4He * (E^4He/Ein) * *4,$

with a second, softer alpha width , alphap, given by

$w^4Hep = 2. * b^4He * (E^4He/Ein) * *8,$

and for deuterons,

$w^2H = a^2H * (E^2H/Ein),$

and for tritons,

$w^3H = a^3H * (E^3H/Ein) * *2,$

and for ^3He,

$w^3He = a^3He * (E^3He/Ein) * *2.$

Normalizations/ constants were selected such that these partial widths are defined compared to unity for the customary neutron /proton precompound cascade.Then a random number from 0 to 1. ' x' may be used to select whether the emission will be nucleon or cluster cascade,

$$branch = x * (1. + w^2H + w^3H + w^3He + w^4He + w^4Hep).$$

If the value of ' branch' is at or below 1., control returns to the usual nucleon precompound decay formulation; if greater than 1., it is tested with respect to each width to determine the type of emitted cluster (and if it is an ^4He cluster, whether the harder or softer component). These commands are found in the subroutine ' clustpe' of the HMSAlice code.Cluster emission rates into the continuum are calculated as for nucleons, using appropriate inverse reaction cross sections, reduced masses and spins. Spreading rates are more problematic; for the clusters we have based them on the imaginary optical potential in the OVER optical model routine of HMSAlice. The results are calculated and stored in the nucmfp subroutine used to calculate nucleon spreading rates based on N-N scattering cross sections. The question of spreading rates for clusters may be inappropriate to discuss, depending on the actual mechanism(s) of cluster emission. We leave it as one of many treatments needing scrutiny in the formulation implemented. We will hope that many sins are contained in the fact that width formulation factors are determined assuming the correctness of the spreading/ emission ratios; errors will - if we are lucky- show up as changes in the empirically deduced width formulas.We will name this principle of formulation 'SLIRP', pronounced 'slurp', the acronym for 'Sins Lessened In Renormalixation Process'; this concept is not new or original, nor oft acknowledged. But by naming it, we can take credit!

2.2 Emission spectra for clusters

For the cluster to be emitted, an effective energy is determined as the available excitation less the pairing correction for the residual nucleus if the emission were to take place,

Eeff = Ein - pair(z,a),

where "z,a" refer to the residual nucleus and Ein is the incident nucleon energy.For 4He emission we use pair(z,a)=0. since parent and daughter will always have the same odd/even character. For this discussion, for all clusters, we will use "x" to represent a random number between 0 and 1.

For deuterons, the emission energy measured from parent nucleus Fermi energy is:

$$E^2H = x * Eeff,$$

and the emitted channel energy in center of mass is

$$E^2Hch = x * Eeff - BE(Z, A,^2 H)\ ,$$

where BE(Z,A,^2H) is the binding energy of the deuteron in the emitting nucleus. The ratio of emission to spreading plus emission rates is tested by a second random number (0-1) to determine if the cluster is emitted or re-scatters. If it rescatters, the secondary nucleon partner is returned for further cascade participation. If emitted, a totally arbitrary algorithm is applied to produce an emission angle,

$$\text{Theta}^2H = (1. - E^2Hch/E^2H) * pi/2.$$

The angular algorithms were introduced simply to produce a forward peaked result which is more pronounced for greater asymetries in incident and exit energies, in order to apply the semi-classical algorithm for angular momentum change. It is an area where much better algorithms likely exist and should be sought.

For triton emission, the energy of the triton is selected as

$$E^3H = Eeff - E^3Hch * (x * *0.5), \text{ and}$$

$$E^3Hch = E^3H - BE(Z, A,^3 H),$$

with anologous expressions for ^3He emission. Definition of quantities are analogous to the formulation for deuteron emission. The emission angle is parametrized as:
$theta^3H = (1. - E^3Hch/E^3H) * pi/2.$

with ^3He substituted for ^3H for ^3He emission angles. For ^4He emission,

$$E^4He = Ein - E^4He * (x * *0.25)$$

or if the harder component is selected (based on the branch due to the random number selected and relative widths of harder vs. softer components),

$$E^4He = Ein - E^4He * (x * *0.125),$$

and as for all cluster emission formulas, E^4He must be decremented by the alpha binding energy to get the channel energy in center of mass frame. For ^4He emission, the angle of emission is taken as for other clusters,

$$Theta^4He = (1. - E^4Hech/E^4He) * pi/2.$$

If an alpha particle is excited but not emitted, the cluster is assumed to rescatter, and the result of this is treated as if the alpha were a nucleon to calculate secondary alpha energy, then the MC technique is used with the emission to total rates to determine if the alpha cluster will be emitted, or if the energy will end up in the equilibrated nucleus.

