Simulation of light ion collisions from Intra Nuclear Cascade (INCL-Fermi Breakup) relevant for medical irradiations and radioprotection.

A. Boudard [1], J. Cugnon[2], P. Kaitaniemi [1,3], S. Leray [1], D. Mancusi[2]

[1] CEA/SPhN, Saclay, France
[2] Univ. Liège, Physics Department B5, Liège, Belgium
[3] Helsinki Institute of Physics, Helsinki, Finland

Email contact of main author: Alain.Boudard@cea.fr

Abstract. An extension of the Intra Nuclear Cascade code INCL for light ion beams (up to C-O) is presented. Calculations of neutron double differential cross sections and of beam fragmentation are compared to data and to other models. Neutrons are especially good in the quasi-elastic peak (emission at small angles). Predictions for projectile charge changing cross sections are realistic but suffer from a too large odd-even effect in the dependence with the fragment charge.

1. Introduction

An increasing interest is now well established in medicine for the treatment of tumours by irradiations with light ion beams (especially Carbon) of a few hundred MeV per nucleon. The radio-protection of manned spacecrafts irradiated by cosmic rays also has to face the modelling of ion interactions with human tissues. In that case, relevant ions range from protons to iron ions and the energy spectra is much larger, extending up to a few GeV per nucleons.

In both cases the nuclear targets are dominantly Hydrogen, Oxygen and Carbon with a few heavier nuclei up to Calcium. A similar subsidiary question is the damage to spacecraft electronics which adds to our purpose Silicium as a target nuclei of interest.

The availability of reliable simulation tools for the study of various configurations and screenings, dependence with the beam energy and nature, etc is certainly important. Monte-Carlo techniques based on physics models for the basic interactions and transport of particles in various medium assembled in complex geometries have proven to be useful tools relevant for these types of problems. Several such codes has MCNPX, FLUKA or GEANT4 are available and extensively used to simulate complex experimental setups.

All of them are well established to treat the transport of particles (elastic scattering at low energy, electronic energy loss, ionization…) and complex geometries, but the nuclear interactions are more questionable. This is due to the fact that on one hand more and more outgoing channels are open when the energy grows up (above a few hundred MeV per nucleon) which makes unrealistic a full knowledge based on experimental measurements especially if we consider also the variety of beams (nature and energy) and targets which are needed. This problem can be fulfilled by Intra Nuclear Cascade models which aim at giving all outgoing channels for any nuclei and at all energies since they are based on series of nucleon-nucleon interactions (experimentally known) taking place inside realistic nuclear potentials. But on the other hand these models are theoretically established for nucleon beams on heavy target nuclei (the target nucleus is a statistical ensemble of nucleons) and at rather high energy. The wavelength associated to the beam nucleon should be of the order of the nucleon size and of the nucleon-nucleon inter-distance which put a low energy limit around 150-200 MeV . Dr. Y. Yariv for example has discussed this point during the present conference [1].

Intra Nuclear Cascades (complemented by a de-excitation code) are also extremely appealing since they give naturally the correlations between all type of outgoing particles their nature and kinematics including the fluctuations around the mean values and without parameter adjustments for the best of them. It means that they are especially adapted for the optimisation of conditions (beam energy, nature, thicknesses of screening etc.) for a given purpose.

Several specific models are available and presently developed (ref [2] for a detail description of some of them). It was the subject of one satellite meeting in this conference [3] to start a critical analysis of their predictive power for proton beams especially on Iron and Lead targets.

Some of these models (ISABEL, FLUKA, CEM) are already used in the present context of light ion collisions at rather low energy. Since our cascade (INCL4 originally developed at Liège) is well established for nucleon beams but also for a composite as the deuteron [4], it was natural to extend the code up to Carbon-Oxygen beams. It is important to try an evaluation of systematic uncertainties due to the use of models at the limit of their domain of strict applicability and the availability of several models is probably a way to access this delicate information.

2. The model

The version INCL4.3 that we have used here is described in ref [4]. It includes basically a unique nuclear potential for protons and neutrons and a first version of cluster production described in ref [5]. It was formally working up to ^{4}He beams but was very poorly tested for composite projectiles heavier than the deuteron. The version 4.2 (without clusters) is available in the transport code LAHET, MCNPX and GEANT4 [6].

