From sources to detection...

**SOURCE**
- Acceleration in astrophysical sources
- **Interactions with photons and protons**

**PROPAGATION**
- adiabatic losses
- **Interactions with extragalactic background photons**
- magnetic fields
From sources to detection...

**SOURCE**
- Acceleration in astrophysical sources
- Interactions with photons and protons

**PHOTO-DISINTEGRATION**

**PROPAGATION**
- adiabatic losses
- Interactions with extragalactic background photons
- magnetic fields

**EARTH**
Indication of proton composition → TA experiment

Challenged by **multimessenger approach** (neutrino and photon fluxes) → see talk by J. Heinze

Indication of a trend towards heavy composition at highest energies from Auger measurements

What are the conditions for escape of nuclei from the various source classes?

How does the presence of nuclei affect the expected flux of neutrinos?

Work in progress
Interaction framework

Boltzmann Equations for each particle species (and energy bin)

\[
\frac{\partial N_i}{\partial t} = \frac{\partial}{\partial E} \left( -b(E)N_i(E) \right) - \frac{N_i(E)}{t_{\text{esc}}} + \tilde{Q}_{ji}(E)
\]

Evolution of density for particle species i

Energy loss: synchrotron adiabatic ...

Escape: interactions decays ...

\[
\tilde{Q}_{ji}(E) = Q_i(E) + Q_{ji}(E)
\]

Injection from: acceleration zone interactions or decays

Beam of p, A, ...

Radiation zone: Interactions

\[ Q_{v,\text{out}} \]

\[ Q_{A',\text{out}} \]

\[ Q_{\gamma,\text{out}} \]
How does nuclear physics enter?

- How often does a nucleus/particle in a source interact?

\[ \tilde{Q}_{ji}(E) = Q_i(E) + Q_{ji}(E) \]

\[ \Gamma_j(E_j) = \int_{-1}^{+1} d\cos\theta_{j\gamma} \int d\varepsilon \left( \frac{d\cos\theta_{j\gamma}}{2} (1 - \cos\theta_{j\gamma}) \cdot n_{\gamma}(\varepsilon, \cos\theta_{j\gamma}) \sigma_{j}^{\text{abs}}(\varepsilon_r) \right) \]

- Depends on:
  - target photon field
  - nucleus-photon cross section

Photon energy in nucleus rest frame

\[ \varepsilon_r = \frac{E_j \varepsilon}{m_j} (1 - \cos\theta_{j\gamma}) \]

- The uncertainties in cross sections and extragalactic photon fields are partially studied for the case of propagation of UHECRs
  → see for example Batista, DB, di Matteo, van Vliet and Walz, JCAP 1510 (2015) 10, 063

- In the current work, we want to:
  - model cosmic ray interactions in photon fields
  - check situation of available cross section measurements and models
  - apply to candidate sources for cosmic ray, in order to study the necessary conditions for UHECR escape and for high radiation densities
What do we need to model interactions in photon fields?

1) Is a nucleus able to escape the source without disintegrating?
   → to answer this, I need to know the absorption cross section and to compare the interaction length of the process to the size of the source

2) The radiation field is so dense that photodisintegration cannot be avoided… a nuclear cascade inside the source starts
   → competitive processes have to be taken into account, so residual cross sections are needed for the development of the cascade

Khan et al, Astropart.Phys. 23 (2005) 191-201
What do we need to model interactions in photon fields?

1) Is a nucleus able to escape the source without disintegrating?

→ to answer this, I need to know the absorption cross section and to compare the interaction length of the process to the size of the source.

Unstable elements are important! Their lifetime is dilated due to relativistic boost → they can re-interact and create other secondaries.

2) The radiation field is so dense that photodisintegration cannot be avoided… a nuclear cascade inside the source starts.

→ competitive processes have to be taken into account, so residual cross sections are needed for the development of the cascade.
Situation on experimental data and theoretical models

- EXFOR contains 14 absorption cross sections \( \leq \text{Fe} \)
- 47 measurements where at least one inclusive cross section available
- Located mostly on main diagonal (stable elements)
- All other isotopes need model prediction → not always well reproducing data
Impact of nuclear cross sections on astrophysical quantities

- Ca-40: double magic nucleus
- TALYS predictions not dependent on the element
- PEANUT predictions are different in the same isobar; if data available, at least the central GDR peak is reproduced
- Box approximation, used for example in Murase and Beacom, Phys Rev. D81 2010, underestimates data and models for A=40

