

## Nuclear physics aspects of relevance to the sources of UHECRs

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Although the accelerators of ultra-high energy cosmic rays (UHECR) are still not identified, we have new hope to constrain their properties using a multi-messenger approach. Every astrophysical environment, where UHECR nuclei are accelerated and interact with the dense photon fields, will also emit neutrinos. This depends on several modeling aspects of the related photo-nuclear physics in the energy range of the Giant Dipole Resonance and the Quasi Deuteron processes, and also in a regime where the production of pions occurs, which eventually will decay into neutrinos. We have studied in detail the properties of nuclear disintegration rates and chains inside candidate accelerators and during the extragalactic propagation of UHECR. We find that over-simplified models of nuclear interactions, which are often used in UHECR propagation codes and source models, have noticeable impact on the theoretical description of the source and they can introduce a systematic bias to analyses based on statistical arguments. These additional uncertainties can be potentially resolved with accelerator measurements.

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## 1. Introduction

In the last years, the quest to identify the main accelerators of UHECR has been expanded by combining air-shower observations with astrophysical neutrinos and specific gamma-ray measurements. This field has been titled multi-messenger astrophysics, where the contributors try to model particle acceleration and radiation processes in candidate sources, propagate the emitted fluxes of messengers through intergalactic space and derive constraints on source properties using observations of UHECR, neutrinos and gamma rays.

Thanks to the remarkable effort of the Pierre Auger Observatory to relate air-shower observables to the chemical composition of UHECR, there is now evidence for the highest energy cosmic rays to be very likely a mix of elements heavier than helium, reaching masses of the oxygen group [1, 2]. Heavier composition is not excluded, but the experiment runs out of the necessary statistics to discriminate among the different mass groups. The next generations of UHECR detectors is therefore highly anticipated.

In current theoretical or phenomenological approaches to this problem is tackled using source radiation models based on coupled transport equations of the form

$$\frac{\partial N_i}{\partial t} = \frac{\partial}{\partial E} (-b(E)N_i(E)) - \frac{N_i(E)}{t_{\text{esc}}} + \tilde{Q}_{ji}(E). \quad (1.1)$$

$N$  is the particle density in a certain frame, the differential in  $E$  represents continuous energy losses (synchrotron for example). The the “escape” rate  $t_{\text{esc}}^{-1}$  defines the total particle loss rate, either due to escape of particles from a radiation zone or due to absorption by inelastic interactions. The re-injection terms  $\tilde{Q}_{ji}$  are couplings between the different individual equations for each species. Species refers to individual particle populations, i.e. photons, leptons, hadrons and all kinds of nuclear isotopes. The equations are discretized in energy and the evolution of each energy follows its own equation. In case of nuclear systems, one has to solve number of species times the number of energy bins coupled differential equations, which can easily exceed ten thousand equations.

Solutions to source models containing nuclei are available in the literature [3, 4]. However, there is no such example that can compete in terms of the level of detail with reference codes for UHECR propagation problems, such as CRPropa 2 and 3 [5, 6]. The latter can handle hundreds of different nuclear isotopes and thousands of reaction channels.

In our recent publications [7], we have raised the questions about how to model these nuclear reactions exactly, which models are available and how do they perform in comparisons with data from nuclear physics experiments. This contribution closely follows [7] and includes some aspects of newer results from [8].

## 2. Modeling of nuclear interactions

For a Gamma Ray Burst (GRB) target field, roughly a broken power law with a break around 1 keV and indices -1 and -2, the relevant energy range in nuclear rest frame  $\varepsilon_r$  spans from the interaction threshold around 8 MeV up to several GeV. The different regimes are called Giant Dipole Resonance (GDR) ( $\varepsilon_r \lesssim 30$  MeV), Quasi Deuteron (QD) ( $\varepsilon_r \lesssim 150$  MeV) and Isobar ( $\varepsilon_r \lesssim 1$  GeV). In [7], we focused on the first two regimes that govern the disintegration of nuclei and define

the survival (maximal energy) and escape, which are both the crucial requirement for sources of UHECR.