Composite projectiles (light ions) are treated in the following way:

For a random impact parameter b, A nucleons with Z protons are randomly taken from Gaussian distributions in geometrical (r) and momentum (p) space. The r.m.s. in r space is realistic of the light ion considered. The p space r.m.s. is fixed (100 MeV/c). They are Lorentz-boosted in the laboratory system. The sum of individual energies is taken as equal to the incident total energy but the sum of vector momenta is slightly biased due to the fact that nucleons are on mass shell.

From this collection of beam nucleons some of them will miss the target potential. They are called projectile spectators. The other ones will enter the target region and will interact in series of N-N interactions as independent particles and as in a standard nucleon-nucleus calculation. Some of them may pass through the nuclear volume without interaction. In that case they will be also considered as projectile spectators. All projectile spectators are grouped together to form a nucleus. Its fluctuating charge, mass number and momentum are easily determined by summation. Its excitation energy comes from the excess of energy compared to the realistic mass (from tables).

With light nuclei, it is well known that the excitation energy per nucleon can easily reach a value similar (or even larger) than the binding energy and a treatment of the de-excitation by a sequential evaporation of nucleons as for heavy targets is no more appropriate. Consequently the so-called Fermi-Breakup is used (in almost all codes). It corresponds to a partition of a light nucleus in on step with an evaluation of the probability for each of them by the available phase space and the statistical weight. We have always used it for the projectile spectators and for the target residue when during the cascade process the nuclear mass falls below ten.

3. Results

Double differential cross sections of neutron inclusive production for Carbon beams of 400 MeV and 290 MeV per nucleon on Carbon Copper and Lead targets have been measured [7]. Experimental results at 400A MeV for Cu and Pb targets are compared to our calculation in *Fig 1* and *Fig 2*. The de-excitation code used here is the standard version of ABLA [8]. For Pb, the coupling of ISABEL [9] with the same de-excitation is also displayed. Clearly our code has a rather realistic cross section especially for the quasi elastic production in the forward direction. It should be said that there is no arbitrary global normalisation of our calculations. This is true also for the ISABEL calculation. Both models have an important excess of evaporation neutrons below 20 MeV. On the other hand, the incredible raise of very low energy neutrons measured only at 30° suggests that error bars should be seriously underestimated in this domain. Similar results are obtained at 290A MeV on Cu and Pb but with a shift of the quasi-elastic peak measured around 200 MeV and found around 290MeV in our model.

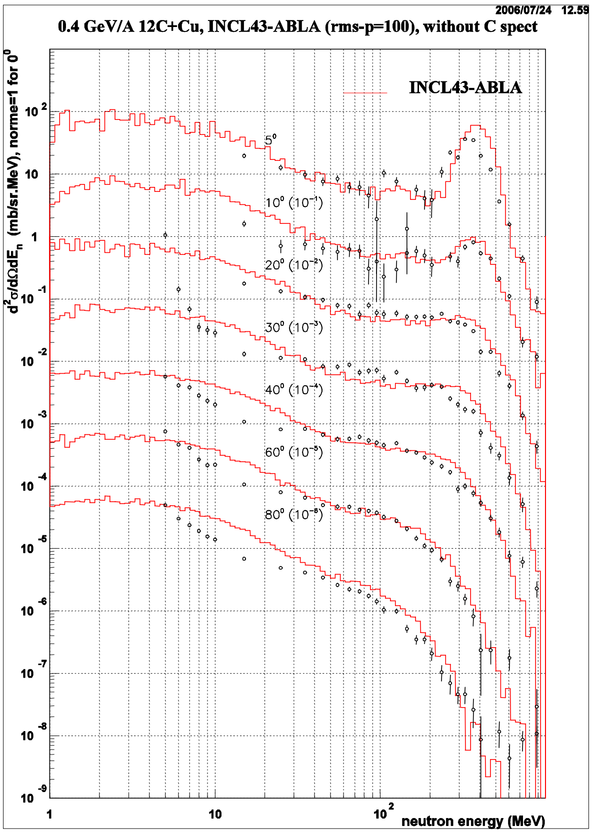

Fig 1: Neutron double differential cross-sections for C of 400A MeV on Cu. Data points are from[7]. The line is the INCL-ABLA calculation.

