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# Co/Ni Ratio Between 0.8 - 5.0 GeV/nucleon from the TIGER-2001 Flight

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**Abstract:** The Trans-Iron Galactic Element Recorder (TIGER) was launched in December 2001 and 2003 from McMurdo, Antarctica and was designed to observe elements ranging from $14 \leq Z \leq 40$ over an extended energy range. Observations of radioactive isotopes produced during explosive nucleosynthesis such as $^{59}$Ni that decay only through electron capture provide important constraints on the delay between nucleosynthesis and the acceleration of galactic cosmic rays (GCRs). The isotopes of Co and Ni at low energies, in particular, the observations of the $^{59}$Ni and $^{59}$Co from the Cosmic Ray Isotope Spectrometer (CRIS) on the Advanced Composition Explorer, indicate a significant time delay (>7.6 $\times$ $10^4$ yr) between GCR nucleosynthesis and acceleration. While TIGER is not able to resolve isotopes, observations of the elemental abundances of Co and Ni at high energies further constrain models for the acceleration and propagation of GCRs. The 2001 & 2003 flights of TIGER lasted a total of ~50 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 ~0.8-5.0 GeV/nucleon and compare these results with previous measurements and models for cosmic-ray propagation.

## Introduction

It is generally believed that galactic cosmic rays (GCR) are powered by supernova. Supernova events can account for both the observed energy density of GCRs as well as the synthesis of heavy elements, and clearly play an important role in the evolution of GCRs. Recent observations from the Advanced Composition Explorer (ACE) with the Cosmic Ray Isotope Spectrometer (CRIS) suggest that a substantial fraction of GCRs originate within OB associations [1], [2]. In addition, observations of electron capture isotopes from CRIS/ACE are also consistent with the Higdon et al. (1998) suggestion that GCRs originate from within OB associations. Radioactive isotopes produced during explosive nucleosynthesis, such as $^{59}$Ni, which decays via electron capture with a half life of 7.6 $\times$ $10^4$ years, can be used to constrain the delay between nucleosynthesis and the acceleration of GCRs [3]. The CRIS/ACE observation that $^{59}$Ni has completely decayed in GCRs, show clear evidence that low energy GCRs ($\leq$ 0.5 GeV/nuc) do not originate from freshly synthesized material but are accelerated to GCR energies after at least $\geq 10^5$ yr [4].

In addition to the precise observations from ACE/CRIS, the isotopes of Ni and Co have been observed at low energies by several other experiments on ISEE 3 [5], Ulysses [6], and Voyager [7]. These isotopic observations also suggest a long delay between nucleosynthesis and acceleration, although the statistics and mass resolution of these experiments were rather limited. On the other hand, at energies above a GeV/nucleon, there exist only elemental observations of Co an Ni. The results of the HEAO C3 experiment [8], which observed the elements of Co and Ni over and extended energy range, suggest an insufficient amount of time for the complete decay of $^{59}$Ni, although the interpretation of the elemental abundance is limited by the accuracy of the propagation models [9].

The Trans Iron Galactic Element Recorder (TIGER), has measured nuclei over the charge range $14 \leq Z \leq 40$ 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 5.0 GeV/nucleon from the 2001-02 Antarctic flight, including a correction for atmospheric secondaries based on observed growth curves for cobalt and nickel. In addition, we hope to present the combined results from both Antarctic flights of TIGER in 2001-02 and in 2003-04.

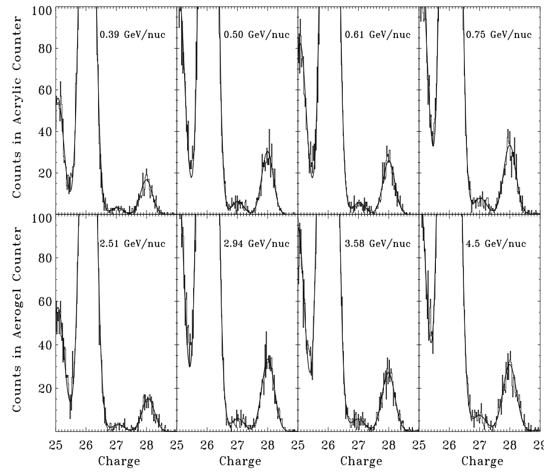


Figure 1: Charge histograms for manganese, iron, cobalt, and nickel in the eight energy ranges used in this study. The mean energy at the Cherenkov counter is indicated in each figure. The resulting fits from a multiple Gaussian maximum likelihood algorithm are also shown (solid curve).

## Data Analysis

TIGER is designed to measure nuclei between $14 \leq Z \leq 40$ with an emphasis on the measurement of the ultra-heavy (UH) cosmic rays between zinc and zirconium. TIGER observations of UH cosmic rays from the first flight in 2001-02 are discussed in [10] and [11]. The combined UH results from the Antarctic flights of 2001 and 2003 are discussed in these proceedings (see Rauch et al.). TIGER employs an ensemble of detectors to measure the trans-iron nuclei. These detectors include four scintillation counters to provide a measure of dE/dx, two Cherenkov counters to measure energy and charge, and a scintillating fiber hodoscope to determine the incoming particle track. This ensemble of detectors results in an excellent charge resolution of $< 0.25$ cu over an extended energy range from ~800 MeV/nucleon to ~ 5-10 GeV/nucleon. In addition, the energy response of the two Cherenkov counters has been modelled and is discussed in detail in [12].

The 2001-02 flight of TIGER from Antarctica lasted 31.8 days with two circumpolar trips about Antarctica. The average residual atmosphere above TIGER was 5.5 g/cm$^2$, despite a slight average loss in altitude over time due to a slow leak in the high-altitude balloon. The 2003-04 flight lasted 18 days with an average residual atmosphere of 4.1 g/cm$^2$.

