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Spallation Modeling - What's new on nuclei production with INCL4.5-Abla07?

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Abstract. Spallation reactions play a role in the production of isotopes in meteorites by Galactic cosmic ray (GCR) particles. For several decades cosmogenic nuclide production rates have been measured in different types of meteorites and calculation models have been improved. The main microscopic ingredients of these models are: i) the particle fluxes responsible of the nuclide production (primary and secondary particles) and ii) the production cross-section of nuclides from a given particle (in the whole energy range). Up to now the best choice seems to compute the particle fluxes with Monte-Carlo codes and to use experimental measurement for the production cross sections, if available. Meanwhile spallation models have also been improved, especially the combination INCL4-Abla. New versions of these combined models have been recently benchmarked within the "Benchmark of spallation models" carried out by IAEA and it comes out that INCL4.5-Abla07 is one of the best combinations to describe spallation reactions. In this paper we will show, with microscopic excitation functions, the significant improvement brought in the estimates of nuclides of interest in stony and iron meteorites (^{10}Be, ^{53}Mn, ^{59}Ni, ...) by these models.

Key words. Nuclear reactions – Meteorites – ISM: cosmic rays

1. Introduction

Meteorites are irradiated by Galactic cosmic rays (GCR). Measuring the production rates (PR) of specific cosmogenic nuclei on the one hand, and knowing both the microscopic production cross sections and the particle spectra inducing reactions on the other hand, enable us to get information on the meteorite history and also on the cosmic rays.

Due to GCR spectrum, the relevant reaction energy domain is around 1 GeV, which is the nuclear spallation domain (say between 150 and 3000 MeV) and below (down to thresholds). Therefore spallation reaction modeling plays an important role in meteorite studies. Spallation codes are mainly used to obtain the spectral fluences of the particles propagating inside the meteorite, but they can also help in providing the needed isotope production cross sections. These latter quantities, as main ingredients of the calculated cosmogenic nuclei production rates, must be as reliable as possible. Most of the time PR calculations are based on experimental production cross sections, but sometimes data are questionable and/or scarce, then models are needed (Leya & Masarik 2009).

Up to few years ago spallation models were not able to give good results for isotope production in the whole mass and charge range. The main deficiency was the light isotope production yields, i.e. isotopes much lighter than the nucleus target (e.g. ^{10}Be from Fe target). As a result it was concluded in (Ammon et al. 2008) that *[...] the predictive power of nuclear model codes [...] does still not allow to reliably predict the cross sections needed*. Since then spallation models have been improved and especially the combination INCL4.2 (Boudard et al. 2002)-Abla (Junghans et al. 1998) which was used in (Ammon et al. 2008). New emitted particles were included and missing mechanisms added to fix, for example, the light nucleus production. A worldwide *Benchmark of Spallation Models* carried out by IAEA (IAEA 2008) showed in 2010 the high quality of the improved model combination INCL4.5-Abla07.

This paper is then dedicated to test this new spallation model on excitation functions for cosmogenic nuclei production in meteorites. The results are divided in three parts. The first one deals with proton projectile on O, Fe and Ni targets to compare the new model with experimental data and other models. Since neutron-induced reaction data are scarce and not as good as the proton-induced, sometimes the same cross sections are assumed as for proton-induced reaction. Differences between neutron and proton-induced reaction cross sections will be studied in the second part. The last one is devoted to α+Fe. Here again experimental data are missing and models could help.

2. INCL4.5 and Abla07 improvements

Spallation reactions are usually described by two stages: An Intra Nuclear Cascade (INC) leading to a remnant nucleus de-exciting in a second step. The spallation model combination INCL4.2-Abla gave good results on neutron spectra (projectile energy > 150 MeV), on residue yields for nuclei close to the target and on fission fragments (Boudard et al. 2002), but failed to reproduce light isotopes. To cure this shortcoming new mechanisms have been developed and implemented in both models. Here are below, briefly described, the main ingredients. More details can be read at (IAEA 2008).