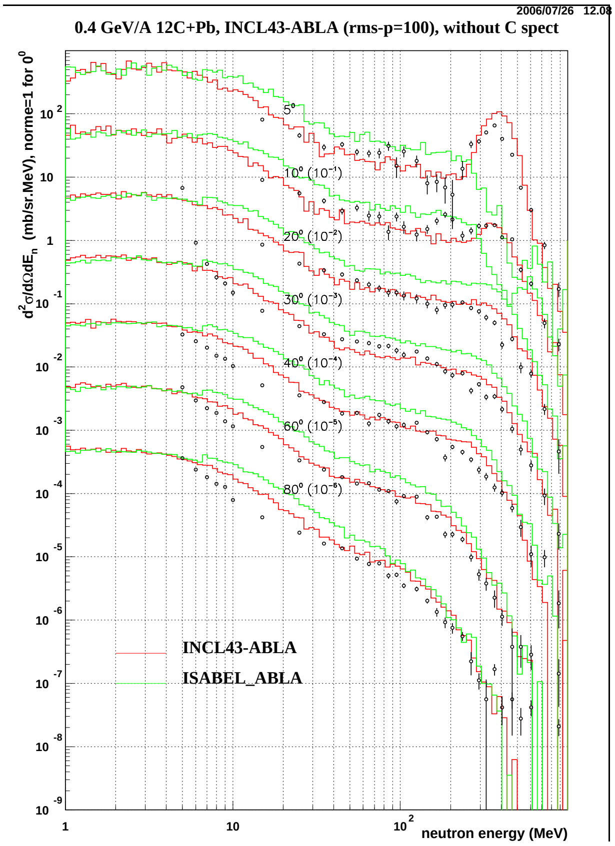

Fig 2: Same as Fig 1 for a Pb target. The ISABEL-ABLA calculation is also shown as a line.

At the same energy the neutron production for a C target is rather correctly reproduced (*Fig 3*), but we can again notice that the model overproduces neutrons of low energy.

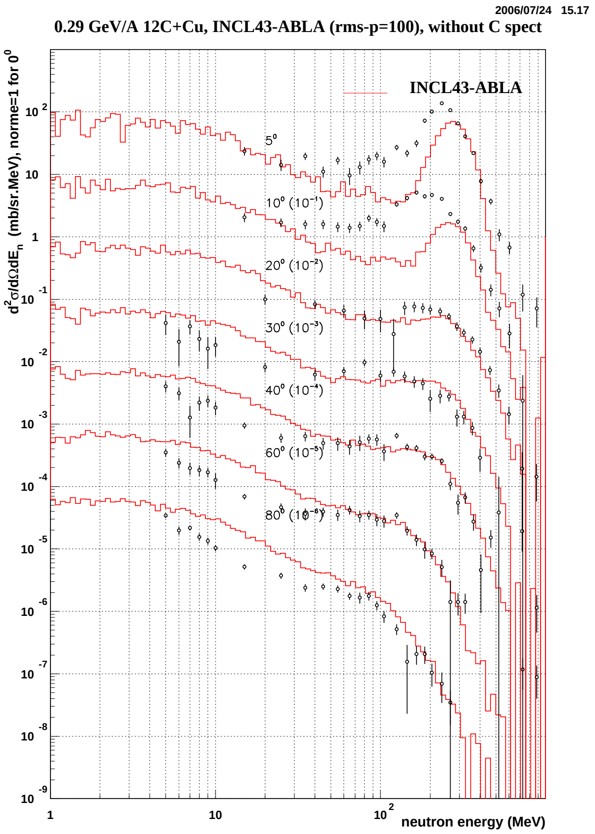

Fig 3: Neutron double differential cross sections for a C beam of 290A MeV on a Cu target. The data points are from [7]. The line is the INCL-ABLA calculation.