DB, A. Fedynitch, W. Winter, arxiv:1607.07989
Impact of nuclear cross sections on astrophysical quantities

\[ n_\gamma(\epsilon) = \frac{1}{\pi^2 (hc)^3 \exp(\epsilon / KT)} - 1 \]

GRB, source

Baerwald, Bustamante and Winter, Astrophys. J. 768 (2013) 186

\[ N_\gamma'(\epsilon') \propto \begin{cases} 
\left( \frac{\epsilon'}{\epsilon'_{\gamma,\text{break}}} \right)^{-\alpha_\gamma} & \epsilon'_{\gamma,\text{min}} \leq \epsilon' < \epsilon'_{\gamma,\text{break}} \\
\left( \frac{\epsilon'}{\epsilon'_{\gamma,\text{break}}} \right)^{-\beta_\gamma} & \epsilon'_{\gamma,\text{break}} \leq \epsilon' < \epsilon'_{\gamma,\text{max}} \\
0 & \text{else}
\end{cases} \]
Impact of nuclear cross sections on astrophysical quantities

DB, A. Fedynitch, W. Winter, arxiv:1607.07989
Impact of nuclear cross sections on astrophysical quantities

DB, A. Fedynitch, W. Winter, arxiv:1607.07989
Effects on the nuclear cascade

- One nuclide for each A
- Only small fragments can be ejected in photodisintegration
- The cascade is not completed, smaller masses are not populated

Population of isotopes in terms of total energy per isotope and collision in the shock rest frame

DB, A. Fedynitch, W. Winter, arxiv:1607.07989
Effects on the nuclear cascade

- Much more channels wrt PSB
- Small fragments ejected: p, n, d, t, He-3, He-4
- Chart almost fully populated (however, this also depends on the target photon density)
- PEANUT gives similar results

Population of isotopes in terms of total energy per isotope and collision in the shock rest frame

DB, A. Fedynitch, W. Winter, arxiv:1607.07989
Effects on the nuclear cascade

Population of isotopes in terms of total energy per isotope and collision in the shock rest frame

- Cross sections reduced by:
  - 1 if the absorption cross section is measured
  - 0.5 if any other cross section is measured
  - 0 if no data available

- Relying on data, the cascade cannot be populated

DB, A. Fedynitch, W. Winter, arxiv:1607.07989
UHECR composition at the source

- No propagation effects considered
- Simplified model PSB leads to a sharper increase of composition wrt more sophisticated models
- If only measured cross sections are included in the models, similar results to PSB

DB, A. Fedynitch, W. Winter, arxiv:1607.07989
Summary and conclusions

The study of interactions of nuclei in sources and extragalactic photon fields is critical for our understanding of cosmic-ray astrophysics.

In particular, we are interested in understanding the conditions for escape of nuclei from the sources and the connections with neutrinos → work in progress.

Measurements of total absorption cross sections → needed for interaction rate calculations → measurements are sparse.

Especially, clarify isobar situation (unstable elements).

Development of the cascade depends on branching ratios/multiplicities for different channels → data on residual cross sections will ensure that we don’t have systematic offsets in models.

We propose systematic measurements to improve the predictability of unmeasured cross sections → measuring the total absorption cross section for two or more different isobars.
Effects on the nuclear cascade

Population of isotopes in terms of total energy per isotope and collision in the shock rest frame

Cross sections reduced by:
- 1 if the absorption cross section is measured
- factor between 0.5 and 1.5 if any other cross section is measured
- factor between 0 and 2 if no data available

DB, A. Fedynitch, W. Winter, arxiv:1607.07989
Pre-selection of isotopes

For an efficient computation, we need to pre-select the isotopes which are dominantly populated. Our isotope selection scheme is a fully automated recursive algorithm starting (in this case) with $^{56}$Fe, following all disintegration and beta decay paths recursively. We also allow for again. Since one isotope has typically very many (disintegration) branchings into daughters, some of these being very small, we impose a cutoff on the secondary multiplicity (number of secondaries produced on average) at a value of 0.01. As a further complication, the multi-

TALYS disintegration model, the software uses 481 isotopes, about 41000 inclusive disintegration channels and about 3000 photo-meson channels as primary input, selects 233 isotopes, and attaches 4943 disintegration, 10 beta decay (relevant on the GRB timescale) and 1344 photo-meson channels to them. With this level of com-
The choice of isotopes in Fig. 1 labeled “Astro, priority 1” and “Astro, priority 2” has been obtained with a similar method by repeating the above recursive procedure for a number of possible injection elements: we inject for each atomic number the most abundant stable isotope. The multiplicity threshold has been chosen to be 0.2 for priority 1 and 0.05 for priority 2. As these numbers are
Interaction framework and terminology

