Isotopic Production Cross Sections for CR Applications (ISOPROCS Project)

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Abstract: Nuclear production cross sections have for a long time been the Achilles heel of cosmic ray (CR) propagation models. Accurate evaluation of the isotopic production cross sections is important also for studies of Galactic chemical evolution and cosmology. Fitting the B/C ratio in CR is a standard procedure to derive the propagation parameters, while other isotopes can give information about CR (re-)acceleration mechanisms, large-scale Galactic properties, and our local neighborhood. We report on the current state of a new effort to improve on the **ISO**topic **PRO**duction **C**ross **S**ections (ISOPROCS Project). We use all means at our disposal, such as the LANL nuclear database, EXFOR, and ENDF libraries, semi-emphirical systematics, as well as modern nuclear codes, to produce evaluated production cross sections for all isotopes $Z \leq 28$.

Keywords: cosmic rays, propagation, nuclear reactions, isotopic production cross sections

1 Introduction

The accuracy of calculations of the isotopic production cross sections used in astrophysics is far behind the accuracy of recent CR measurements and clearly becomes a factor restraining further progress. The two popular semi-empirical systematics [1, 2] utilized in calculations of propagation of CR are often used beyond their validity energy range, while their accuracy is often being overestimated. The results of such calculations are further used to derive the confidence intervals for CR propagation parameters using sophisticated techniques (e.g., [3, 4]) and used for interpretation of a wide range of CR data and/or for setting limits on exotic signals, such as, e.g., from dark matter annihilation. Any improvements in the calculations of the isotopic cross sections are making such calculations more reliable and thus are very welcome. Meanwhile, there are not so many experimental groups which are able to measure relevant nuclear cross sections and their number is even decreasing with time as many low-energy accelerators are being retired.

The accuracy of the isotopic production cross sections employed in the GALPROP[1] propagation code [5, 6] 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 [7]. The most important isotopic production cross-sections are calculated using our fits to major production channels [8, 9]. Other cross-sections are computed using phenomenological approximations [1] and/or [2] renormalized to the data where they exist. The

nuclear reaction network is built using the Nuclear Data Sheets.

As the accuracy of the current CR experiments increases (e.g., ACE [10, 11], ATIC [12, 13], PAMELA [14, 15, 16], CREAM [17, 18], while AMS-02 [19] was recently successfully launched) there is a strong demand for reliable calculations of the relevant cross sections. This paper summarizes the current state of a new effort to improve on the calculation of the isotopic production cross sections. More details will be provided at the forthcoming conference.

2 The ISOPROCS project

The ISOPROCS project uses an extensive experience that was gained in the previous years. Below we provide a short description of the key points of the new approach.

First we eliminate a number of reaction channels which are of minor importance for calculation of CR propagated abundances (see Figure 1). We are doing this using an approach which resembles a method of the Green's function, but in the isotope space. This is done by running a plain diffusion or reacceleration model where a non-zero primary abundance (=1) is assigned to a single isotope. Propagation of this single isotope and its spallation produces a vector of abundances of secondary isotopes. This procedure is repeated for every stable or long-lived radioactive isotope (≥ 1 yr). A linear combination of such Green's functions weighted with the estimated source abundances pro-
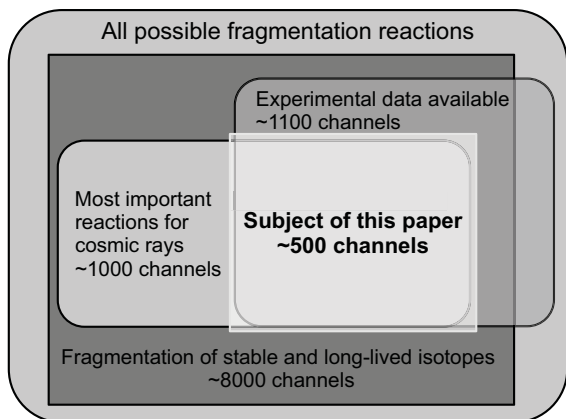
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1. http://galprop.stanford.edu

Figure 1: The subject of this paper vs. total relevant fragmentation reactions space.