3 Comparisons of results with data

Results of the formulation summarized are presented for (p,^4He) reactions at several incident proton energies up to 200 MeV on ^{27}Al,^{59}Co, and ^{197}Au targets, in figs 1-3. It appears that the formulation may need to increase the harder alpha component for low mass targets at

Au197(p,4He)

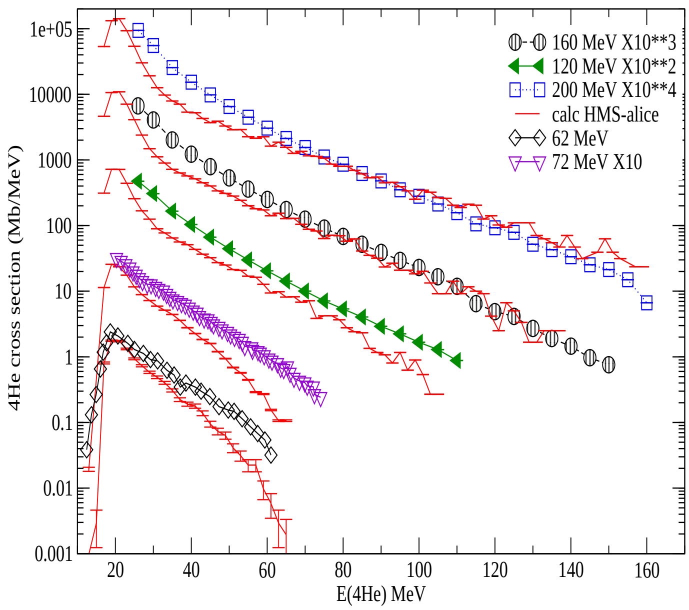

Figure 1: Single differential spectra for alpha particle emission from proton irradiation of ^{197}Au targets at incident energies of 29- 200 MeV. The experimental data in this and following $(p,^4He)$ spectra are from ref (3) for 29, 39 and 62 MeV incident protons, from ref. (4) for 90 MeV protons, and from ref. (5) for 120, 160 and 200 MeV protons.and from ref (6) for 72 MeV protons.

the lower incident beam energies, but this may in part be an artifact of comparing experimental data in the laboratory coordinate system with calculated c.m. channel energies. Results for (p,^2H) reactions at incident proton energies up to 62 MeV appear in figs.4 and 5. Spectra for emitted ^3H and ^3He resulting from neutrons on natural Si targets at 63 and 96 MeV are presented in fig.6.The data of refs.(3) and (4) are reported in the laboratory coordinate system, whereas all calculated results presented are in the center of mass channel energy system. For gold targets, the differences will be small; for lighter targets, there may be significant issues in making such comparisons as noted above.

4 references

1. C.H.M. Broeders, A.Yu. Konobeyev, Yu.A. Korovin, V.P.Lunev, M.Blann, Forschungszentrum Karlsruhe Report FZKA 7183, 2006;

27Al (p,4He)

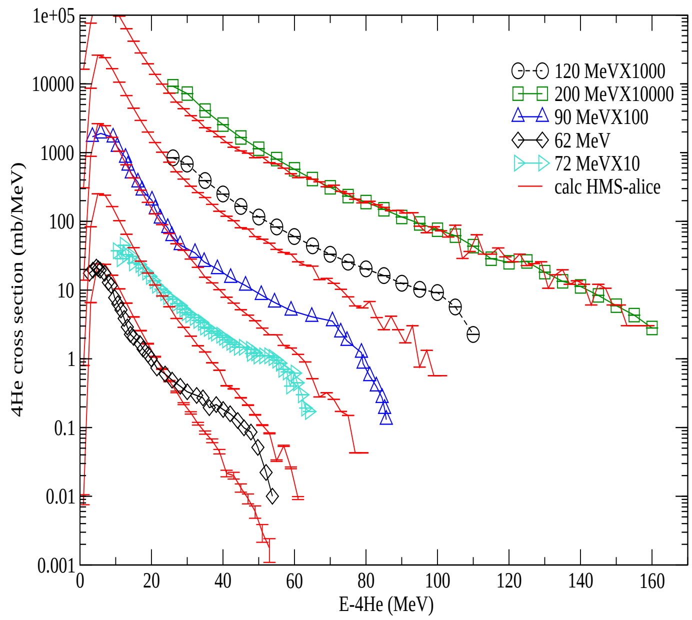

Figure 2: As in fig1, for a ^{27}Al target.

http://bibliothek.fzk.de/zb/berichte/FZKA7183.pdf

2. M.Blann, Phys. Rev. C54 (1996) 1341.

3.F.E.Bertrand, R.W.Peelle, Phys. Rev. C8 (1973) 1045.

