Title

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Résumé - La collision de deux noyaux est traitée comme un ensemble de collisions des nucléons du projectile avec ceux du noyau cible. Les fragments primaires ne comportent que les nucléons qui n'ont pas subit une collision. Les sections efficaces inclusives et les coincidences résultent de la désintégration des fragments primaires excités.

Abstract - The collision of two nuclei is treated as a collection of collisions between the nucleons of the projectile and those of the target nucleus. The primary projectile fragments contain only those nucleons that did not undergo a collision. The inclusive and coincidence cross sections result from the decay of the excited primary fragments.

I - INTRODUCTION

It has been known for a long time that the inclusive yield of neutron-rich fragments from the collision of a heavy ion with a neutron-rich target is substantially larger at low beam energies (20-44 MeV/A) than at high energies [1-3].

The total cross section for n-p scattering at low energies is about three times larger than for n-n or p-p scattering, while all these cross sections are nearly equal at high energies. This suggests that primary projectile fragments are formed as a result of collisions of projectile nucleons with target nucleons. When the target is neutron-rich and the energy is low, projectile protons are more likely to be scattered than projectile neutrons. If this scattering process removes nucleons from the projectile, the resulting primary fragments will be proton-deficient and neutron-rich in low energy reactions on neutron-rich targets.

In spite of arguments to the contrary [4], it is now clear that most primary fragments will be sufficiently excited to undergo sequential decay. In the calculation of inclusive cross sections and especially of coincidence cross sections, the effect of sequential decays of the primary fragments must be included. In the present paper, this is done in an approximate way. The final results are in generally good agreement with experimental inclusive cross sections as well as with the limited amount of coincidence data that is available.

II - CALCULATION OF PRIMARY YIELDS

The Monte Carlo technique that is used to calculate the primary fragment yields is described in detail in ref. 4. Briefly, the calculation proceeds as follows.

The density distributions of the two colliding nuclei are described by Fermi functions with, in general, different radii and diffusivities for protons and neutrons. Starting at a given impact parameter, the two nuclei approach each other along orbits in the Coulomb plus nuclear potential until the 20% densities overlap. From that point on, the projectile nucleons are assumed to follow straight paths into and through the target nucleus.

At all energies, the N-N cross sections are assumed to have the free nucleon values for collisions in the surface of the target. At energies below the Fermi energy, Pauli blocking reduces the effective N-N cross sections in the interior of the target. Values are chosen to be consistent with the mean free path of nucleons in nuclei. They rise as the density falls until the free values are reached in the surface. At energies well above the Fermi energy, free N-N cross sections are assumed at all densities of the target nucleus. The primary fragment cross sections and reaction cross sections are very insensitive to assumptions about N-N cross sections in the interior of the target nucleus.

The coordinates of a nucleon in the projectile are chosen at random to reflect the proper density distributions. Each projectile nucleon is allowed to pass through, or near, the target. The primary fragment consists of those projectile nucleons that did not scatter. The scattering probability for a nucleon is calculated by numerical evaluation of the integrals:-

$$P_p = 1 - \exp - \left(\int \rho_n(R)\sigma_{pn}(R)dz + \int \rho_p(R)\sigma_{pp}(R)dz \right) \quad (1)$$

$$P_n = 1 - \exp - \left(\int \rho_n(R)\sigma_{nn}(R)dz + \int \rho_p(R)\sigma_{np}(R)dz \right) \quad (2)$$

Here, $\rho_n(R)$, $\rho_p(R)$ are the densities of neutrons and protons at radius R in the target. The N-N cross sections are functions of R, as discussed above. At each impact parameter, a few thousand projectiles are allowed to collide with the target. The impact parameter b is then incremented and the whole process is repeated until no more collisions occur. The cross section for a primary fragment (Z,A) at impact parameter b is:-

$$\sigma_b(Z,A) = 2\pi b\ db\ F \quad (3)$$

where F is the fraction of interactions at b that produce (Z,A). The total cross section for a given fragment is just the sum over all impact parameters, and the total reaction cross section σ_r is the sum of all fragment cross sections.

Two results emerge at this point. First, the production of a given primary fragment is strongly localized in impact parameter space. The lighter fragments come from smaller impact parameters, and the heavier fragments come from more peripheral collisions. Second, the values of σ_r are in remarkably good agreement with experimental results at all energies from 20 MeV/A to 2 GeV/A [4].