2.1. INCL4.5

INCL4.2 was only able to emit nucleons and pions. Then a surface coalescence model has been added in INCL4.5 to emit composite particles (up to A=8). This mechanism is based on the idea that a nucleon escaping from the nucleus can drag with him other nucleons which are sufficiently close (in phase space), and form an emitted light charged cluster. Moreover, although spallation models are not supposed to be reliable below 150 MeV, since nucleon should be sensitive to the nuclear structure, it is interesting to try to extend to lower energies.

2.2. Abla07

The main improvement in Abla07 is the implementation of evaporation of all particles from nucleons up to alpha and the heavier ions emission via two processes: Breakup (or multifragmentation), when temperature of the remnant is high enough, and evaporation (or binary fragmentation). Evaporation mechanism has been refined with much more sophisticated Coulomb barriers and inverse cross sections.

3. Results

Since this paper is focused on cosmogenic nuclei in meteorites we decided to run calculations with proton and neutron projectiles on O, Fe and Ni, which are typical nuclei contained in stony and iron meteorites, and only Fe for α-induced reactions. We will plot not only INCL4.5-Abla07, but also the previous version INCL4.2-Abla to quantify the improvements, the Bertini-Dresner combination, which is the well known default option still used in (LAHET3.16 2001) and (MCNPX2.6.0 2008) transport codes, and the TALYS results (via TENDL10, TALYS-based Evaluated Nuclear Data Library 2010 - Koning & Rochman 2010)

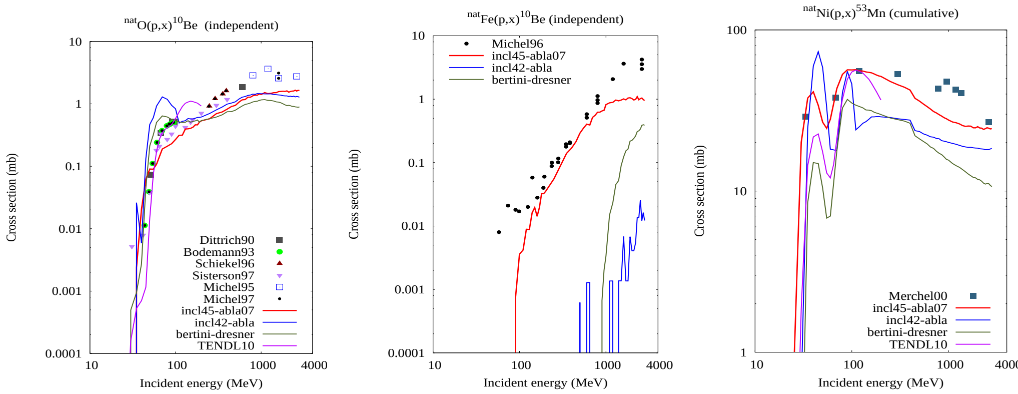

Fig. 1. ^{10}Be production cross sections from proton-induced reaction on natural O (left) and natural Fe (middle) and ^{53}Mn production cross sections on natural Ni (right). Experimental data come from (Michel et al. 2002; Sisterson et al. 1997) and references therein.

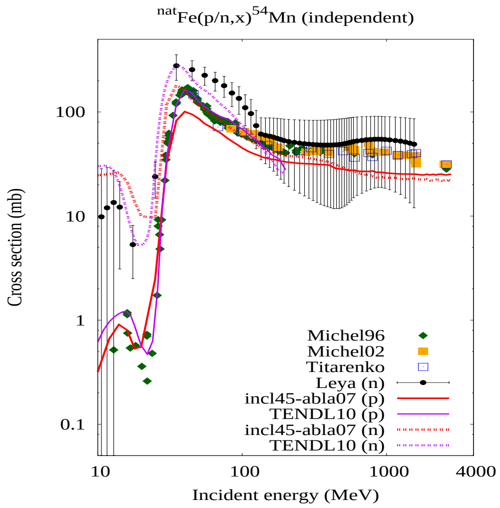

Fig. 2. ^{54}Mn production cross sections from proton and neutron-induced reactions on natural Fe. Solid lines are for proton-induced reactions and dashed lines for neutron. Experimental data for proton come from (Michel et al. 2002; Titarenko et al. 2008) and references therein. For neutron (Leya (n)) data have been submitted to NIM B.