Figure 2: Cross section of the reaction $^{28}Si(p, X)^{11}C$. Thick lines show the fits, while thin lines show the original parameterizations. Symbols with error bars show the data points from different experiments. The lower bound of the energy range used in the fit is indicated by the thin vertical line.

duces the measured composition of CR near the Earth. This method can be used to explicitly identify channels that are responsible for a production of the threshold amount (e.g., 99%) of isotopes measured by the ACE [10]. This allows us to narrow down the list of most important channels.

The matrix P composed of vectors with propagated isotope abundances may also be used to calculate the abundances of isotopes in CR sources, as well as their errors. In order to do so naively, the inverse of this matrix, P^{-1}, needs to be multiplied by the vector with measured abundances at Earth. Due to uncertainties in the propagation models and data, this may lead to negative source abundances of some isotopes. For a more physical calculation, least-squares method may be used with P^{-1} to calculate the best non-negative source abundances and their uncertainties (a method alternative to the iterative scheme [20]). This work is currently in progress.

The cross section data for the remaining channels 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 ~100 MeV/nucleon, we eliminate them from future analysis by setting up the low energy bound for each reaction channel.

As in our previous work we use semi-empirical systematics by Webber [1] and Tsao and Silberberg [2], but 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
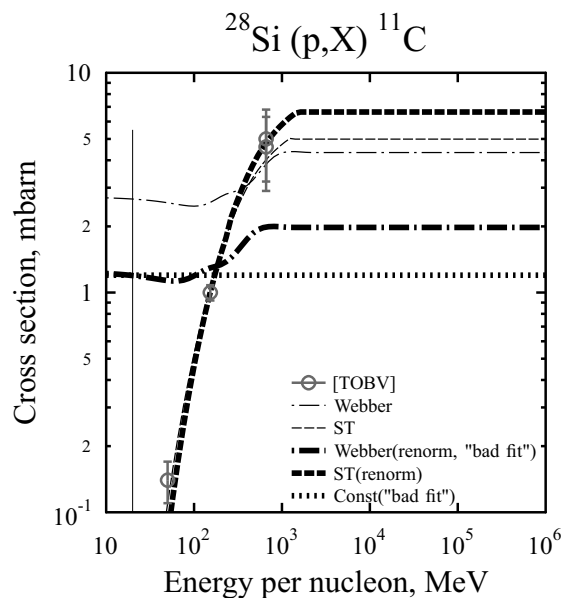
relative errors of data points. This gives more importance to the larger values of the cross section data points which usually have smaller relative errors. If the data points cover less than one decade in energy, or if there are too few data points, we set $b = 1$, i.e., the energy scale is preserved. In addition to the above-mentioned systematics we also find the best fit for a constant function $\tilde{\sigma} = a$.

To discriminate between "good" and "bad" fits we use the χ^2 statistics test. The fit is also marked as "bad" if achieving a good fit requires the value of a or b to be too large or too small compared to 1. If a semi-empirical estimate for a particular channel is not available, the fit is marked as "bad". If a "good" fit cannot be achieved with either of the three parameterizations, a manual interpolation between the data points is used. On the other hand, if a good fit can be achieved with more than one parameterization, all these fits are marked as "good".