The primary fragment cross sections do not agree well with the experimental inclusive values. Their mass distributions for a given Z-value are too broad, especially on the neutron-excess side of the line of stability, and they do not show the characteristic peaks for fragments that are formed by the removal from the projectile of one or two alpha particles. In ref. 4, these discrepancies were removed by the use of the fragmentation model of Friedman [5] which assumes that the probability for removing a given cluster of nucleons from the projectile, and for the remaining fragment to escape further interaction, depends on the separation energy of the projectile into the two parts.

Cole [6] uses an analytic approximation to the collision geometry, and considers that direct N-alpha collisions can occur as well as N-N collisions. This too has the effect of increasing the cross sections for fragments having low separation energies.

III - SEQUENTIAL DECAY

While there is some information about the excitation energies and decay modes of primary fragments from low beam energy experiments [7-8], there is very little for energies above 20 MeV/A. Nevertheless, any model must be consistent with the following experimental observations:-

1. At E < 20 MeV/A, the number of charged particles in coincidence with a fragment is small, either 0 or 1 except for the lightest fragments such as Li isotopes from a ^{16}O projectile [7]. This suggests that the primary fragments decay by the emission of no more than one charged particle and/or by the emission of neutrons.
2. At high energies, all fragments, even such light nuclei as ^{6}Li, come from peripheral collisions [9]. They must therefore result from the decay of excited projectiles and from excited fragments close in mass to the projectile.
3. In the collision of ^{12}C + ^{12}C at 2 GeV/A, about 25% of the ^{11}B fragments are in coincidence with a small-angle beam velocity proton. They are produced by the decay of excited ^{12}C. The other 75% are not in coincidence with such a proton and are presumably surviving primary ^{11}B fragments [10].

In the same system, the channel $^{12}C \to {}^{6}Li + {}^{6}Li$ is observed with a cross section of very roughly 1 mb [10]. This shows that the temperature of the excited ^{12}C nuclei is high enough for fission processes to occur [11]. The cross section for the decay of ^{12}C into three alpha-particles is 9.7 + 5-2.5 mb [10].

It has been shown [1,12] that inclusive cross sections at low and high energies can be reproduced by the assumption that primary fragments decay into a large number of channels and that the probability of decay into a specific channel is:-

$$P(Z,A) \propto \exp(-E_S/T) \qquad (4)$$

Here, E_S is the separation energy of the primary fragment into the two or more parts, and T is a parameter. A very similar method has been used to calculate the relative probabilities of fission of light and medium nuclei [11]. The cross section for the formation of a given fragment (Z',A') from primary fragment (Z,A) can therefore be written:-

$$\sigma(Z',A') = \frac{\sigma(Z,A)\exp(-E_S/T)}{\sum \exp(-E_S/T)} \qquad (5)$$

where $\sigma(Z,A)$ is the calculated primary cross section. The sum includes all decay channels of (Z,A) as well as $E_S = 0$ to represent the probability that the fragment does not decay by particle emission.

At E $\leq$ 20 MeV/A, it is essential to include all primary fragments down to ^{6}Li in the decay process. Fig. 1 shows a comparison of the fraction of each primary fragment that survived charged particle decay with an experimental measurement [8]. The system was ^{20}Ne + ^{197}Au at 17 MeV/A. Fig. 2 shows a comparison, for the same system, of the calculated and experimental ratios of the cross sections of fragments that are not in coincidence with a charged particle (but possibly in coincidence with one or more neutrons) to the inclusive cross sections. Both figures show quite good agreement between experiment and calculation.

Fig. 3 shows a comparison of the experimental and calculated inclusive cross sections for ^{16}O + ^{208}Pb at 20 MeV/A. The primary yields are also shown for isotopes of Li, B and C. They are broader than the experimental values on the neutron-rich side. The maximum yield for C isotopes falls at ^{13}C instead of at ^{12}C.

