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Co/Ni Ratio Between 0.8 - 5 GeV/nucleon from TIGER-2001

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The 2001 flight of TIGER lasted 31.8 days and collected sufficient statistics to study the Co/Ni elemental ratio over a wide range in energies. We present the elemental ratio of Co/Ni in galactic cosmic rays between ∼0.80-5 GeV/nucleon and compare our results with previous measurements and propagation models.

1. Introduction

It is generally accepted that supernovae provide the power for galactic cosmic rays (GCR). In addition, many of the heavy elements are synthesized within supernovae. The question still remains, however, whether supernova ejecta itself provides the source material for cosmic rays or whether GCRs are derived from an older, ambient interstellar medium, and subsequently accelerated to high energies by diffusive shock acceleration from supernova blast waves. It has been pointed out [1] that radioactive isotopes produced during explosive nucleosynthesis that decay only through electron capture can provide constraints on the delay between nucleosynthesis and the acceleration of GCRs. One such nucleus is the radioactive isotope ^{59}Ni which decays via electron capture with a half life of 7.6x10^4 years.

Recent observations of the isotopes of Ni and Co have been made at relatively low energies (150-500 MeV/nuc) with high statistical accuracy with the Cosmic Ray Isotope Spectrometer (CRIS) on board the Advanced Composition Explorer (ACE). CRIS observes essentially no ^{59}Ni placing a rather definitive lower limit on the delay between nucleosynthesis and acceleration of greater than 10^5 years [2]. In addition, there have been several other observations of the isotopes of Ni and Co at low energies from experiments on ISEE 3 [3], Ulysses [6], and Voyager [5], which tend to agree with a long delay between nucleosynthesis and acceleration despite the rather limited statistics and mass resolution of these experiments.

At higher energies, above a GeV/nucleon, there exist only elemental observations of Co and Ni. The results of the HEAO-3 C2 experiment [4], which observed the elements of Co and Ni over an extended energy range, suggest that not enough time has elapsed between nucleosynthesis and acceleration for the complete decay of ^{59}Ni, although interpretation of the abundances depends on the accuracy of the propagation models.

Additionally, Davis et al. [15], and Moskalenko et al. [16], have considered models in which cosmic rays that originate within our Local Bubble contribute ∼20% of the intensity of primary species such as Fe at ∼300 MeV/nucleon, without contributing significantly to the production of Ti, V, and Cr. Such a local bubble contribution would depress the observed Co/Ni ratio, since much of the observed Co is secondary, and thus make this element ratio a poor indicator of ^{59}Ni decay.

The Trans Iron Galactic Element Recorder (TIGER), has measured nuclei between $14 \leq Z \leq 40$ in the energy range from 800 MeV/nucleon to ∼5 GeV/nucleon on two highly successful long duration flights from the

Antarctic in 2001-02 and 2003-04. This paper presents the observations of the Co/Ni ratio over an energy range up through 5 Gev/nucleon from the first Antarctic flight of TIGER in 2001-02.

2. Data Analysis

TIGER is designed to measure nuclei between $14 \leq Z \leq 40$ with an emphasis on the measure of the ultra-heavy cosmic rays between zinc and zirconium. Preliminary results of the ultra-heavy cosmic ray observations from the first flight in 2001-02 are discussed in [7] and from the combined Antarctic flights of 2001 and 2003 in these proceedings (see S. Geier et al.). The detection of nuclei ranging from silicon to zirconium is accomplished with an ensemble of detector elements, including four scintillation counters to provide a measure of dE/dx, two Cherenkov counters to provide a measure of the velocity, and a scintillating fiber hodoscope to provide a measure of the incoming particle track. With this ensemble of detectors, TIGER achieves an excellent charge resolution of < 0.25 cu over an extended energy range from 320 MeV/nucleon to $\sim$ 5-10 GeV/nucleon.

The 2001-02 flight of TIGER from the Antarctic lasted 31.8 days with two circumpolar trips about the Antarctic. The average residual atmosphere above TIGER was 5.5 g/cm^2, despite a slight loss in altitude over time due to a slow leak in the balloon.

The raw data have been corrected for zenith angle, for small diurnal variations in the temperature during the flight and for mapping variations across the scintillation and Cherenkov counters. In addition, in order to remove those particles that have interacted within the instrument, we require consistency between the charge determined at the top of the instrument and the charge determined at the bottom of the instrument.

The energy of incoming particles is determined from the response of the two Cherenkov counters. The two counters have radiators with different indices-of-refraction. The top Cherenkov counter is aerogel with an index of refraction of 1.042 and thus an energy threshold of 2.4 GeV/nucleon. The bottom Cherenkov counter has an acrylic radiator with an index-of-refraction of 1.5 and thus an energy threshold of 320 MeV/nucleon. To establish a correspondence between the particle's incoming energy and the Cherenkov counter response, we developed a model for the expected response of both Cherenkov counters, taking into account the input spectrum of nuclei at the top of the atmosphere, the contribution to the total Cherenkov signal from knock-on electrons and additional scintillation, and finally expected convolution from various uncertainties such as photoelectron statistics, variations in the index-of-refraction across the counters, and fluctuations in the contribution from knock-on electrons to the total signal. The energy resolution for the acrylic radiator is less than 1% and rises to $\sim$10% for the aerogel radiator at 5 GeV/nucleon.

Charge histograms for Mn through Ni for six different energy ranges are shown in Figure 1. The Co and Ni peaks are clearly resolved. The Co/Ni ratio is determined by fitting multiple gaussian peaks using a maximum likelihood algorithm. The results are shown as the solid curve overlaying the charge histograms.