The simplest model in astrophysics is the box model, where the GDR peak is approximated by a box function (see the analytical example in [9]). The simplicity of the model permits (semi-) analytical solutions of transport equations using a set of additional assumptions. A very successful model is the Puget-Stecker-Bredekamp (PSB) model [10], which uses a one-dimensional path along the representative isotopes of each mass lighter than iron. The model survives for a remarkable amount of time and it is still a good first order approximation. One of the weak spots in the model is the absence of the emission of light fragments, for example alpha particles. Current state-of-the-art codes, such as CRPropa or our work, use TALYS [11] 1.8, which contain numerous nuclear models, in particular a Hauser-Feshbach part. The model in CRPropa and the SimProp code [12] includes a few additional settings and parameter files [13]. TALYS works for nuclei heavier than carbon. For lighter elements the interaction models have to be complemented by additional data-driven parameterizations, since the behavior of very light nuclei is extremely challenging for theoretical models. A further class of reaction models are the Intranuclear Cascade Pre-equilibrium Evaporation codes, which can generate realistic event shapes for particle transport Monte Carlos. Prominent examples are FLUKA [14, 15] and MCNP [16].

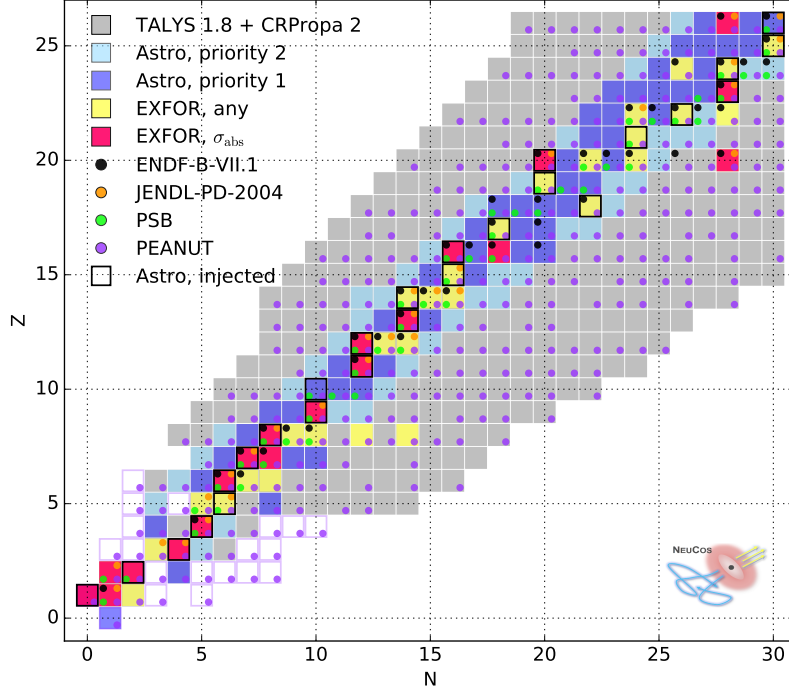
### 3. Situation on experimental data

To compare the various models to data and extract an idea of related uncertainties, we extracted relevant data sets from the most complete EXFOR database [17]. We found 14 photo-nuclear absorption cross sections, and 47 other measurements that can be used to obtain model evaluated cross sections. Since we pursue a self-consistent modeling, we do not take into account evaluated cross sections which employ non-public codes (of Hauser-Feshbach type for example). PEANUT [18], an interaction model from FLUKA, has an internal database. MCNP uses ENDF-B-VII.1, which is based on evaluations using the GNASH code. TALYS contains for the majority of measured cross section parameters Lorentz-type fits to the giant dipole resonance region. Isotopes without measurements seem to be predicted in a rather simplistic way, in particular this is apparent when making comparisons among isobars (isotopes of same mass), where absorption cross sections are equal. EXFOR does not contain any entries for two isobars and we believe that measurements of unstable isotopes could help in deriving a more predictive cross section parameterizations for the models.