Fig. 4 shows the inclusive cross sections for ^{12}C + ^{12}C at 2 GeV/A. In this case, the decaying primary fragments were restricted to ^{12}C, ^{11}C and ^{11}B, and decays by the emission of any number of nucleons or bound nuclei up to half the proton and neutron number of the primary fragment were included. The ^{12}C was given a temperature of 8 MeV and the A = 11 nuclei, 9 MeV. 21% of the ^{11}B comes from ^{12}C decay and 79% is surviving primary ^{11}B, in excellent agreement with experiment. The channel cross section for fission of ^{12}C into two ^{6}Li nuclei is 1.9 mb, in agreement with the experimental value. The channel cross section for decay of ^{12}C into three alpha-particles is 25 mb, somewhat higher than the experimental value of 9.7 + 5-2.5 mb.

For ^{12}C + ^{12}C at 85 MeV/A, the same method and parameters as those used at 2 GeV/A gave good agreement with inclusive cross sections [13]. This suggests

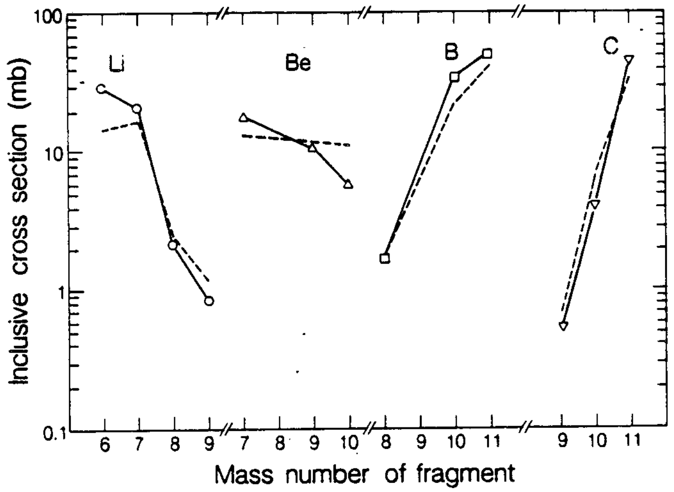

Fig. 4 - Inclusive fragment cross sections, $^{12}C + ^{12}C$, 2 GeV/A. Inclusive cross sections for ^6Li to ^{11}C at 85 MeV/A differ by only 3.3% from those at 2 GeV/A.

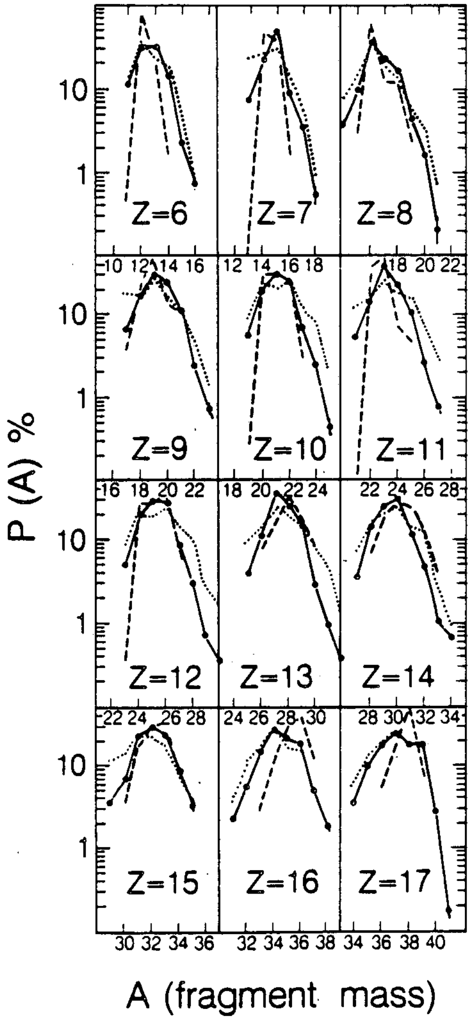

Fig. 5 - Experimental and calculated isotopic distributions for $^{40}Ar + ^{197}Au$ at 44 MeV/A. Dotted lines are the present calculation, dashed lines are calculation from ref. 14.

that, at twice the Fermi energy, the reaction mechanism has already reached some limiting form. Indeed, the N-N cross sections at these two energies are not very different.