4.J.R.Wu, C.C.Chang, H.D.Holmgren, Phys. Rev. C19 (1979) 698.

5.A.A.Cowley, G.J.Arendse, J.W.Koen, W.A.Richter, J.A.Stander, G.F.Steyn, P.Demetriou, P.E.Hodgson, Y.Watanabe , Phys. Rev. C54 (1996) 778.

6. Z.Lewandowski, E.Loeffler, R.Wagner, H.H.Mueller, W.Reichart, P.Schober, E.Gadioli, E.Gadioli Erba, Lett. Nuovo Cimento 28 (1980) 15.

7. U.Tippawan, S.Pomp, A.Atac, B.Bergenwall, J.Blomgren,S.DANGTIP, A.Hildebrand, C.Johansson, J.Klug, P.Mermod, L.Nilsson, M.Osterlund, N.Olsson, K.Elmgren, O.Jonsson, A.V.Prokofiev, P.-U.Renberg, P.Nadel-Turonski, V.Corcalciuc, Y.Watanabe, A.J.Koning, Phys. Rev. C69 (2004) 064609.

8. V.Blideanu , F.R.Lecolley , J.F.Lecolley, T.Lefort, N.Marie, A.Ata, G.Ban, B.Bergenwall, J.Blomgren, S.Dangtip, K.Elmgren, Ph.Eudes, Y.Foucher, A.Guertin, F.Haddad, A.Hildebrand, C.Johansson, O.Jonsson, M.Kerveno, T.Kirchner, J.Klug, Ch.Le Brun, C.Lebrun, M.Louvel, P.Nadel-Turonski, L.Nilsson, N.Olsson, S.Pomp, A.V.Prokofiev, P.-

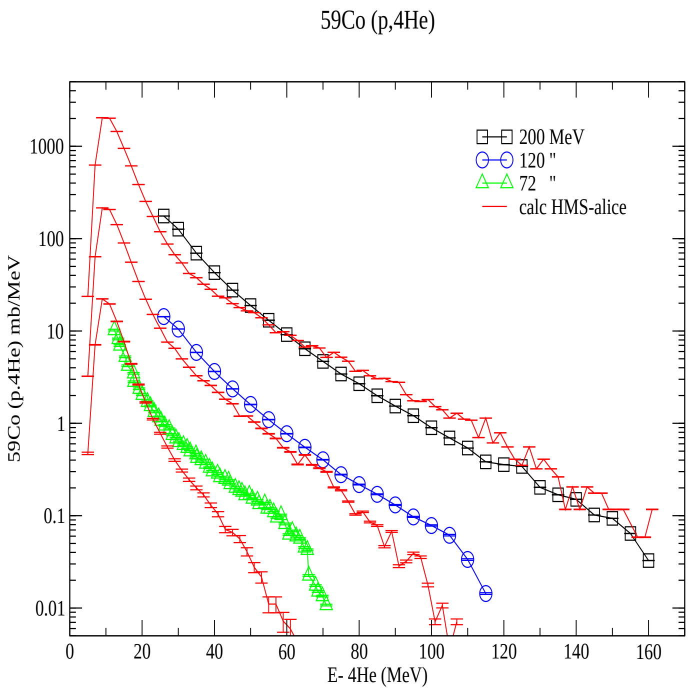

Figure 3: As in fig 1 for a ^{59}Co target.Experimental data are from refs.(5),(6) Data/calculations at 200 MeV are plotted X100; intermediate energy data/calculations X10.

