EPJ Web of Conferences **31**, 00010 (2012)
DOI: 10.1051/epjconf/20123100010

Chemistry of nuclear particle production in 32 A MeV ^{136,124}Xe+^{124,112}Sn reactions and nuclear symmetry energy*

M. Kabtoul[1,**], R. Bougault[1], M. Colonna[2] and E. Galichet[3,4]
(INDRA Collaboration)

[1] LPC Caen, ENSICAEN, Université de Caen, CNRS/IN2P3, France
[2] LNS-INFN, I95123, Catania, Italy
[3] IPN Orsay, CNRS/IN2P3, Université Paris-Sud 11, France
[4] Conservatoire National des Arts et Métiers, Paris, France

Abstract

Nuclear particle production from peripheral to central events is presented. N/Z gradient between projectile and target is studied using the fact that two reactions have the same projectile+target N/Z and so the same neutron to proton ratio for the combined system and the impact parameter size dependent geometrical overlap region. Data in the forward part of the centre of mass indicates that N/Z equilibration is achieved for impact parameters below 6 fm and a comparison with transport model SMF calculations is done. SMF results agree with the data in average and by using the fragment multiplicity difference between ^{136}Xe+^{112}Sn and ^{124}Xe+^{124}Sn systems it seems possible to characterize the density dependence of the symmetry energy.

*Experiment performed at GANIL
**Fellowship from Syrian Arab Republic

1 Introduction

The 4π multi-detector INDRA [1], commissioned twenty years ago, was used to reveal N/Z effects in heavy ion reactions connected to the knowledge of asymmetric nuclear equation of state [2]. Four reactions were studied using beams of ^{136}Xe and ^{124}Xe, accelerated at 32 MeV/nucleon, and thin (330 μg/cm^2) targets of ^{124}Sn and ^{112}Sn. During the experiment minimum bias trigger and exclusive data were recorded. The results contained in this article concern the inclusive measurements.

For the studied reactions the INDRA multi-detector possess excellent performances in term of detection in the centre of mass forward hemisphere. Whereas in the backward part, energetic detection thresholds avoid to detect with full efficiency peripheral reactions. This study is thus performed on the forward part of the c.m and **all figures, tables and measured quantities are related to this half hemisphere**.

2 Impact parameter

For minimum bias trigger, the detected reaction cross-section is given in table 1. Events which corresponds to one single fragment of atomic number of 54 and no detected light charged particle were eliminated. This condition ensures the elimination of elastic scattering process but exclude also very peripheral reactions which lead to projectile neutron evaporation. Uncharged particles are not detected by the apparatus nevertheless measured values indicate that a large fraction of the reaction cross-section has been recorded when compared to predictions of [3].

Table 1: Detected reaction cross-section.

^{124}Xe+^{112}Sn	^{124}Xe+^{124}Sn	^{136}Xe+^{112}Sn	^{136}Xe+^{124}Sn
3550 mb	3870 mb	4145 mb	4498 mb

The light charged particle (lcp) transverse energy, $(\Sigma E_t)^{lcp}_{AvCM}$, is used as an impact parameter evaluator [4]. The relationship between $(\Sigma E_t)^{lcp}_{AvCM}$ and the impact parameter is given in figure 1 using the technique of reference [5] with data from minimum bias trigger conditions.

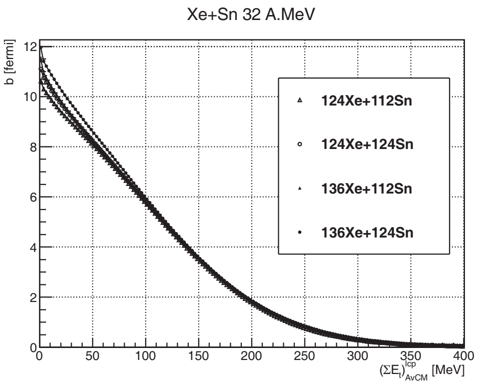

Figure 1: Correlation between lcp transverse energy (forward c.m) and impact parameter for the four studied systems.

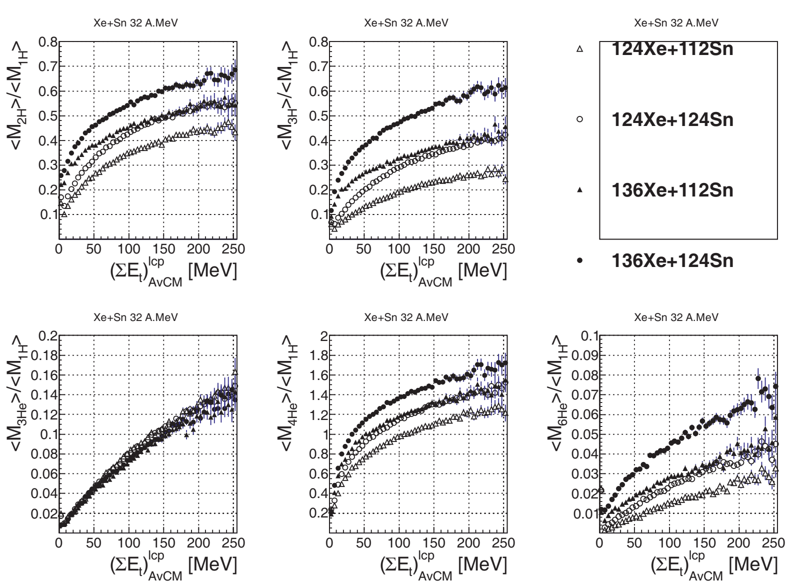

Figure 2: Mean light cluster production (forward c.m) relative to mean proton multiplicity as a function of impact parameter evaluator for the four studied systems.