We are interested in the total photoabsorption cross section and in the inclusive cross sections.

\[ \sigma_j \times \frac{d\sigma_j}{dE_i} = d\sigma_j^{incl} / dE_i \]

Total cross section

Distribution of secondaries of type i per final state energy interval

Average number of secondaries produced per interaction

Comparison of models and measurements in the following:

\[ \sigma_j M_{j-i} \equiv \sigma_j^{incl} \]

Inclusive cross section

\[ \sigma_j^{incl} = \sum_k N_{j-i}^{(k,i)} \sigma_j^{excl,(k,i)} \]

Number of secondaries of type i produced per interaction

Exclusive cross section

\[ \sigma_j^{excl,k} = Br_j(k,i) \sigma_j \]

All exclusive cross sections with the same number of neutron and proton units in the outgoing channel sum up to the same residual nucleus production cross section for the final nucleus → residual cross section, as measured and used in the following.
Interaction framework and terminology

- Interactions of cosmic rays in the source environment or in the propagation can be rigorously followed with a system of differential equations describing the evolution of the differential particle density wrt time, taking into account all interactions that can modify their number and energy.

\[
\frac{\partial N_i}{\partial t} = \frac{\partial}{\partial E} (-b(E)N_i(E)) - \frac{N_i(E)}{t_{\text{esc}}} + \tilde{Q}_{ji}(E)
\]

\[
\tilde{Q}_{ji}(E) = Q_i(E) + Q_{ji}(E)
\]

- Production rate of particles of species \(i\) and energy \(E_i\) from the interactions or decay of the parent \(j\)

\[
Q_{ji}(E_i) = \int dE_j N_j(E_j) \Gamma_j(E_j) \frac{dn_{j \rightarrow i}}{dE_i}(E_j, E_i)
\]

- After considering isotropy of the photon distribution, and calculating the quantities in the shock rest frame:

\[
\Gamma_j(E_j) = \int d\varepsilon n_{\gamma}(\varepsilon) f_j(\varepsilon)
\]

\[
y \equiv \frac{(E_j\varepsilon)}{m_A}
\]

- Escape rate of the primary particle

\[
f_j(y) \equiv \frac{1}{2y^2} \int_0^{2y} d\varepsilon \varepsilon \sigma_j(\varepsilon)
\]

- All integrations need to be performed only once if the target photon density is constant over time → the interaction rate is only a function of energy
Data set used in the current work

The nuclear gamma-ray absorption cross section of $^{40}\text{Ca}$ has been measured with the 260 MeV electron synchrotron of the Lebedev Physical Institute, using the total absorption method with a 9-channel pair magnetic spectrometer as a detector. The resolution of the spectrometer for $\gamma$-quanta of energy $E_{\gamma} = 20$ MeV was approximately 220 keV. A block of natural calcium (96.97% $^{40}\text{Ca}$), 70.84 g/cm$^2$ thick, was used as absorber.

Spectra of photoprotons from the nucleus Na-23 are measured in the bremsstrahlung beam. Cross sections of the reaction Na-23($\gamma$,p)Ne-22 with production of the final nucleus in various states are obtained from the photoproton spectra.

Investigation of the Reaction $^{23}\text{Na}(\gamma, p)^{22}\text{Ne}$ with Production of the Final Nucleus in Various States

Total Photonuclear Cross Sections for Low Atomic Number Elements

Total photonuclear cross sections have been measured in an attenuation experiment using a scintillation pair spectrometer and an x-ray spectrum with a fixed maximum energy of 90 MeV. The cross sections as a function of x-ray photon energy for beryllium, carbon, oxygen, sodium, magnesium, aluminum, silicon, sulfur, calcium, nickel, cobalt, copper, and silver show detailed structure in many cases at x-ray energies of 15-30 MeV and display a consistent trend in shapes and magnitudes. The integrated cross sections up to 35 MeV relative to the classical dipole sum rule show a monotonic increase with atomic weight. Other analyses of the total photonuclear cross sections in terms of mean $D$ energies and of the ratios of the total cross sections to photoneutron cross sections are also presented.
Situation on experimental data and theoretical models