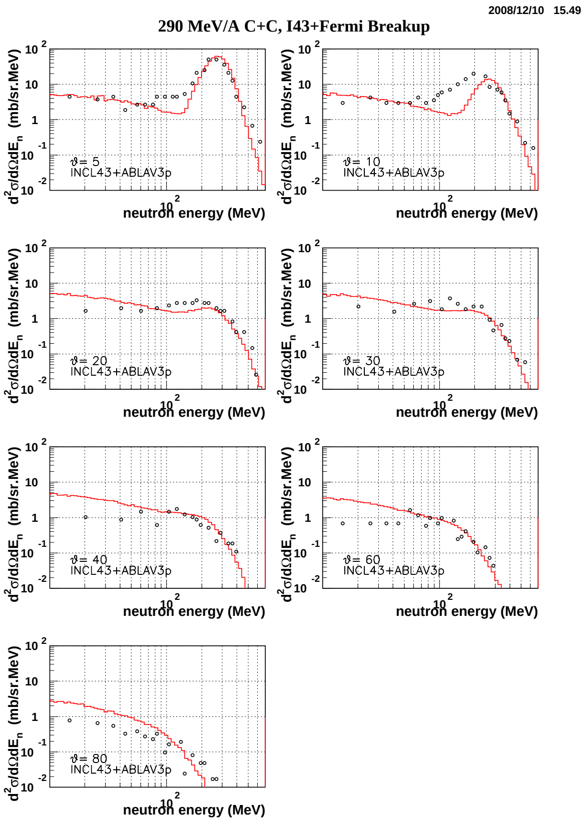

Fig 4: Same as for Fig 3 but with a C target.

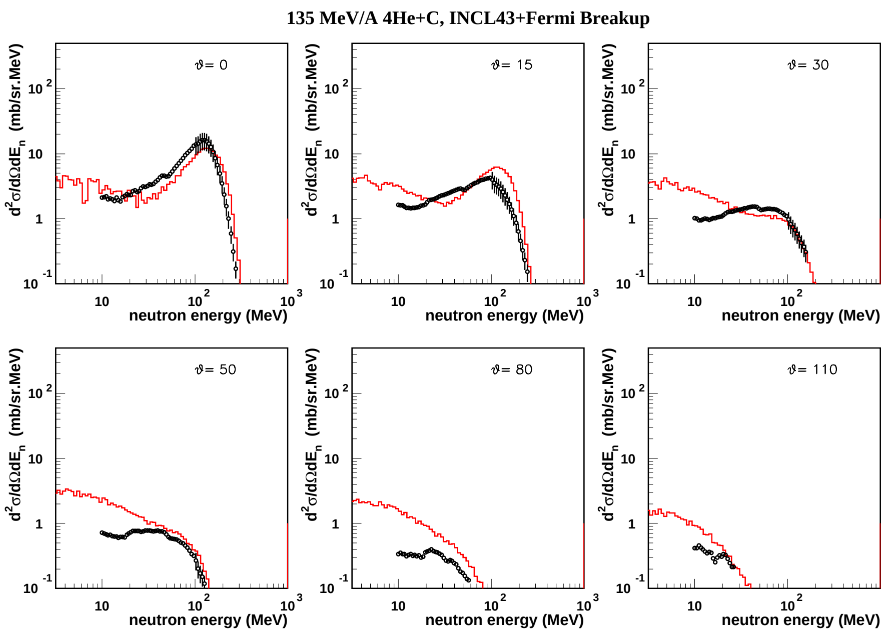

Fig 5: Neutron double differential cross-sections for a 4He beam of 135MeV per nucleon on a C target. Data points are from [10]. The line is the INCL calculation.

A lot of data on n production has been obtained at 135 MeV per nucleon with alpha and Carbon beams [10]. Some of them are shown here in Fig 5 to Fig 8. It is promising to note that the model gives a reasonable account of the data even at this rather low energy. This was also shown by the GEANT4 hadronic working group [11] on the same set of data using the Binary Cascade (BIC) or the Quantum Molecular Dynamic (QMD) models. Our calculation gives a more realistic quasi elastic peak at 0° especially for the Alpha beam but the unrealistic deep around 40-50 MeV at 15°-30° is more pronounced for our calculation. All calculations predict systematically more neutrons of very low energy (below 20-30 MeV) than it is measured. For the C target, the de-excitation is dominantly obtained by the Fermi-Breakup. In all cases when appropriate, the evaporation is from ABLA.