In general, we find that the agreement between nuclear data files from PEANUT, ENDF or JENDL follow precisely the data where available. Without data, the models fall back to simple parameterizations. It was therefore impossible to identify one model, which can reliably predict nuclear phenomenology in the mass range relevant for cosmic ray astrophysics. Of highest relevance for radiation and disintegration modeling are absorption cross sections, inclusive yields of nucleons and light fragments, and yields of residual nuclei.

### 4. Effect on interaction rates

We attempt to quantify the differences between models by computing interaction rates for



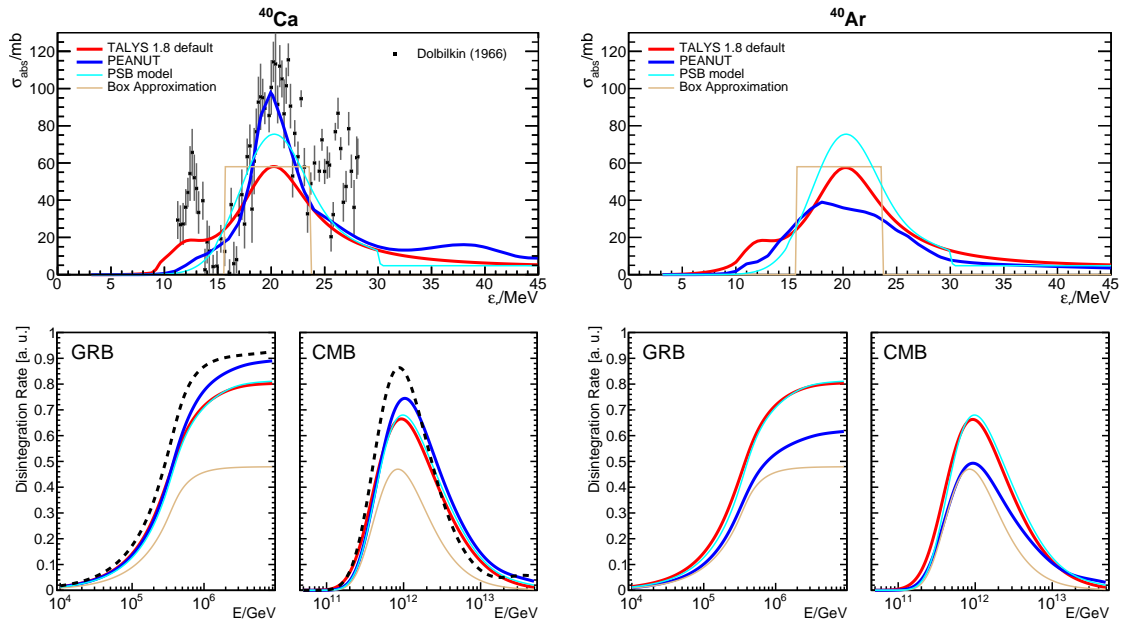
**Figure 1:** Experimental situation versus available model predictions of total absorption cross section from [7]. The dark and light blue elements are those which occur in nuclear cascades inside a GRB. Dots represent availability of model predictions. Grey boxes cover the range of isotopes for which TALYS technically works. Black frames are candidates for injection isotopes. Violet frames are very unstable isotopes that immediately decay.

two typical astrophysical setups in Figure 2. UHECR encounter interactions with the cosmic microwave background (CMB) (a thermal target photon field) during their propagation through the extragalactic space. In a GRB the target field is a non-thermal broken power-law spectrum.