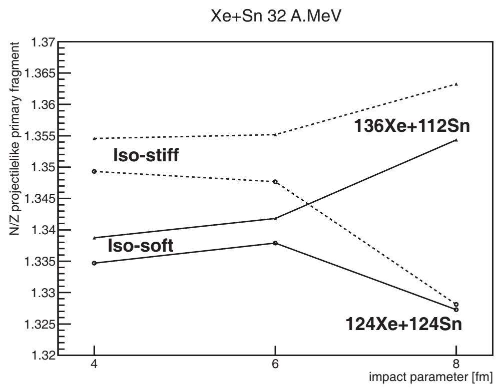

Figure 3: ^{124}Xe+^{124}Sn and ^{136}Xe+^{112}Sn system SMF transport model predictions concerning N/Z of the primary projectile-like fragment for three impact parameters and for two functionals of the density dependence of the symmetry energy.

3 N/Z equilibration

In figure 2, N/Z equilibration between the projectile and the target is tested through light cluster production relative to free proton multiplicity (forward c.m). Except ^{3}He whose production could be explained largely by early coalescence processes [6], light cluster relative multiplicity evolution indicates the following: (i) N/Z projectile dependence for very peripheral reactions, because systems with same projectile behave the same way, (ii) impact parameter (b) dependence evolution towards N/Z equilibration because ^{124}Xe+^{124}Sn and ^{136}Xe+^{112}Sn systems produce the same chemistry from $(\Sigma E_t)^{lcp}_{AvCM} >$ about 100 MeV.

In the forward part of the centre of mass, particles originate from the decay of primary projectile-like and mid-rapidity processes. Therefore the N/Z equilibration, achieved for b below about 6 fm, means that on top of mid-rapidity emission, the lcp production via Xe-like emission is identical for the two considered systems below 6 fm. For ^{124}Xe+^{124}Sn and ^{136}Xe+^{112}Sn, lcp production from the overlap region acts as a system independent background and the total multiplicity difference between the two systems is mainly connected to Xe-like emission. It follows that for b below 6 fm, the primary projectile-like N/Z is identical for the two systems.

This result is in agreement with SMF Transport Model calculations [7] for ^{124}Xe+^{124}Sn and ^{136}Xe+^{112}Sn systems at 32 A.MeV. N/Z of projectile-like primary fragment for three impact parameters is shown in figure 3. The analysis has been performed at t=360 fm/c for b=4 fm, t=260 fm/c for

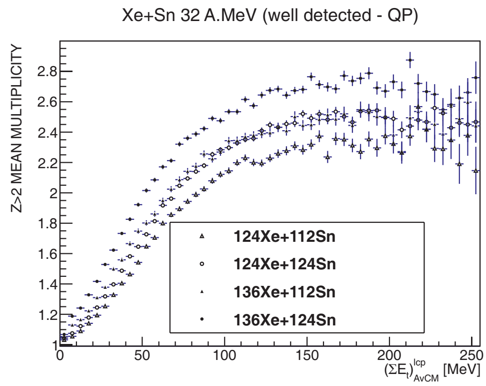

Figure 4: Mean fragment (Z>2) multiplicity as a function of impact parameter evaluator for the four studied systems.

b=6 fm and t=240 fm/c for b=8 fm. For impact parameters below 4 fm, a clear separation between projectile-like and target-like fragments is not possible because of occurrence of fusion events and fully damped binary collisions. SMF calculations use two functionals for the density dependence of the symmetry energy ($E^{pot}_{sym} = S_0 \, (\rho/\rho_0)^\gamma$ with γ=1 or 0.5). The results indicate almost equal N/Z for the projectile-like primary fragment from b around 6 fm whatever γ is.

4 Fragment production

We now concentrate on fragment (Z>2) production (forward c.m). In order to extract correct mean values of fragment multiplicities we must select well detected events and ensure a good sampling. These two conditions are fulfilled by retaining events with total atomic number collected in the forward c.m greater than 90% of that of the projectile. This selection ensure, for the four studied systems, a 20% constant sampling relative to total minimum bias events for all impact parameters below 8 fm ($(\Sigma E_t)^{lcp}_{AvCM} > 60$ MeV).

Two types of events are present for the four studied systems, fusion events and events with the presence of a projectile-like fragment in the forward part of the centre of mass ("QP-events"). The selection between the two types of events is performed by means of kinetic criterion upon the velocity of the biggest fragment in each event [8]. In the following fusion events will be eliminated in order to compare with SMF results where only events with a projectile-like fragment were analyzed.