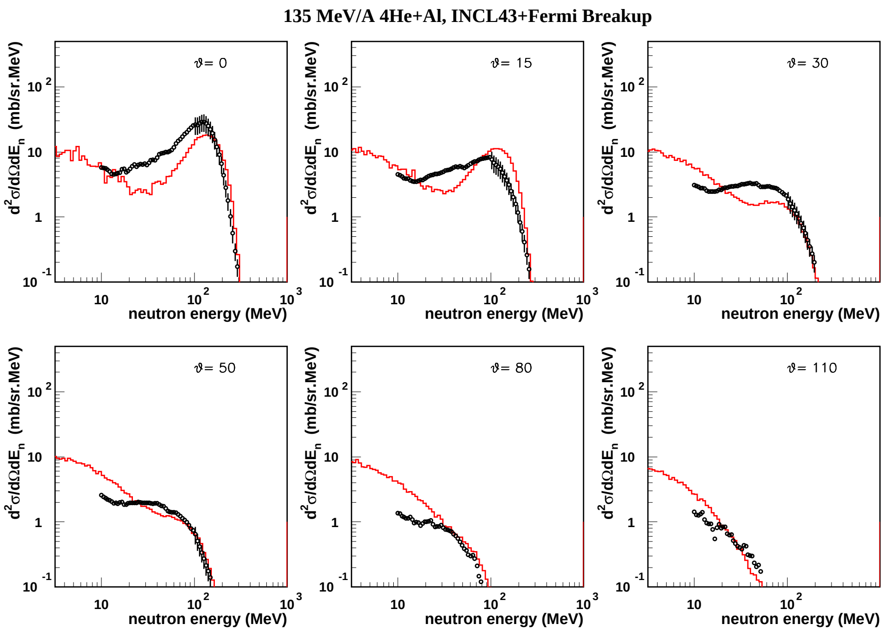

Fig 6: Same as for Fig 5 but with an Al target

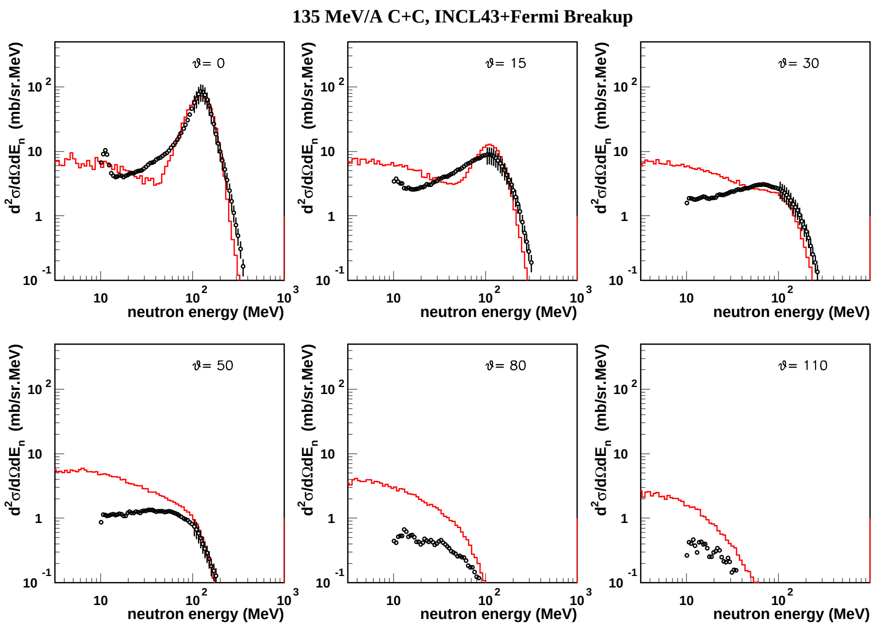

Fig 7: Same as Fig 5 but for a C beam on a C target.

