Isotopic Production Cross Sections (ISOPROCS Project)

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Abstract: Last several years were rich with discoveries in astrophysics of cosmic rays (CRs), thanks to improved instrumentation, moving us closer to understanding of the origin of CRs. Even more is expected in the near future. However, continued progress in this field requires adequately precise calculation of the cross sections of the nuclear reactions experienced by CRs in the interstellar medium (ISM). While some theoretical and experimental effort on this topic has been made in the past two decades, the current accuracy of the nuclear production cross sections is way behind the accuracy of astrophysical data. This paper applies the state-of-the-art CR isotopic production cross section library used in the GALPROP code to identify the most important channels for the production of measured CR species.

Keywords: cosmic rays, propagation, fragmentation

1 Introduction

Current and planned CR experiments (e.g., ACE [1, 2], PAMELA [3, 4, 5], CREAM [6, 7], AMS-02 [8], ISS-CREAM) provide progressively more accurate data. Their interpretation requires reliable predictions of the CR abundances and fluxes, which, in turn, rely on the quality of the models. Isotopic production cross sections are the most basic set of physical data used by both, experimentalists and theoreticians.

CR nuclei studies necessarily require the consideration of nuclear spallation, production of secondary particles, and radioactive decay. Calculation of isotopic abundances and the propagation parameters themselves is impossible without inclusion of hundreds of stable and radioactive isotopes produced by spallation of CR nuclei. Measurements of secondary stable and radioactive nuclei in CRs provide information necessary to probe large-scale Galactic properties, such as the diffusion coefficient and the halo size, the Alfvén velocity and/or the convection velocity, as well as the mechanisms and sites of CR acceleration.

Knowing the number density of primary nuclei from satellite and balloon observations, the production cross-sections from accelerator experiments, and the gas distribution from astronomical observations, the production rate of secondary nuclei can be calculated. The observed abundances of stable secondary CR nuclei (e.g., B) and radioactive isotopes (^{10}Be, ^{26}Al, ^{36}Cl, ^{54}Mn) allow the separate determination of the halo size and diffusion coefficient [9, 10, 11, 12, 13, 14]. K-capture isotopes in CRs (e.g., ^{49}V, ^{51}Cr) can be used to study energy-dependent propagation, such as diffusive reacceleration in the ISM and heliospheric modulation [15, 16, 17],

The accuracy of the isotopic production cross sections employed in the GALPROP[1] propagation code [10, 18] (see also Moskalenko et al., these proceedings) is one of our primary concerns. During a number of years we built an extensive cross section database using all available experimental data from different sources, as well as nuclear codes, and parameterizations [19]. The most important isotopic production cross sections are calculated using our fits to

major production channels [20, 21]. Other cross sections are computed using phenomenological approximations [23] and/or [24] renormalized to the data where they exist. The nuclear reaction network is built using the Nuclear Data Sheets.

The Isotopic Production Cross Sections (ISOPROCS) for CR applications is an ongoing project [25] that uses an extensive experience gained in the previous years. We aim at an open source library which could return the cross section value for any given channel. The library function could return the type of the fit, fitting parameters, type of the cross section – cumulative or direct, and even the data points used for the fitting. Existing routines from the current distribution of GALPROP will be included in the library to calculate the reaction network, decay channels and the half-life, original fits, etc. More details will be provided at the forthcoming conference.

2 Dominant isotopic production channels

The number of different production channels is overwhelming, but not all of them are equally important. In order to determine the dominant channels, we calculated the instantaneous rates of isotopic production for the most abundant seventy three CR isotopes from ^{12}C to ^{64}Ni at energy $E_k = 500$ MeV/nucleon. This energy was selected because of two reasons: (i) above a few hundred MeV/nucleon the energy dependence of the cross sections is usually flat lacking the resonances and other features observed at lower energies; (ii) this kinetic energy in the interstellar space corresponds to the modulated energy $E'_k \sim 200 - 300$ MeV/nucleon in the heliosphere (for $A/Z \approx 2$), exactly where the most accurate measurements of CR isotopic abundances by ACE [1] are available.