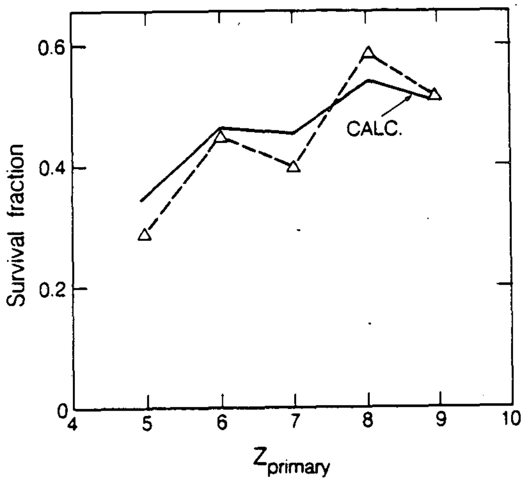

Fig. 1 - Fraction of primary fragments that survive decay by charged particle emission. $^{20}Ne + ^{197}Au$, 17 MeV/A.

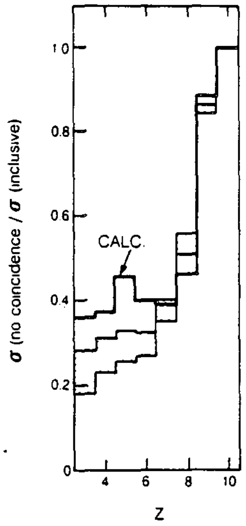

Fig. 2 - Ratio of cross section for fragments without a coincident charged particle to the inclusive yield. $^{20}Ne + ^{197}Au$, 17 MeV/A. Hatched areas are uncertainty in experiment, heavy line is calculation.

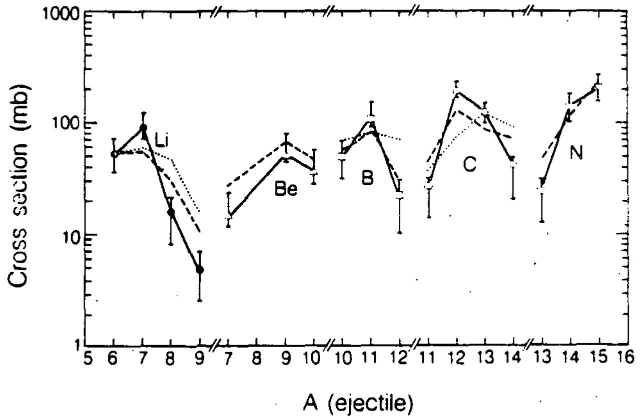

Fig. 3 - Experimental and calculated (dashed line) inclusive cross sections for $^{16}O + ^{208}Pb$, 20 MeV/A. Primary fragment cross sections for Li, B and C are dotted lines.

For the system $^{16}O + ^{208}Pb$, the calculated cross section ratio (20 MeV/A)/(2 GeV/A) shows enhancement of the most neutron-rich fragments at 20 MeV/A by an average factor of 3.5. For these same fragments, the experimental enhancement is 4.2 ± .85. Half of the enhancement comes from the neutron skin of the target combined with the large n-p cross section at 20 MeV. It is increased, for the neutron-rich fragments, by a further factor of 1.9 in the decay process.

Reactions of ^{40}Ar present a special problem arising from the neutron excess of the projectile itself. Any assumptions about the excitation energy and the decay modes of the primary fragments always lead to cross sections for each Z that have a maximum two mass numbers higher than observed experimentally [14]. This can be "cured" by the rather drastic assumption that the two neutrons of ^{40}Ar outside the N = 20 closed shell are always lost. The fragment thus produced then decays by the emission of light particles or by fission. A comparison with experiment of the isotope distributions thus obtained is shown in Fig. 5. The agreement is better than that obtained with a standard statistical evaporation model [14] (dashed lines). A substantial fraction of the yields of light elements comes from the fission process.

IV - SUMMARY

Below the Fermi energy, primary fragments are produced with sufficiently low excitation energies that a substantial fraction survive sequential decays, especially for heavier fragments.

Above twice the Fermi energy, the primary fragment excitations are large enough that decays include the fission channels. Primary fragments formed by the removal of more than a very few nucleons from the projectile do not survive as bound nuclei. They are probably disintegrated into nucleons and very light particles by the cascade of scattered nucleons coming from the overlap region of projectile and target nuclei [15].

V - ACKNOWLEDGEMENTS

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