135 MeV/A C+Cu, INCL43+Fermi Breakup

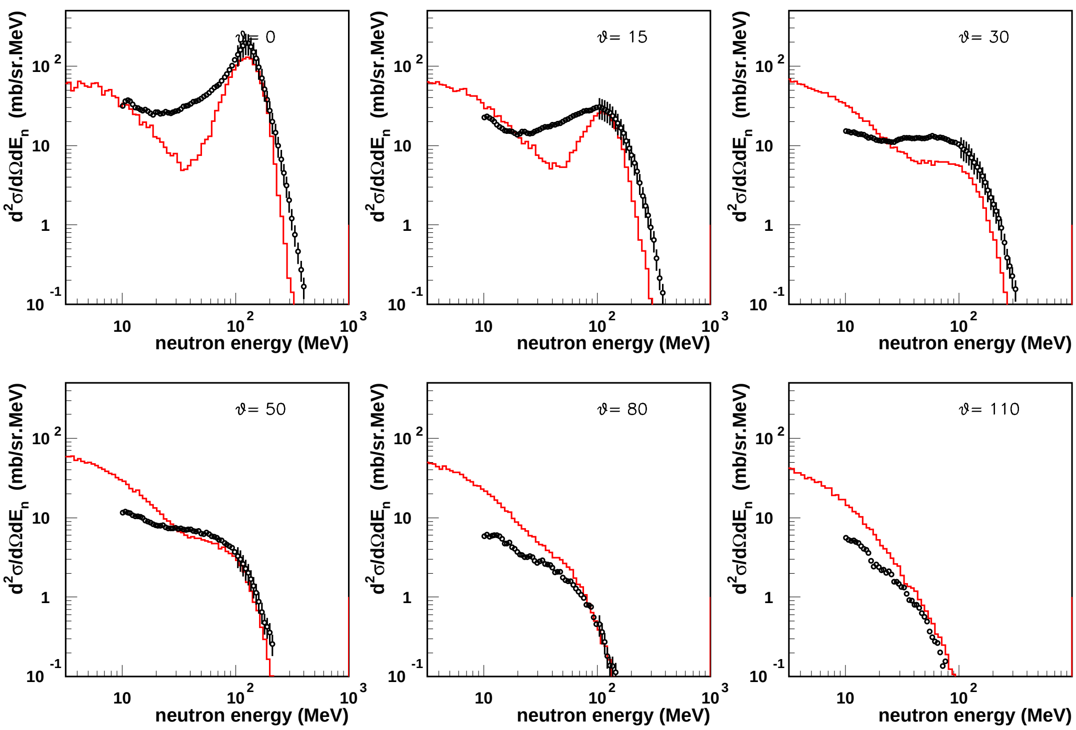

Fig 8: Same as Fig 5 but for a C beam on a Cu target.

The calculation of the cross section for the production of residues from the target or for the fragmentation of the projectile in reverse kinematics can be compared to data [12]. This is done in Fig 9 for the fragmentation of Oxygen at 290 Mev and 400 MeV per nucleon and in Fig 10 for the fragmentation of Iron on Carbon. Only the charge of the fragment is measured. The scale is linear and the results are rather close to the data. We can however note that there is an odd-even effect (coming from the de-excitation step) which is not large enough, especially for the C-O system. Our results are here qualitatively the same as obtained with the FLUKA code [13].

