Chapter 8: Connection and input to astro (particle) physics

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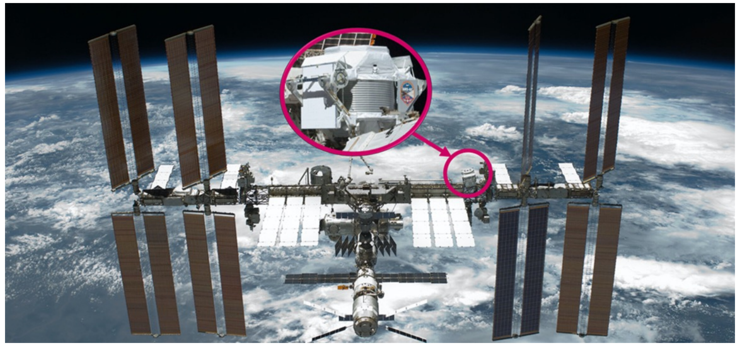
The chapter will cover several topics that connect different aspects of heavy-ion, nuclear and hadron physics at FAIR with astro (particle) physics. The chapter will be organized in several sections addressing the following arguments:

- ✓ Beams of protons, pions, and medium mass nuclei of particular relevance in the FAIR energy range for propagation of galactic cosmic rays (Alpha Magnetic Spectrometer (AMS) and future Chinese Space Station physics with cosmic rays)
- ✓ Photo disintegration cross sections for specific isotopes (relevant for intergalactic and galactic cosmic ray propagation)
- ✓ Neutrino (atmospheric and astrophysical neutrino calculations, charm production → prompt muons)
- ✓ Dark Matter and dark photon measurements
- ✓ High-energy nuclear fragmentation reaction & their importance in astrophysics
- ✓ Opens questions & future experimental and astrophysical constraints of the nuclear EoS

Cosmic ray propagation and nuclear fragmentation



AMS-02 in the Int. Space Station

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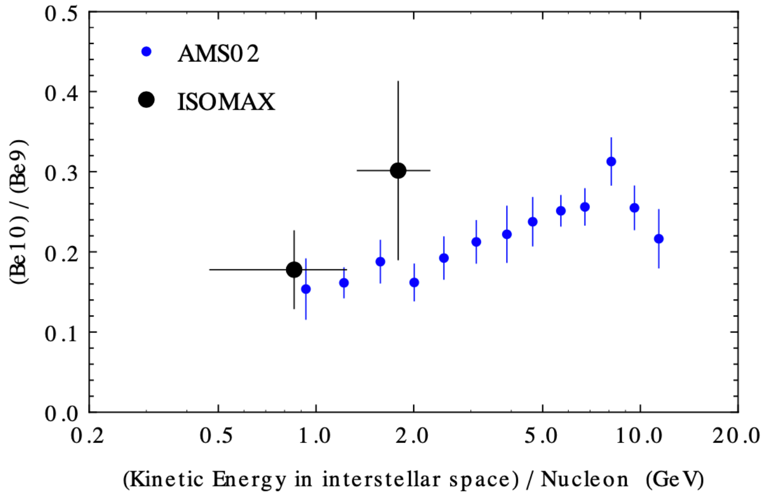


FIG. 1: Measurements of the isotopic ratio beryllium–10/beryllium–9 at high energy, plotted as a function of kinetic energy per nucleon. The data is from ISOMAX [3] and (only preliminary) from AMS02 [2].

arXiv.2204.13085v1

^{9}Be: stable

^{10}Be: $T_{1/2}$ = (1.387±0.012) x 10^{6} years

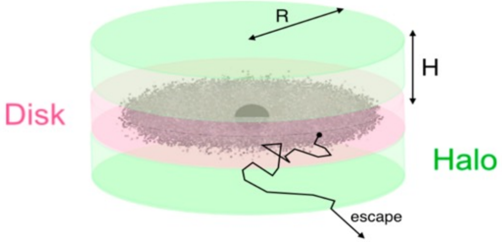
Similar to a typical period for cosmic rays staying inside the galaxy