For the comparison in Figure 2, we have chosen the isotopes  $^{40}\text{Ca}$  and  $^{40}\text{Ar}$ , since are isobars (have equal mass) but their level structure is very different. Calcium-40 is a double magic nucleus while Argon is not, therefore we expect to see differences in their cross sections. We use this example (and other similar examples) to get a feeling for the quality of parameterizations for isotopes without photo-nuclear measurements. What we find is that TALYS outputs equal predictions for both elements, PEANUT (FLUKA) contains a database entry for Calcium and falls back to some parameterization for Argon. The box and the PSB model by design predict equal cross sections.

We compute the effect on the interaction rates (coupling coefficients in Eq. 1.1) in the lower panels of Figure 2. The rates computed for  $^{40}\text{Ca}$  with more realistic models vary within 20% and increase up to a factor two for the box model. A naive interpolation of data (dashed line) adds further differences of the order of 10%. For Argon only model predictions are available with a somewhat higher variation between the models. In case of FLUKA (and ENDF) the absorption cross section has been evaluated from one inclusive yield measurement.

Based on this and other similar observations, we conclude that differences among models are relatively small where data is available and reach up to a factor 2 in the contrary case. There are



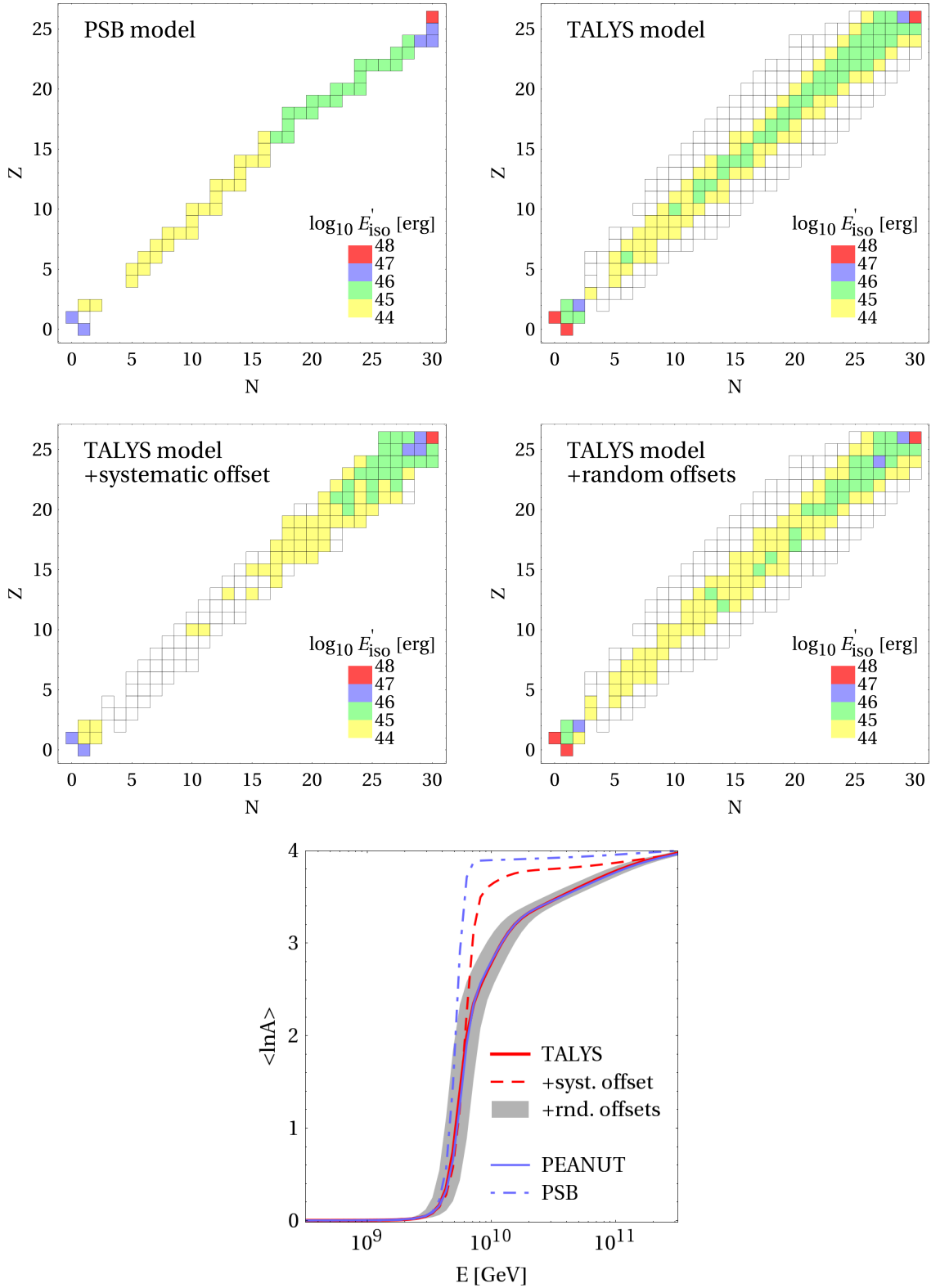
**Figure 2:** Comparison of cross sections (upper row) and disintegration rates (lower row) for two different isobars (columns) with  $A = 40$ .  $\epsilon_r$  is the energy in the nucleus rest frame. The disintegration rates are computed for a GRB spectrum, a broken power law with spectral indices  $\alpha \sim 1$  and  $\alpha \sim 2$  and a break at 1 keV (in shock rest frame), whereas the CMB rate is obtained using a thermal target photon spectrum with  $T = 2.73$  K. Dashed lines are computed from a naïve interpolation of data.