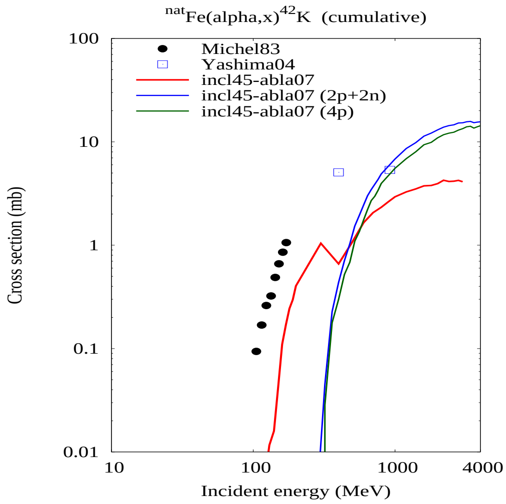

Fig. 3. ^{42}K production cross sections from alpha-induced reaction on natural Fe. Experimental data come from (Michel et al. 2002; Yashima et al. 2004) and references therein

3.1. p + O, Fe, Ni

Fig. 1 shows in left and middle panels ^{10}Be production from O and Fe. It is clear that different mechanisms are involved. From O, ^{10}Be is produced as the residue after emission of light particles (below α). Then all models are more or less able to reproduce the experimental data. For the Fe case, ^{10}Be can only be obtained by models including other mechanisms: emission of heavier particles and/or break-up. INCL4.5-Abla07 is the only one which gives good results, even if below 100 and above 1000 MeV discrepancies have to be understood. The right panel of Fig. 1 confirms the good results, here for an isotope, close to the mass target, over the whole energy range.

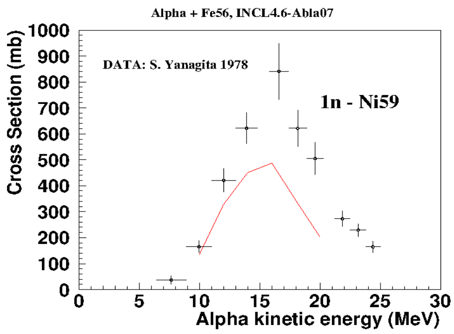

Fig. 4. ^{59}Ni production cross sections from alpha-induced reaction on ^{56}Fe. Experimental data come from (Yanagita et al. 1978). The calculation results have been obtained with an improved version of INCL4.5 combined to Abla07.

3.2. n + O, Fe, Ni

If GCRs are made of protons (87%), α (12%) and heavier ions (1%), secondary neutrons are produced in meteorites via spallation and then induce also reactions. Data being scarce, people assume often that n and p give the same production cross section. This assumption is valid only at high energy or for isotopes much lighter than the target. Fig. 2 exhibits the different low and high energy behaviours. It can also be seen that INCL4.5-Abla07 at low energy gives rather good results and is competitive with TALYS.

3.3. α + Fe

Experimental data for α-induced reaction are sparse and few models are able to compute these cross sections. Therefore to take into account the 12% of α it is sometimes assumed that α's break-up and so can be considered as two protons and two neutrons. We tried to investigate the validity of this approximation by comparing calculations done with incident α or 2p+2n and Fig. 3 gives us some lights. First, α as 2p+2n is clearly a bad approximation especially at low energies. Second, if results with a real α are better, two points have to be improved: cross section is too low and around 200-300 MeV the curve should be smooth which it is not the case. The too low cross section is due to a too low α-induced reaction cross section and the 200-300 MeV jerk is being investigating. Improvements are already in progress (Fig. 4 is a preliminary result showing the way).

4. Conclusions

INCL4.5-Abla07, known as one of the best spallation model combination (IAEA 2008), has been tested in this paper on cosmogenic nucleus production cross sections, main ingredients of nucleus production rates in meteorite studies. New mechanisms added in INCL4.5 (surface coalescence, low energy extension, ...) and in Abla07 (Break-up, heavy ion evaporation, ...) lead to much better results in proton and neutron-induced reactions on the whole energy range. Concerning α-induced reactions results are promising and better agreement should be obtained in the next months.

Experimental data are sometimes scarce or questionable, thus INCL4.5-Abla07, becoming an accurate and comprehensive model, aims at providing the missing information needed in meteorite study.

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