^{10}Be/^{9}Be is sensitive to how cosmic rays propagate in the galaxy

Propagation calculations of cosmic-rays with existing nuclear fragmentation reaction cross section models

Distribution of galactic magnetic field

However,



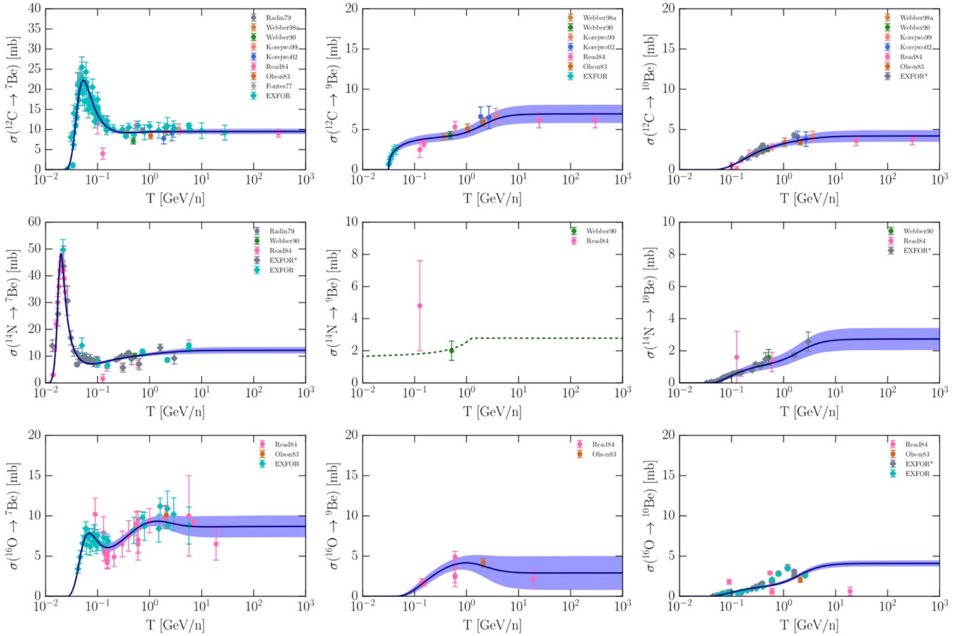
	Webber	GALPROP	DRAGON2
D_0 (10^{28} cm^2 s^{-1})	2.3	6.65	7.1
v_A (km/s)	29.9	25.5	27.7
η	−0.25	−0.55	−0.6
δ	0.42	0.44	0.42
H (kpc)	2.07	6.93	6.76

P. De La Torre Luque, et al., JCAP03 (2021) 099.

Ambiguity is caused by the accuracy of the fragmentation data

Cosmic ray propagation and nuclear fragmentation

Poor experimental data, unfortunately



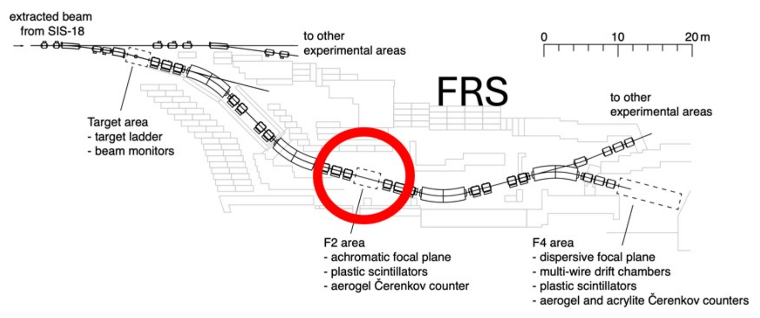
C. Evoil et al., Phys. Rev. D 99 (2019) 103023.