The result of this work will be a database with the values of fitted parameters a and b together with the test results ("good" or "bad") for all three cross section parameterizations which will also include special cases. Finally, an open source library will be developed which could return the cross section value for any given channel. The user will also be able to indicate if he/she wants a "good" recommended fit or may require a fit for a specific model (Tsao and Silberberg, Webber's, or constant). Our goal is to provide at least one "good" recommended fit for each reaction channel. The library function may also return additional
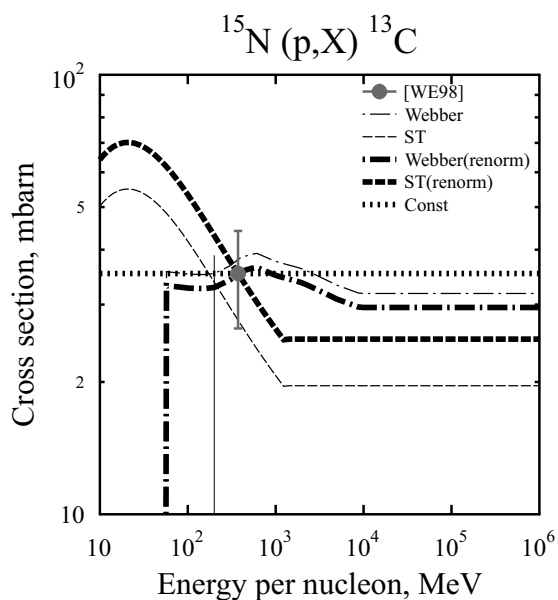
Figure 3: Cross section of the reaction $^{15}N(p, X)^{13}C$.
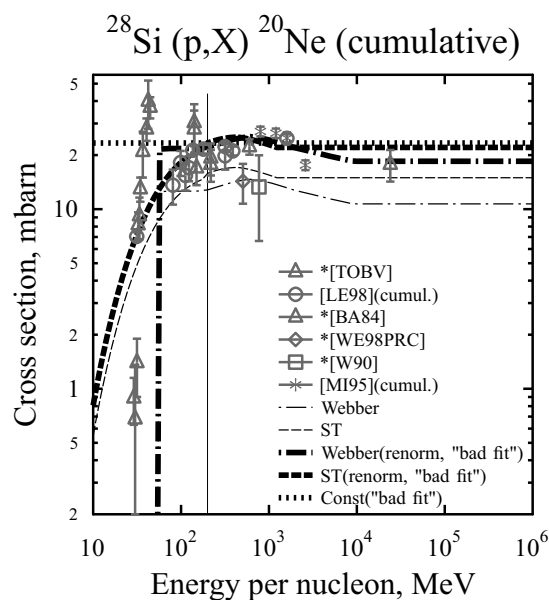
Figure 5: Cross section of the reaction $^{28}Si(p, X)^{11}C$.
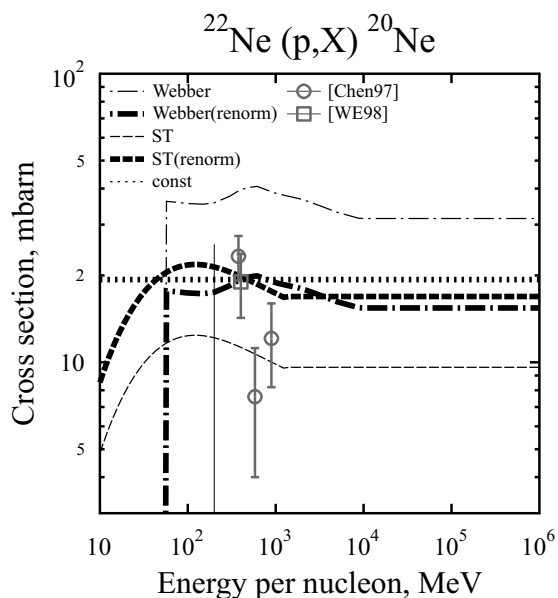
Figure 4: Cross section of the reaction $^{22}Ne(p, X)^{20}Ne$.
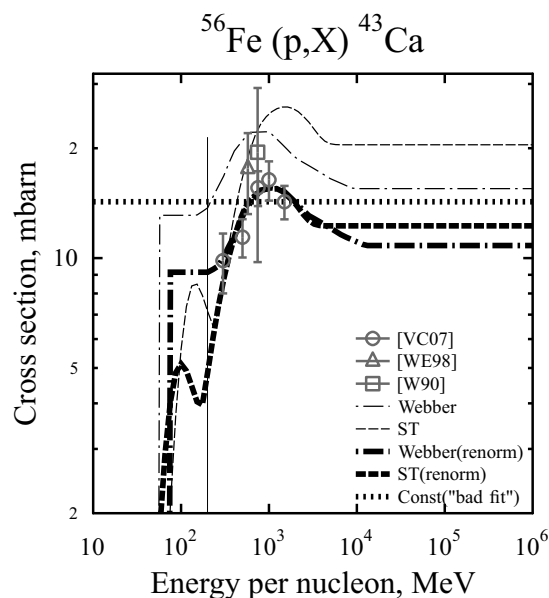
Figure 6: Cross section of the reaction $^{56}Fe(p, X)^{43}Ca$.