The instantaneous rate is proportional to the flux of the progenitor isotope (i.e., the CR species experiencing fragmentation) times the cross section of the production of the secondary isotope (i.e., the daughter species in the
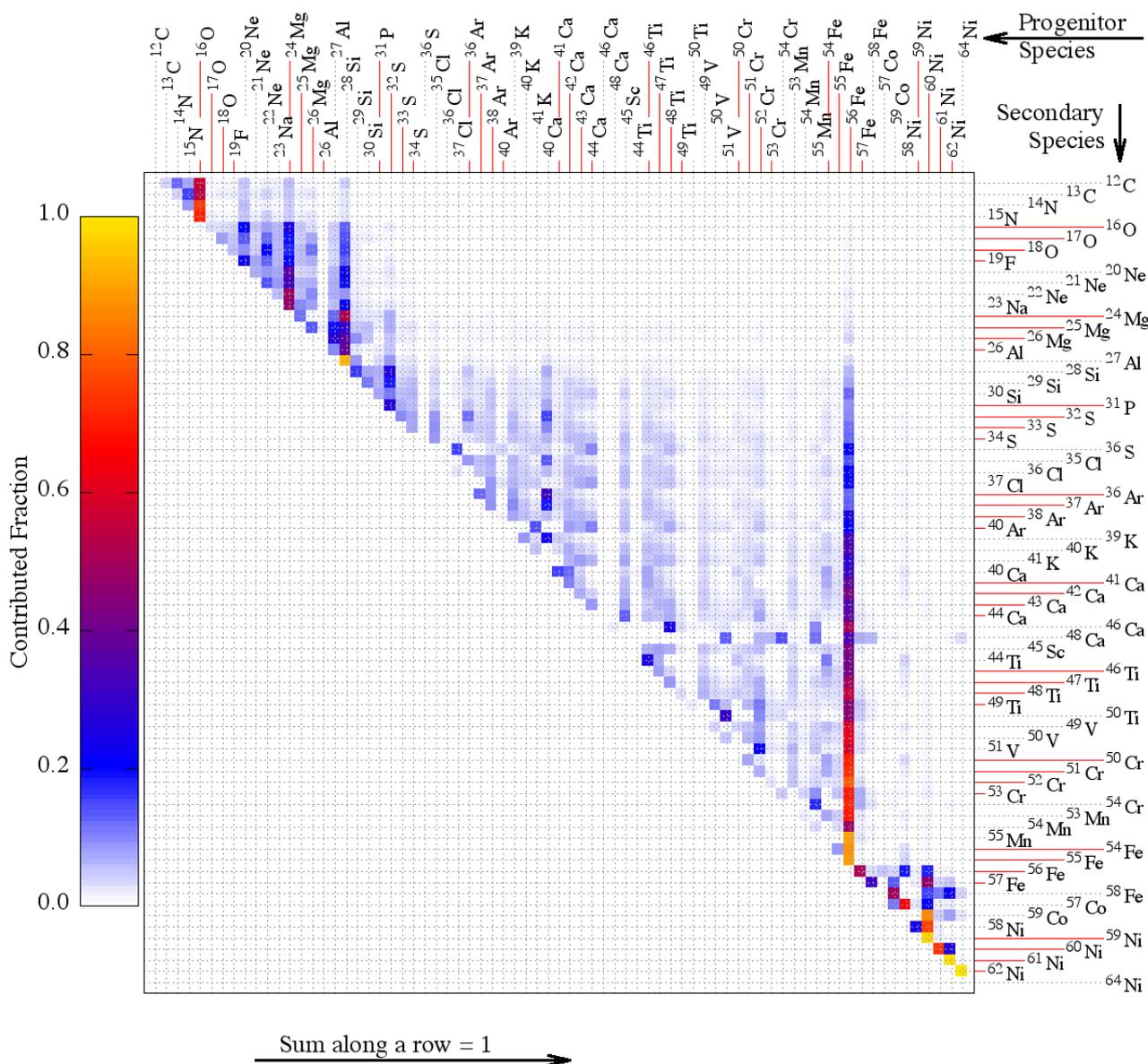
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1. http://galprop.stanford.edu