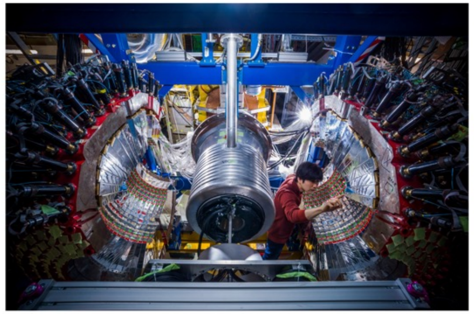
Robust fragmentation cross-section model valid up to 10 A GeV is needed

Taking data with FRS + WASA up to 2 GeV

- Measuring hadrons produced simultaneously with fragmentation
- Measurement on unstable 10Be

Details of fragmentation mechanism → Fragmentation models

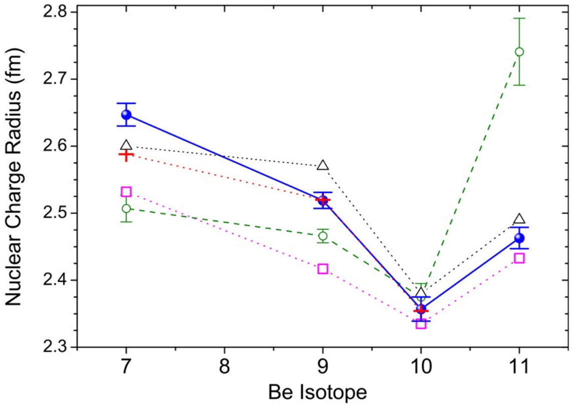




Validation by CBM and pCBM (inverse kinematics)

We also need data for
$^{9}Be + p \to X$
$^{10}Be + p \to X$

Both cross sections are assumed to be equal, but <u>different charge radius</u>



W. Norterhauser et al., Phys. Rev. Lett. 102 (2009) 062503.

Details will be presented by Take Saito on Wednesday

The open questions of the nuclear EoS

- How robust are different nuclear-physics models in describing the interiors of neutron stars ?. Up to which densities are they sitll applicable ?.

- What particles are present in neutron-star interiors and which states of matter do they form ?.

- How can we best connect experiments with atomic nuclei to the properties of neutron-rich matter in the crust and core of neutron stars ?.

- Do we fully understand the systematic uncertainties in the analyses of radio, x-ray, and gravitational-wave data from neutron stars, and of experimental nuclear structure and heavy-ion collision data ?.

- How can we robustly combine this multitude of constraints spanning widely different scales ?.

Future Expetimental & Astrophysical Constraints

Upcoming new data on neutron-rich matter from experiments & observations of NS will provide improved uncertainties allowing a more refined picture of the nuclear EoS and NS with tighter constraints on their properties

- **Experimental information:**

  - Neutron-skin thickness in heavy nuclei crucial to obtain key information on nuclear matter probed in the outer core of NS
  - Nature of very-neutron rich nuclei at the limits of existence from rare isotope facilities such as FAIR
  - Heavy-ion collision experiments at these facilities to probe matter at high densities & neutron-proton asymmetries. Crucial to better understand systematic uncertainties in the analysis of such experiments & improve transport model simulations

- **NS observation:**

  - New x-ray telescopes (Imaging x-ray polarimetry explored (Dec. 2021), XRISM (2023), Athena (2031)) will enable further advances & improve modelling of x-ray sources
  - The improvement in the next decade of the sensitivity of LIGO & Virgo detectors will increase the prospects for dense matter science with GW
  - Third generation of GW detectors (Einstein Telescope, Cosmic Explorer) in the 2030s will allow the detection of a post-merger GW signal & its electromagnetic counterpart
  - Future observations of young NS (Cas A or the potential remnant of SN 1987A) will constraint theoretical cooling models & potentially set constraints on energy gaps of superfluid matter.