Figure 4 presents the fragment (Z>2) mean multiplicity (forward c.m)

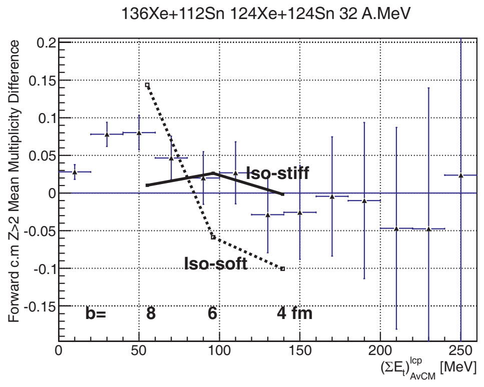

Figure 5: Difference of average fragment multiplicities (^{136}Xe+^{112}Sn minus ^{124}Xe+^{124}Sn) for data (final fragments) and SMF calculations (primary fragments).

behavior against centrality for well detected "QP-events" and for the different studied systems. As it was pointed out in [9], at any impact parameter the neutron rich system produces more fragments. The general trend is the same for the four systems: an increase with decreasing impact parameter and a saturation for central events. For impact parameters below 6 fm the fragment production is about the same, within few %, for ^{124}Xe+^{124}Sn and ^{136}Xe+^{112}Sn which confirms the quoted above N/Z equilibration from that b-value. The slight difference, few %, is due to neck emission and we will study this in the following.

5 Fragment production and symmetry energy

This section is an attempt to compare directly SMF and data results. The comparison of model transport calculations and data is difficult since all transport model needs an after burner for primary excited formed fragments to describe the full history of the process induces by the collision. Therefore the comparison relies indeed on the used evaporation or multi-fragmentation code. To avoid this problem the use of double ratios seems an alternative [10]. We present here a complementary method based on results concerning ^{124}Xe+^{124}Sn and ^{136}Xe+^{112}Sn systems.

The goal is to compare SMF primary fragment multiplicities and data thus, final (i.e cold) fragment multiplicities. In the forward c.m part, the final fragment production (M^{total}_{final}) for a given system is the sum of the fragment multiplicity from the excited projectile-like (M^{PLF}_{final}) and the fragment multiplicity from mid-rapidity or neck emission (M^{neck}_{final}). For the two considered systems and for a given impact parameter below 6 fm, $M^{PLF}_{final}(^{124}\mathrm{Xe}+^{124}\mathrm{Sn})$ and $M^{PLF}_{final}(^{136}\mathrm{Xe}+^{112}\mathrm{Sn})$ are identical (same primary PLF N/Z). It results that the subtraction of M^{total}_{final} between the two systems is reduced to the difference between the fragment multiplicities from mid-rapidity for each b below 6 fm. Concerning neck fragments, we may assume that M^{neck}_{final} difference is equal to $M^{neck}_{primary}$ difference in average. This hypothesis is related to the fact that secondary decay does not affect or even occur for these light mid-rapidity fragments. This is based on the good agreement of mid-rapidity fragment characteristics with extended Goldhaber Monte Carlo calculations [11] or with a prompt emission from the neck region itself, with also a successive emission from the surfaces of the separating nuclei in a time scale lower than 300 fm/c [12].

Thus using the fragment multiplicity subtraction between the two systems, it is possible to compare, in average, data and SMF predictions for b=6 and 4 fm (not 8 fm). The comparison is presented in figure 5 (preliminary for SMF). It is seen that the Iso-stiff hypothesis is in agreement with data values for b=4 and 6 fm. The Iso-soft calculation which leads to a difference of 3% and 4% for b=6 and 4 fm respectively may be excluded.

6 Conclusion

By choosing appropriate systems and experimental set-up, it is possible to test N/Z equilibration in heavy-ion collision. SMF calculations are in agreement with the experimental results. It appears that a direct data-model comparison concerning subtraction of fragment multiplicities between 32 A.MeV ^{136}Xe+^{112}Sn and ^{124}Xe+^{124}Sn systems is possible and could help to parametrize the density dependence of the symmetry energy.

References

[1] J.Pouthas, Nucl.Instr.and Meth. A357(1995),418

[2] "Dynamics and Thermodynamics with Nuclear Degrees of Freedom", edited by Ph. Chomaz, F.Gulminelli, W.Trautman and S.J. Yennello, Eur. Phys. J. A30, III (2006)

[3] S.Kox et al., Phys. Rev. C35 (1987) 1678

[4] E.Plagnol et al., Phys. Rev. C61 (1999)014606

[5] C. Cavata et al., Phys. Rev. C42 (1990) 1760

[6] W. Neubert and A.S. Botvina, Eur. Phys. J. A7 (2000) 101

[7] M. Colonna et al., Nucl. Phys. A642 (1998) 449

[8] M. Kabtoul, thesis of Caen University (2012)

[9] G.J. Kunde et al., Phys. Rev. Lett. 77 (1996) 2897

[10] M.B. Tsang et al., Phys. Rev. Lett. 102 (2009) 122701

[11] J. Lukasik et al., Phys. Lett. B566 (2003) 76

[12] S. Piantelli et al., Phys. Rev. Lett. 88 (2002) 052701