- We use the EXFOR database
  [https://www-nds.iaea.org/exfor/exfor.htm](https://www-nds.iaea.org/exfor/exfor.htm)

- No measurements of **absorption cross section** for the same isobar

  Our current model:

- TALYS 1.8 is used with the strength function \texttt{strenght 1}, based on a Kopecky-Uhl generalized Lorentzian model, as in Khan et al. paper

- TALYS is not recommended for A<12. For these nuclei we use a collection from CRPropa2 (Khampert et al, Astropart.Phys. 42 (2013) 41-51), based partially on data

---

**What is TALYS?**

TALYS is software for the simulation of nuclear reactions. Many state-of-the-art nuclear models are included to cover all main reaction mechanisms encountered in light particle-induced nuclear reactions. TALYS provides a complete description of all reaction channels and observables, and is user-friendly.
Situation on experimental data and theoretical models

- Model predictions and parametrizations
  → use of interpolated or fitted absorption cross sections where available, as done in PEANUT, ENDF-B-VII.1, JENDL/PD-2004
  → use of parametrizations if cross sections are totally unknown

Other models:
- PSB model is obtained from Puget, Stecker and Bredekamp, Astrophys. J. 205, 638 (1976). Use of one nucleus for each mass; cross section for one and two nucleon emissions is approximated by a Gaussian in the low energy range and by a constant above 30 MeV. Threshold for reactions taken from Stecker and Salamon, Astrophys. J. 512 (1999). The list of nuclei has been slightly modified to be used in the current code for photodisintegration

- Box approximation is used in Murase and Beacom, Phys Rev. D81 2010

\[ \sigma_{GDR} \approx 1.45 \times 10^{-27} \text{A cm}^2 \]
Situation on experimental data and theoretical models

ENDF-B-VII.1 \cite{18} is an evaluated nuclear data library based on calculations using the GNASH code system. Its photo-nuclear part contains absorption cross-sections a sometimes inclusive emission spectra of neutrons and protons, but no residual cross-sections. Comparisons with data reveal a very good agreement with the measurements.

JENDL/PD-2004 \cite{19} is another evaluated library, based on Lorentz fits at GDR energies and quasi-deuteron emission above. Elements without $\sigma_{\text{abs}}$ measurements are evaluated through branching ratios from pre-equilibrium and evaporation models, together with photo-neutron data. The description of $\sigma_{\text{abs}}$ is good for all measured elements.
GRB parameters used in the current work

- GRB observations exhibit strong time variability over a scale $t_v$ (in the observer frame).

- The fireball has a time evolution: first zone, the shell gets accelerated, powered by the energy transfer from the thermal photons to the baryons in the shell. The Lorentz factor of the shell grows with the radius until a maximum value is reached. The second zone starts: the shell is accelerated to its maximal velocity, so it coasts with constant Lorentz factor.

- Development of the cascade of nuclei in the GRB field depends on the photon density.

\[
L_{\gamma,iso} = 10^{52} \text{ erg/s}, \quad \Gamma = 300, \quad t_v = 0.01 \text{ s}, \quad z = 2
\]

\[
E_{Fe,\text{max}} \simeq 10^{11} \text{ GeV}
\]
Injection parameters

we only inject $^{56}$Fe into the system with a power law $E^{-2} \exp \left(-\left(E/E_{\text{Fe, max}}\right)^2\right)$, where $E_{\text{Fe, max}}$ is determined by balancing the dominant energy loss process with the acceleration rate $t_{\text{acc}}^{-1} = \eta c/R_L$. Here $R_L$ is the Larmor radius and a relatively high $\eta \simeq 10$ has been chosen to reproduce the composition transition observed by Auger [3]. The target photons are assumed to follow a broken power law with a break at 1 keV in the shock rest frame between the power law index $-1$ (low energy) and $-2$ (high energy). Note that we choose the minimal photon energy low enough such that photodisintegration will always dominate at the highest energies. The baryonic loading is assumed to be ten, which means that there is ten times more energy injected into iron compared to electrons, and energy equipartition between magnetic field, electron and photon energy is assumed.

For the nuclear energy losses, we include synchrotron losses, adiabatic losses, pair production losses, and photonicuclear losses, where we distinguish between photodisintegration (focus of this work, dominated by the GDR) and photo-meson production (dominated by the $\Delta$-resonance and other processes) by $\epsilon_r$. The photodisintegration is implemented in different models, as discussed in the main text of this work. We include photo-meson production based on SOPHIA [34] using an improved and extended version of Ref. [35] with a superposition interaction model assuming that the cross section scales $\propto A$. 