only very few measurements for unstable elements, so model uncertainties increase outside of the stability valley.

## 5. Effect on UHECR source calculations

From the isotope charts in Figure 3 one can qualitatively understand an impact of different models. By emitting protons, the PSB model follows a one dimensional path, where the second element is  $^{55}\text{Mn}$ , it will therefore inject protons in the equation system, which are magnetically confined and behave differently as neutrons. Recall that neutrons can escape an astrophysical sources (and become cosmic rays). More complete models, like TALYS emit however neutrons first and elements more neutron rich elements are populated. Another key observations are the further extension of the nuclear cascade to lower masses and the higher population of helium. We estimated the impact of measurement errors (or absence of measurements) in the two middle panels by either suppressing less known cross sections systematically, or by varying those randomly within error scales estimated from EXFOR.

As demonstrated in the bottom panel of Figure 3 the impact on the nuclear composition of cosmic rays that escape from the source is sizable. The transition from the injected element to a nucleonic composition is softer, while the differences between more complete models tend to average out (compare TALYS and PEANUT). Simplified models produce too simplified results (even in light of the other astrophysical uncertainties) and a hard heavy-to-light transition. The



**Figure 3:** Disintegration chains from [7]. Pure  $^{56}\text{Fe}$  is injected in a GRB field. Color encodes the energy density of each isotope. The lower panel displays the mean logarithm of the nuclear masses that escape from the source.

implications for combined source-propagation models are studied in more detailed in [8]. A fit to UHECR data by Auger indicated that these differences have a sizable impact on the interpretation of the source composition [19].

## 6. Conclusion

We have studied the dependence of disintegration rates as predicted by current photo-nuclear interaction models. Typical astrophysical parameterizations, such as the box or the PSB model are oversimplified and introduce an artificial bias in the calculations. While astrophysical uncertainties still have the largest impact on multi-messenger calculations and source models, the main target field for cosmic ray propagation, the CMB, is quite well known. By improving the predictive power of nuclear models one can remove one contributing uncertainty from astrophysics that can be studied at accelerators. We claim that uncertainties from nuclear models are a significant contribution and can play a crucial role in the interpretation of UHECR observations, since they can introduce systematic shifts, which can confuse analyses based on statistical arguments. We suggest that it is important to make additional measurements for light and intermediate mass range nuclei resulting in a higher predictive power of the models.

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