The top of the atmosphere Co/Ni ratio is determined by applying a correction for energy loss in $\sim$5.5 g/cm^2 of atmosphere and $\sim$4.2 g/cm^2 of instrument. In addition, we correct the Co/Ni ratio for the contribution to spallation within the 5.5 g/cm^2 of overlaying atmosphere above the instrument. To determine how the Co/Ni ratio grows with depth we scale atmospheric growth curves determined for Mn/Fe [8]. The partial cross sections for Ni into Co and Fe into Mn differ by $\sim$20% [9]. We have added a systematic uncertainty of $\sim$ 20% in the final TIGER results to account for the cross section uncertainties. The cross sections at higher energies may differ considerably although current parametrizations indicate that the cross sections are fairly monotonic with energy.

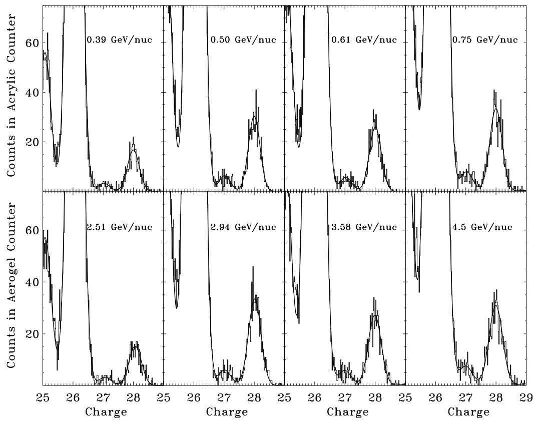

Figure 1. Charge histograms for manganese, iron, nickel, and cobalt in the eight energy ranges used in this study. The mean energy at the Cherenkov counter is indicated in each figure. The resulting fits from a multiple gaussian maximum likelihood algorithm are also shown (solid curve).

3. Results & Discussion

Figure 2 shows the preliminary results from TIGER's first Antarctic flight for the elemental abundance ratio of Co/Ni corrected to the top of the atmosphere and compared with observations from previous experiments. TIGER results tend to lie above the high energy data of HEAO, but are in overall agreement with other observations. However, with the exception of the ACE elemental abundance of Co/Ni, other experiments have large statistical uncertainties and in some cases poor charge resolution. Also shown in the figure are the results of an interstellar propagation model for the abundance of Co/Ni for two scenarios; one in which all of the ^{59}Ni has been allowed to decay at the source (dashed curve) and one in which no ^{59}Ni has decayed (solid curve) [12]. The TIGER results are consistent with the complete decay of ^{59}Ni which is also in agreement with the more precise isotopic measurements of ACE [2].

The interpretation of the elemental abundance measurements of Co/Ni is certainly dependent on the accuracy of the interstellar propagation model in addition to the correction for spallation within the overlying atmosphere above TIGER. The interstellar propagation model assumes new cross section measurements from [9], in addition to the cross section parametrization of [10]. We plan to conduct a current survey of cross section data, particularly at higher energies, in order to constrain the propagation model predictions further. Similarly, a more detailed calculation of the interactions within the atmosphere, accounting for current cross section data, should provide more confidence in our extrapolation to the top-of-the-atmosphere.

4. Summary

The preliminary Co/Ni ratio obtained from the TIGER 2001 Antarctic flight between $\sim$800 MeV/nucleon and $\sim$5 GeV/nucleon varies between 0.11 and 0.17 at the top of the atmosphere. These results are in agreement with the predictions of an interstellar propagation model in which ^{59}Ni has decayed at the source, suggesting a significant time delay between nucleosynthesis and acceleration, at least as large as the half-life of ^{59}Ni of 7.6x10^4 years. This result is consistent with the more precise isotopic observations from CRIS/ACE. Further studies are needed to reduce the systematic uncertainties in the correction to the abundance ratio for spallation

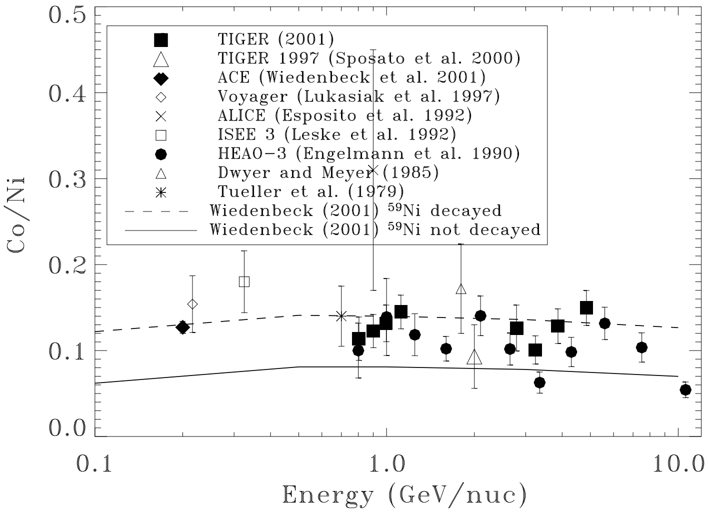

Figure 2. TIGER 2001 results for Co/Ni at the top of the atmosphere as a function of energy compared with data from previous experiments and with an interstellar propagation model [12].

within the atmosphere. Finally, we hope to develop our own interstellar propagation model with up-to-date cross sections in order to better constrain the model predictions.

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