Intranuclear cascade+percolation+evaporation model applied to the $^{12}C+^{197}Au$ system at 1 GeV/nucleon

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The nucleus-nucleus Liège intranuclear-cascade+percolation+evaporation model has been applied to the ^{12}C+^{197}Au data measured by the INDRA-ALADIN collaboration at GSI. After the intranuclear cascade stage, the data are better reproduced when using the Statistical Multiframentation Model as afterburner. Further checks of the model are done on data from the EOS and KAOS collaborations.

1. Introduction

The ^{12}C+^{197}Au reaction at incident energies from 95 to 1800 MeV per nucleon has been studied [1] with the INDRA 4π-multidetector [2] installed at the GSI facility. This direct kinematics experiment aimed to complement previous studies in inverse kinematics by the ALADIN collaboration [3]. At the highest incident energies, the measurement was a challenge for the INDRA detector designed for reactions in the GANIL energy range. In this contribution proton data for the 1 GeV/nucleon reaction will be presented and compared to theoretical predictions.

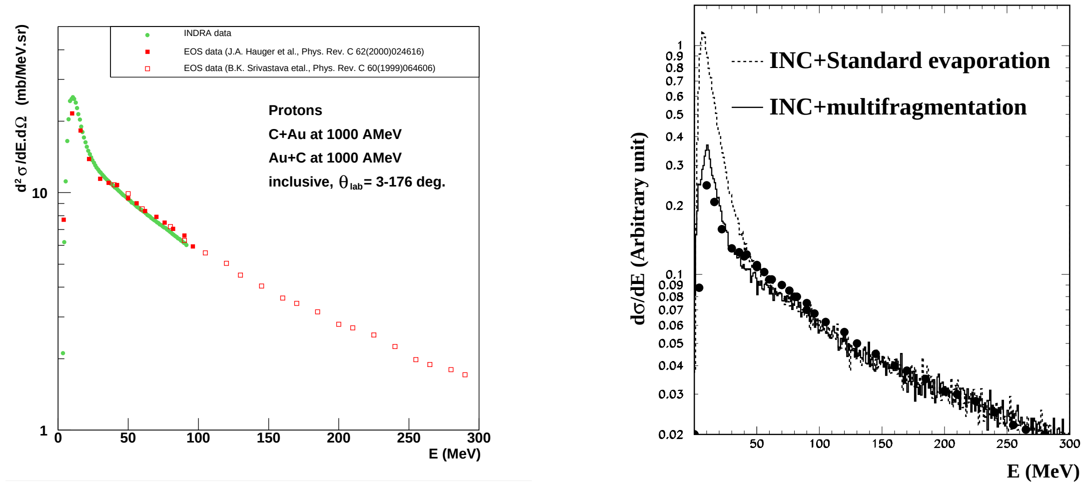

Figure 1. *Left part: The INDRA proton kinetic energy spectrum (full dots) for the C+Au reaction at 1. GeV/nucleon for angle-integrated data between* $3^0 \leq \theta_{lab} \leq 176^o$*, is compared to the EOS spectra (full and empty squares from [4] and [5] respectively). Data are in the gold reference frame. Right part: Comparison between proton EOS data and calculations with the INC+percolation model followed by the Dresner evaporation code (dashed line) or the multi-fragmentation SMM model (full line). The normalization is done on the high energy part.*

2. Proton energy spectra

The proton energy spectra have been measured as a function of detection angles following the INDRA ring configuration. Because of the high incident energies, it was necessary to correct the data from the interaction effects of stray particles with the detectors and the mounting structures. Data from annular veto detectors upstream the INDRA detector and measurements done with an empty target were used in this aim.

The present proton data have been angle-integrated over the whole detector ($3^o \leq \theta_{lab} \leq 176^o$) and the kinetic energy spectrum is compared on Fig 1 left, to the EOS proton data [4,5] obtained in inverse kinematics with a gold beam on a carbon target at 1 GeV/nucleon. The shapes of the spectra obtained from the two different data sets agree nicely. This confirms the good quality of the present proton detection and analysis.

The proton kinetic energy spectra at different angles are shown on Fig. 2 for central and peripheral reactions. The centrality is given by the reduced impact parameter b/b0 determined from the charged particle multiplicity [1], with b/b0=0.0-0.2 and b/b0=0.6-0.8, corresponding to central and peripheral collisions, respectively.

3. Comparison to calculations

The experimental proton energy spectra were confronted with the results of calculations using a hybrid model: the nucleus-nucleus Liège intranuclear cascade (INC)+percolation model [6–8] coupled to different afterburners. The INC stopping time is the same as in [8] but the percolation distances are larger because the system at 1 GeV/nucleon is more expanded. On Fig. 1 right, comparisons are shown between EOS data and the