DB, A. Fedynitch, W. Winter, arxiv:1607.07989
What we measure: UHECR energy spectrum

Features of the spectrum (ankle, suppression) are associated with properties of:

- Sources (distribution of sources, source evolution)
- Transport (modeling of Extragalactic Background Light EBL)
- Composition (protons, nuclei)

of UHECRs
- If UHECR are predominantly nuclei, more uncertainties have to be considered wrt the case of protons: photon fields (sources and propagation), details of interactions (cross section for photodisintegration).
Effect of different EBL models on propagated spectra

differences are more visible in:
- hard injection scenarios than in soft ones, because they are mainly due to different numbers of low energy secondaries (in soft injection scenarios low energy secondaries are subdominant wrt residual primaries)
- low-energy intermediate mass secondaries of iron, because they are produced via repeated photodis by EBL

brighter EBL \rightarrow softer spectrum at Earth and lighter composition

Effect of different choices of cross section for photodis

Stecker and Salamon, Astrop.J. 512, (1999), 521-526

We also note that although the thresholds are lowest for \( \alpha \) emission (because of the \( \alpha \)’s large binding energy), the integrated cross section for \( \alpha \) emission from \( ^{56}\text{Fe} \), for example, is over 2 orders of magnitude lower than the \( \Sigma_d \) value for that nuclide (Skopic, Asai, & Murphy 1980; see also Fuller & Gerstenberg 1983). We therefore neglect the \( \alpha \) emission channels entirely in our calculation.

\[ \operatorname{E}^3 \] [arb. units]

\( \log_{10}(E/eV) \)

\( Z=1 \)
\( Z=2 \)
\( Z=3-7 \)

PSB \( \sigma_{\text{disi}} \)
TALYS \( \sigma_{\text{disi}} \)

\( \langle \ln A \rangle \)

\( 0 \)
\( 0.5 \)
\( 1 \)
\( 1.5 \)
\( 2 \)
\( 2.5 \)

pure H
pure He
pure N
PSB \( \sigma_{\text{disi}} \)
TALYS \( \sigma_{\text{disi}} \)

\( \rightarrow \) alpha particle ejection results in secondaries with 4 times the energy of the nucleon secondaries
\( \rightarrow \) including alpha-ejection: softer spectra at Earth and lighter composition

Fitting models to Auger data

- Auger spectrum and composition fitted above $10^{18.7}$ eV (ankle)

- Sources assumed to be identical, homogeneously distributed, injecting 1-Hydrogen, 4-Helium, 14-Nitrogen and 56-Iron with

$$
\frac{dN_{\text{inj},i}}{dE} = \begin{cases} 
J_0 p_i \left( \frac{E}{1 \text{ EeV}} \right)^{-\gamma}, & E/Z_i < R_{\text{cut}} \\
J_0 p_i \left( \frac{E}{1 \text{ EeV}} \right)^{-\gamma} \exp \left( 1 - \frac{E}{Z_i R_{\text{cut}}} \right), & E/Z_i > R_{\text{cut}}
\end{cases}
$$

- Various models for propagation (SimProp and CRPropa propagation codes with different choices for cross sections and EBL models) and air interactions were used

- See A. di Matteo for the Pierre Auger Collaboration, PoS(ICRC2015)249 for details
Fit results

MODEL

- SimProp propagation
- PSB cross sections
- Gilmore EBL
- EPOS-LHC air interactions

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- $A=1$
- $A=[2,4]$
- $A=[5,26]$
- $A=[27,56]$
Fit results

**MODEL**

- *SimProp* propagation
- TALYS cross sections
- Gilmore EBL
- EPOS-LHC air interactions

| parameters |  
|---|---|
| Rcut      | 18.60 |
| gamma     | 0.69  |
| H         | 0.0   |
| He        | 0.0   |
| N         | 98.95 |
| Fe        | 1.05  |
| Dmin      | 176.5/119 |
Fit results

MODEL

- SimProp propagation
- PSB cross sections
- Dominguez EBL
- EPOS-LHC air interactions

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Fit results

**MODEL**

- SimProp propagation
- PSB cross sections
- Dominguez EBL
- EPOS-LHC air interactions

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The propagation is sensitive to details of photodis cross sections and EBL models.