Figure 1: Relative contribution of CR isotopic species to the production of CR secondaries. For any secondary species, the sum of contributions from all progenitor species (i.e., the sum along the row) is normalized to 1.

nuclear reaction). For the fluxes of the progenitor species, we used the ACE data at energy $E'_k = 200$ MeV/nucleon. Our calculation accounts for radioactive decay of unstable products of fragmentation with lifetime $< 10^4$ years.

The data set for fragmentation cross sections and decay rates used for this calculation is taken from the nuclear data module of the GALPROP code. As in our previous work we use semi-empirical systematics by Webber [23] and Tsao and Silberberg [24], and allow a fitting procedure to choose the best normalization and energy scale so that the new cross section is $\tilde{\sigma}(E) = a\,\sigma(bE)$, where E is the energy per nucleon, $\sigma(E)$ is the original cross section, and a and b are free parameters. The best fit is found by minimizing the weighted sum of squares of residuals, where the weights are inversely proportional to the relative errors of data points. This gives more importance to the larger values of

the cross section data points which usually have smaller relative errors. If the data points cover less than one decade in energy, or if there are too few data points, we set $b = 1$, i.e., the energy scale is preserved.

Figure 1 shows the production rates estimated in this calculation. The displayed rates are normalized so that for any secondary species, the sum of production rates by all progenitor species is equal to 1. This allows to easily spot the channel or channels responsible for the majority of the secondary CR production. The brightest squares in any row of the matrix correspond to these dominant channels.
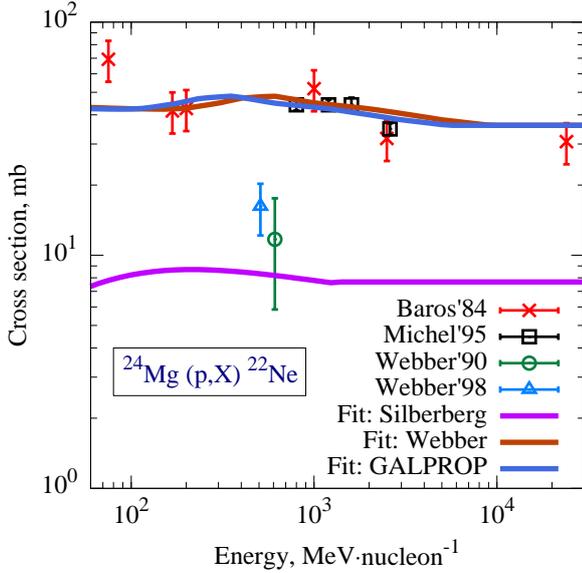
Figure 2: Cross section data and fits for the dominant production channel of secondary ^{22}Ne.
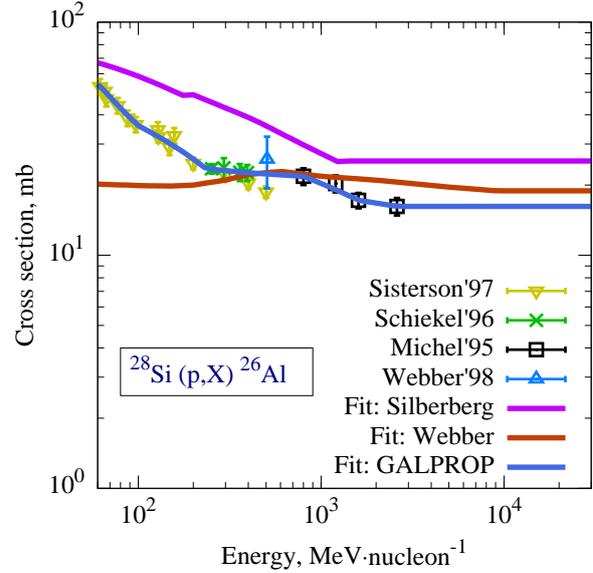

Figure 3: Cross section data and fits for the dominant production channel of secondary ^{26}Al.