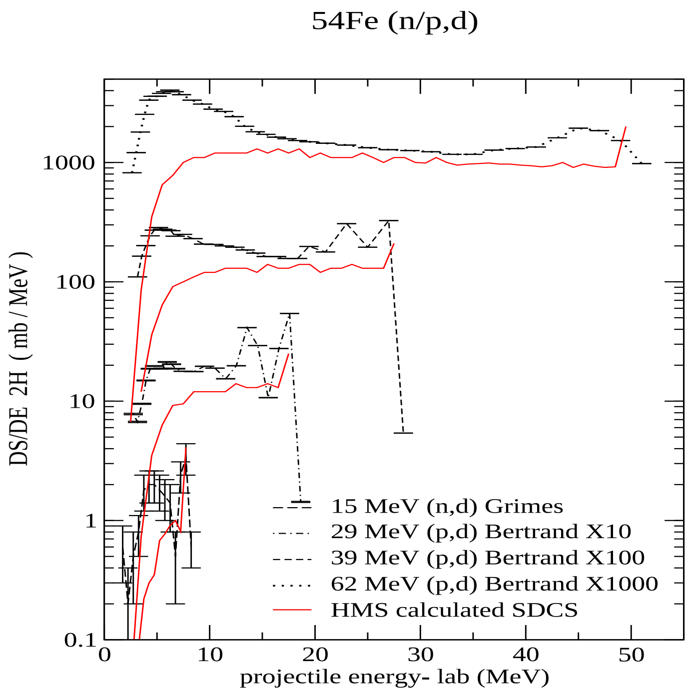

Figure 4: Deuteron emission spectra from 29-62 MeV protons on ^{54}Fe targets. Data are from refs. (3)

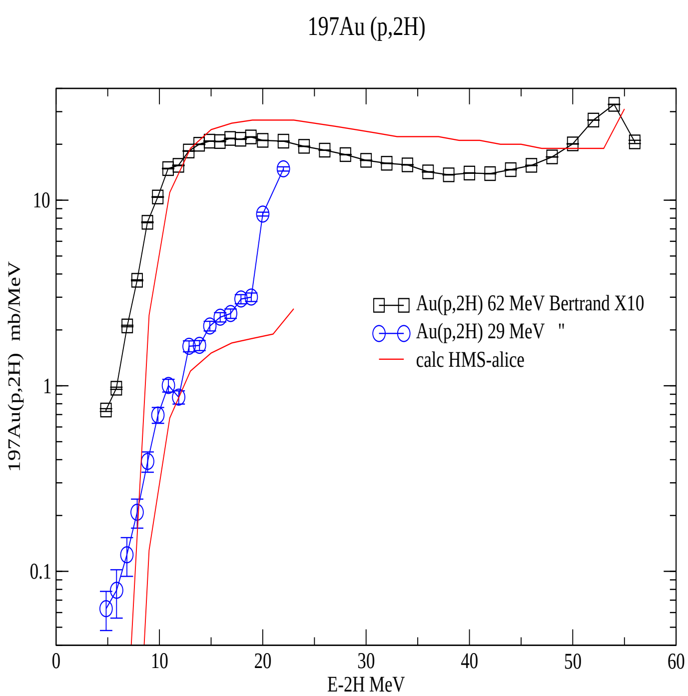

Figure 5: As in fig 4 for a ^{197}Au target.

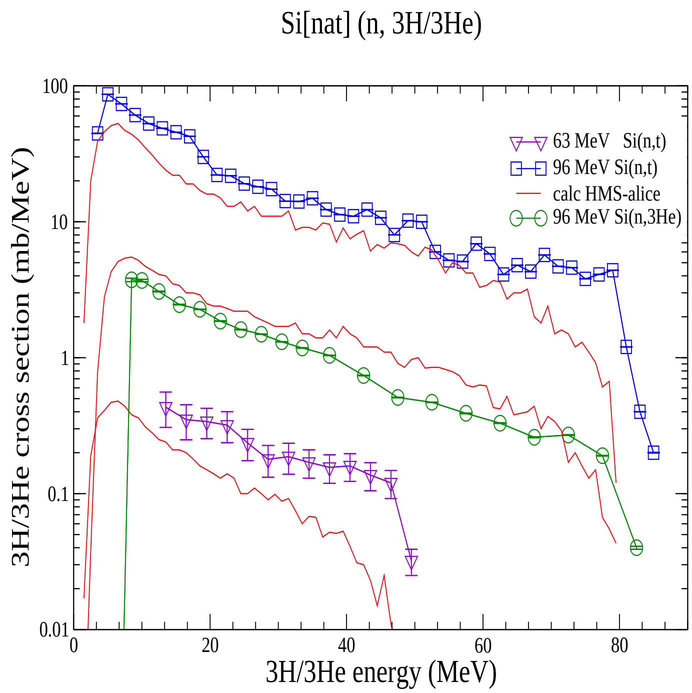

Figure 6: Single differential spectra for the emission of ^3H and ^3He from natural Si targets irradiated with 63 and 96 MeV neutrons (data from refs (7) and (8). Data sets and calculations are displaced by factors of 10 and 100.

U.Renberg, P.-U.Rivire, I.Slypen, L.Stuttg, U.Tippawan, M.sterlund,
Phys. Rev. C 70 (2004) 014607.