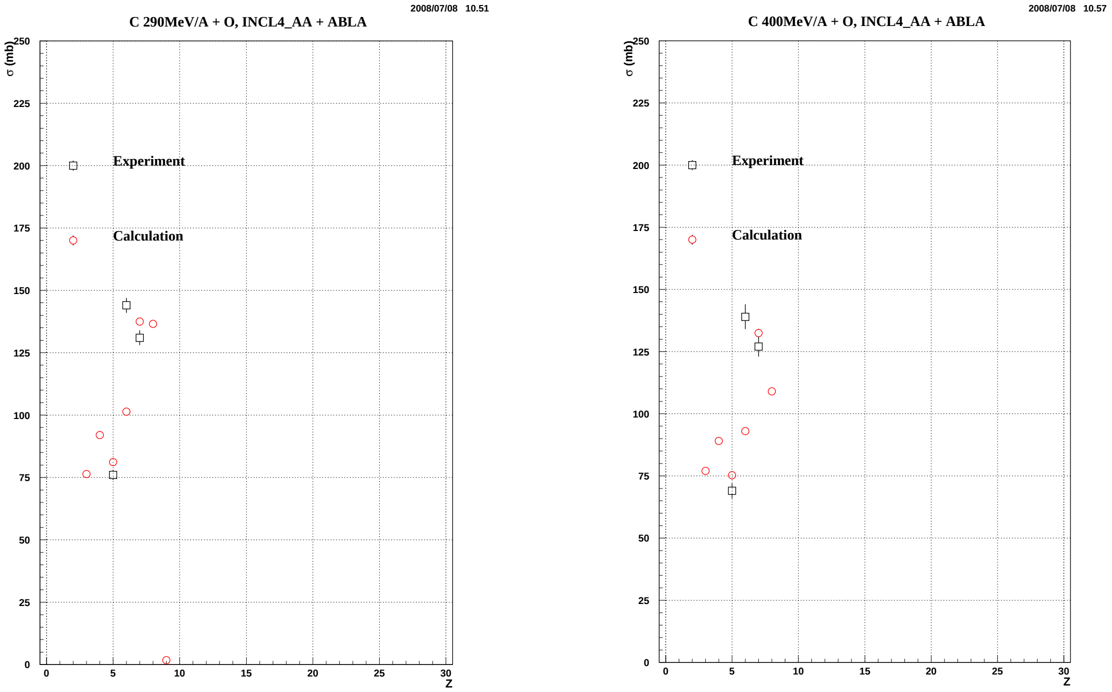

Fig 9: Charge changing cross sections for a O beam of 290 MeV per nucleon (left) and 400 MeV per nucleon (right) on a C target. Data points (black squares) are from [12]. Red open circles are the INCL-ABLA calculation.