3 Available cross section data

The cross section data are collected from all available sources and are carefully selected. We fix possible inconsistencies between data sets from different sources, such as missing or underestimated errors, and duplicated data points. The individual and cumulative cross sections are identified when possible. If a channel has both types of data, we may use cumulative and individual channels separately to do a cross check. Since many production cross sections have resonance structures at low energies, typically below $\sim$100 MeV/nucleon, we eliminate them from future analysis by setting up the low energy bound for each reaction channel.

The nuclear data set used in GALPROP is complete in the sense that it includes all important channels of fragmentation and decay. With the help of the matrix shown in Figure 1, it is possible to identify the most important channels and assess the data and available cross section fits for these channels.

Figures 2, 3 and 4 show three channels as an illustration of the typical situation with cross section data and fits: $p+^{24}$Mg $\to^{22}$Ne, $p+^{28}$Si $\to^{26}$Al, and $p+^{56}$Fe $\to^{54}$Mn. According to Figure 1, these channels are the dominant contributors to the secondary ^{22}Ne, ^{26}Al and ^{54}Mn, respectively.

The three cross section fits shown in Figures 2 – 4 are: the fit of Webber et al. [23], of Silberberg et al. [24] and the fit used in the GALPROP code. The latter, depending on the channel, uses either a re-normalized fit of Webber or Silberberg, or an empirical fit based on the available data points or on a theoretical calculation.

For the reaction $p+^{24}$Mg $\to^{22}$Ne (Figure 2), the available data include the measurements of [26, 27, 28, 29]. The fit of Webber et al. [23] is in a good agreement with the data, while the fit of Silberberg et al. [24] underpredicts the cross section by a factor of $\sim$5. GALPROP in this case uses the fit of Webber, slightly re-normalized to minimize the deviation from data.
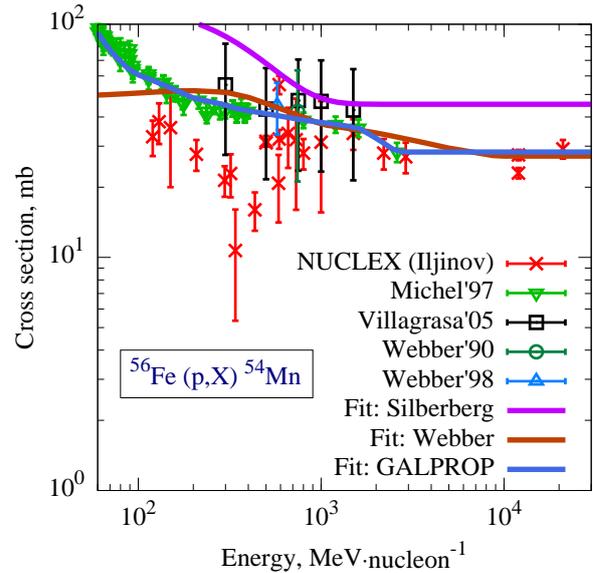

Figure 4: Cross section data and fits for the dominant production channel of secondary ^{54}Mn.

The situation is different for the reaction $p+^{28}$Si $\to^{26}$Al, (Figure 3) where the available data include the measurements of [28, 30, 31, 29]. Cross section fits miss the data, and the asymptotic behavior at high energies is uncertain. GALPROP in this case uses an empirical fit passing through the available data points.

In the case of reaction $p+^{56}$Fe $\to^{54}$Mn (Figure 4), with data from the NUCLEX Compilation [27, 29, 32, 33, 34], there is no agreement in the data. While the fit of Webber et al. is in reasonable agreement with most of the measurements, the fit of Silberberg et al. overpredicts the data at

high energies by a factor of ~ 2. Again, in this case, GAL-PROP uses an empirical fit passing through all data points.

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