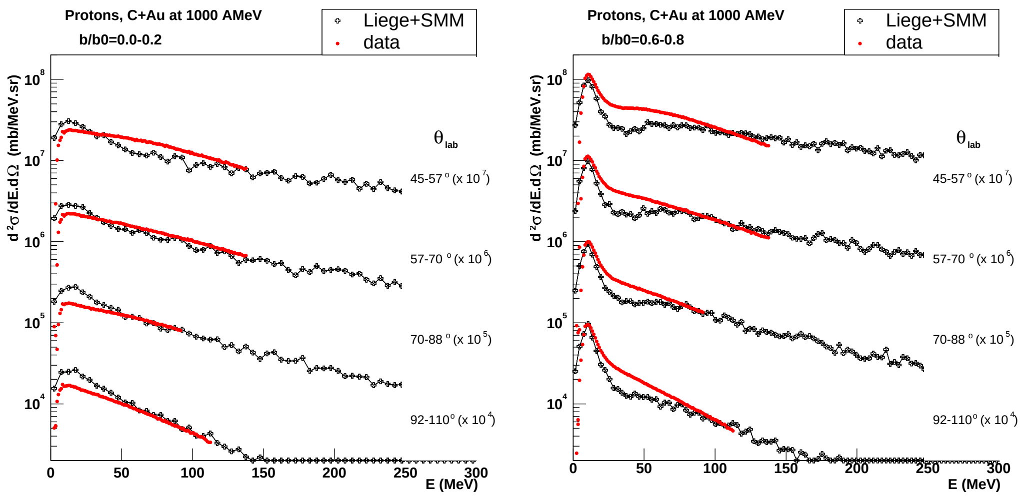

Figure 2. *Proton kinetic energy spectra for central (b/b0=0.0-0.2) collisions (left panel) for the indicated angles compared to calculations. Right panel: similar comparison for peripheral collisions (b/b0=0.6-0.8). Points are the data and crosses are the calculations with the INC+percolation model followed by the SMM model.*

INC+percolation model coupled to the Dresner evaporation code [8,9] or to the multifragmentation SMM model [10]. A good agreement between data and theory is obtained for the high energy part of the angle-integrated proton kinetic energy spectrum. In the calculations, this energy region is only populated with protons from the INC model. However, the low energy part of these spectra is overestimated when using the Dresner evaporation code. The SMM results are much closer to the data. In comparison to an evaporation code, the statistical multifragmentation model produces more fragments and hence cools more efficiently the primary heavy residues. This leads to fewer low-energy light particles, in agreement with the data. More detailed comparisons between INDRA data and this model are shown in Fig. 2. The calculations still overestimate the low energy part of the experimental proton spectra for central collisions. They agree with the data in this energy range for the peripheral reactions but with some discrepancies for $30 \leq E_{kin} \leq 60$ MeV, a region where both INC and SMM models contribute roughly equally to the proton production. The fast proton spectra are well reproduced on the whole angular and centrality ranges.
Further checks of the INC step can be performed by studying properties of pions and fast protons which are produced in the fast interaction stage. On Fig. 3, KAOS data for π^+ kinetic energy spectra at two angles for the same system are compared to the INC results. The nice agreement confirms the ability of the present calculation to treat the hard nucleon-nucleon collisions.

Pion and fast proton productions have also been studied in the INDRA measurements [1]. Correlations between these particles produced in the first interaction step and the fragment production have been investigated. The present calculations are able

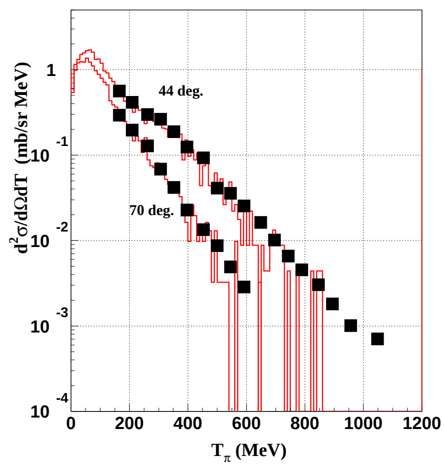

Figure 3. *Energy spectra of π^+ at two angles for the C+Au reaction at 1. GeV/nucleon. Squares are KAOS data and histograms are results of the INC calculations.*

to reproduce these data. This supports the idea of independant processes between particles emitted in a first stage and a thermal fragment emission in the second stage of the reaction.

4. Conclusion

The proton characteristics in the $^{12}C+^{197}Au$ reaction at 1 GeV/nucleon has been measured with the INDRA multidetector at GSI. The quality of the proton data analysis is confirmed by a successful comparison with EOS proton spectra from the same reaction in inverse kinematics. The high energy proton and pion productions are well reproduced by the nucleus-nucleus Liège intranuclear cascade model, this demonstrates the ability of the INC model to treat hard nucleon-nucleon collisions. The low energy protons are compared to the results of two different afterburners following the INC+percolation model: whereas the Dresner evaporation overestimates the experimental data, the SMM model agrees better with these data. These comparisons suggest that the multifragmentation is already reached in this reaction in agreement with the findings of the ALADIN [3] and EOS [4,5] collaborations.

REFERENCES

1. K. Turzó, PhD Thesis, Lyon University, France (2002). K. Turzó et al., in preparation.
2. J. Pouthas et al., Nucl. Inst. and Meth. A357 (1995)418.
3. A. Schüttauf et al., Nucl. Phys. A607 (1996) 457.
4. J.A. Hauger et al., Phys. Rev. C62 (2000) 024616.
5. B.K. Srivastava et al., Phys. Rev. C60 (1999) 064606.
6. J. Cugnon, Phys. Rev. C22 (1980) 1885.
7. J. Cugnon and C. Volant, Z. Phys. A334 (1989) 435.
8. D. Doré et al., Phys. Rev. C63 (2001) 034612.
9. L.W. Dresner, Oak Ridge Report No. ORNL-TM-196, 1962.
10. J. Bondorf et al., Phys. Rep. 257 (1995) 133.
11. F. Laue et al., Eur. Phys. J. A9 (2000) 397.