information such as 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.

Illustrative examples of the fits are shown in Figures 2-7. The line coding is the same in all figures as explained in Figure 2 caption.

Figure 2 shows an example, $^{28}Si(p, X)^{11}C$, where one fit (in this case, Tsao and Silbeberg's scaling) matches the data much better than others. In this case, only the "good" fit will be returned to the user.

Figure 3 shows an example, $^{15}N(p, X)^{13}C$, where all fits give contradictory results, and there is no sufficient data to reject any fit. All types of fits are declared "good", and the user has to choose which fit type to use.
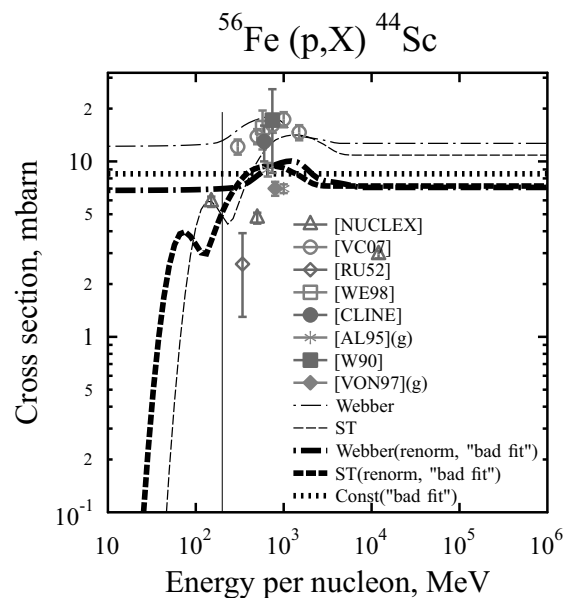
Figure 7: Cross section of the reaction $^{56}Fe(p, X)^{44}Sc$.

Figure 4 shows an example, $^{22}Ne(p, X)^{20}Ne$, where the experimental points are so scattered that none of the scalings produce a reasonable fit. However, all fits are declared "good" in the sense of the χ^2 test due to large uncertainties in the data. A user can choose which parameterization to use in the calculations. Making calculations with different fits is a good way to estimate the uncertainty brought about by the cross section data.

Figure 5 shows an example, $^{28}Si(p, X)^{11}C$ cumulative, where all fits are "bad". Therefore manual adjustment of parameters may be necessary.

Figure 6 shows an example, $^{56}Fe(p, X)^{43}Ca$, where there are more than one "good" fit according to the χ^2 test.

Figure 7 shows an example, $^{56}Fe(p, X)^{44}Sc$, where a scatter in the data points is too large. None of the fits provides a satisfactory agreement with all available data. Manual adjustments to the fit will be necessary in such cases. One of the possible solutions is to eliminate the data from older and less reliable experiments.

3 Conclusion

Our preliminary study shows that a significant progress in the calculation of the isotopic production cross sections is possible. This will lead to more accurate constraints on astrophysical parameters and models derived from CR data. The fitting procedure can be formalized and automated which make it easy to adjust and rerun when new cross section data or parameterizations will become available.

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