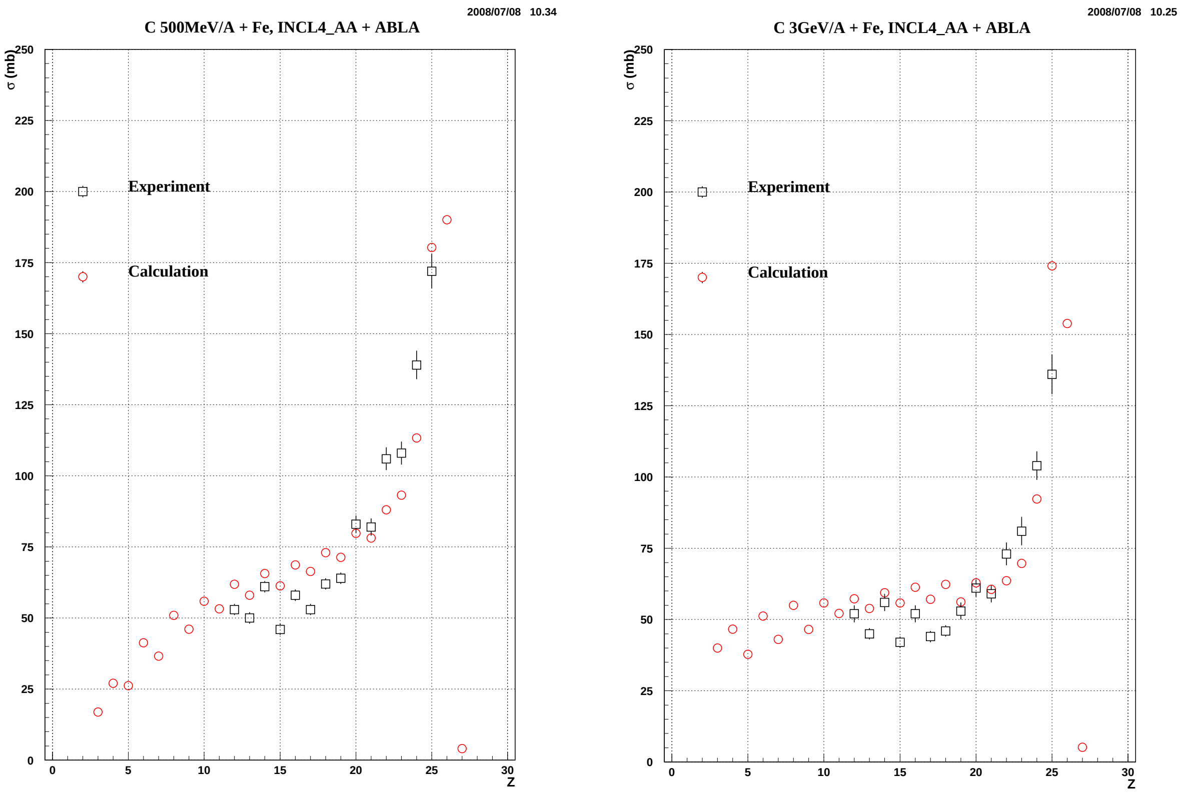

Fig 10: Charge changing cross sections for a Fe beam of 500 MeV per nucleon (left) and 3 GeV per nucleon (right) on a C target. Data points (black squares) are from [12]. Red open circles are the INCL-ABLA calculation.

3. Conclusions

We have shown an improvement of the Intra Nuclear Cascade code INCL for the calculation of nuclear reactions with light ion beams. Having in mind medical irradiations and radioprotection problems in manned spacecrafts, calculations with light nuclei were especially emphasized.
The neutron double differential cross sections are reasonably reproduced in a wide range of energies. The quasi-elastic peak at small emission angles is realistic and rather well reproduced. However the production of neutrons below ~20 MeV is in excess as for the other models.
The fragmentation of the projectile is also reproduced realistically but has not yet been tested enough. For light nuclei, there is a clear need to investigate more carefully odd-even effects in the dependence with the charge.

Our model appears to be already of the same quality as other models and can easily be improved. More attention and several possibilities should be tested for the sharing of excitation energy between the target and the spectators of the projectile especially at rather large impact parameters.

The present modifications could easily be implemented in the version already available in GEANT4 and this will be used in the near future to investigate also results of integral experiments involving thick targets and more complex geometries.

References:

[1] YARIV Y., INC Model for Hadron-Nucleus Reactions, ADS/ND-03 (Proc. Conf. Nuclear Research Applications and Utilization of Accelerators, Vienna (2009); Contributed Papers (CD-ROM).
[2] Joint ICTP-IAEA Advanced Workshop on Model Codes for Spallation Reactions, ICTP Trieste (2008).
[3] N.R.A.U.A., Satellite meeting on Nuclear Spallation Reactions, FILGES D., LERAY S., MANGONI A., MANK G., STANCULESCU A.,YARIV Y. ,Vienna (2009)
[4] BOUDARD A., CUGNON J., LERAY S., VOLANT C., Phys. Rev. C 66 (2002) 044615.
[5] BOUDARD A., CUGNON J., LERAY S., VOLANT C., Nucl. Phys. A 740 (2004) 195.
[6] BOUDARD A., HEIKKINEN A. and KAITANIEMI P., Implementation of INCL4 Cascade and ABLA Evaporation Codes in GEANT4, Journal of Physics: Conference series 119 (2008) 032024, doi:10.1088/1742-6596/119/3/032024
[7] IWATA Y. et al., Phys. Rev. C 64 (2001) 54609.
[8] GAIMARD J.J. and SCHMIDT K.-H., Nucl. Phys. A531 (1991) 709 and A.R. JUNGHANS et al. Nucl. Phys. A629 (1998) 635.
[9] YARIV Y. and FRAENKEL Z., Phys. Rev. C24 (1981) 488.
[10] SATO H. et al., Phys. Rev. C 64 (2001) 34607.
[11] ROMANO F., CIRRONE G. and CUTTONE G., GEANT4 Hadronic working group, Private communication 2008.
[12] LBL repository: http://fragserver.lbl.gov, (ZEITLIN C. et al.)
[13] FERRARI A., NUFRA2007, Antalia Turkey (2007), ed. BOTVINA A.S..