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 underwent nuclear interactions 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.

Figure 1 shows the charge histograms for manganese through nickel for six different energy ranges from TIGER. The cobalt and nickel peaks are clearly resolved. The Co/Ni ratio is determined by fitting multiple Gaussian peaks using a maximum likelihood algorithm. The results of the maximum likelihood fits are shown as the solid curve overlaying the charge histograms.

The Co/Ni ratio observed at balloon altitudes must be corrected for the amount of secondary Co produced from cosmic-ray fragmentation within the atmosphere. We developed a transport model

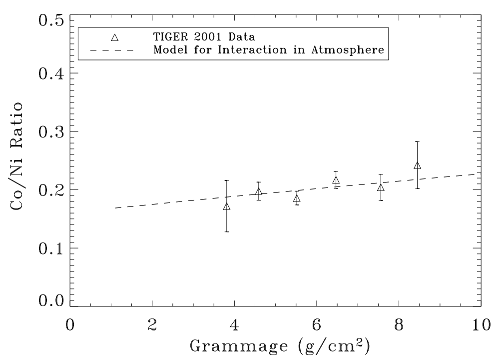


Figure 2: Atmospheric growth curves of Co/Ni derived from TIGER 2001-02 data compared with predictions from an atmospheric transport model (dashed line).

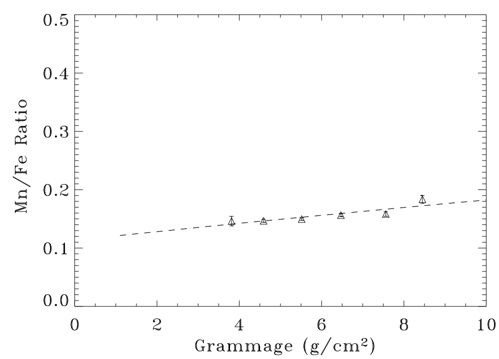


Figure 3: Atmospheric growth curves of Mn/Fe derived from TIGER 2001-02 data compared with predictions from an atmospheric transport model(dashed line).

based on the Weighted Slab technique (see review [13]). A known distribution of Co and Ni at the top of the atmosphere is propagated through separate slabs in the atmosphere. For each slab, the model computes the energy loss, the loss from interactions, and the gain from spallation of heavier nuclei. In addition, we were able to obtain atmospheric growth curves for the 2001-02 flight since the high-altitude balloon experienced a slow leak throughout the flight. Figures 2 and 3 show the growth curves for the Co/Ni ratio as well as the Mn/Fe ratio in the energy range $\sim$800 MeV/nucleon to $\sim$5 GeV/nucleon compared with the predictions for the atmospheric transport model. The average grammage above the instrument of 5.5g/cm$^2$ corresponds to a correction factor of roughly $30\% \pm 10\%$.

## Observations

The elemental abundance ratio, Co/Ni, observed at the top of the atmosphere from the first Antarctic flight of TIGER is shown in Figure 4. The results are separated into two separate energy intervals defined by the two Cherenkov counters in order to improve statistics. The errors include both statistical and systematic uncertainties. The Co/Ni ratio observed by TIGER is in agreement with previous observations, with the exception of the highest energy measurement of HEAO at $\sim$5 MeV/nucleon. The agreement is not surprising since other experiments have large statistical uncertainties and in some cases poor charge resolution. The ACE observation at $\sim$200 MeV/nucleon provides a tight constraint on source models. The disagreement with the HEAO data in the highest energy intervals is not well understood.

Figure 4 also shows the predictions of an interstellar propagation model [4] based on new cross section measurements from [14], in addition to the cross section parametrization of [15]. The propagation model determines 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). The Co/Ni ratio observed from the TIGER 2001-02 flight is consistent with the complete decay of $^{59}$Ni. In addition, TIGER results are consistent with the elemental abundance observation of Co/Ni from ACE [16] and the more precise isotopic measurements of ACE [4].

The predictions of the interstellar propagation model are certainly dependent on the accuracy of the cross section data assumed in the model and this, in turn, influences the interpretation of the Co/Ni ratio as a function of energy. In the future, we hope to better address the uncertainties in the cross section data and how these uncertainties relate to model predictions and the interpretation of the Co/Ni ratio.

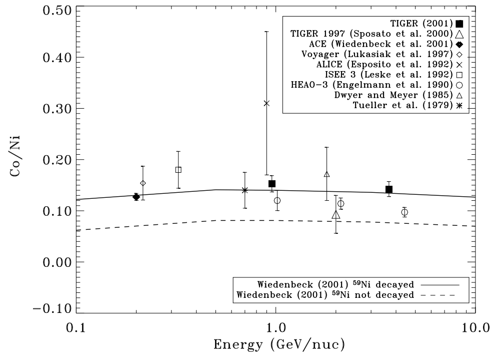


Figure 4: TIGER 2001 results for Co/Ni at the top of the atmosphere as a function of energy compared with data from previous experiments and with an interstellar propagation model [4]. The energy bands for the two TIGER data points correspond to ∼0.75-1.2 MeV/nucleon and ∼2.68-5.5 MeV/nucleon. The errors include both statistical and systematic uncertainties.

## Summary

The preliminary Co/Ni ratio obtained from the TIGER 2001 Antarctic flight between ∼800 MeV/nucleon and ∼5 GeV/nucleon varies between 0.14 to 0.16 and shows a weak dependence on energy above ∼ 800 MeV/nucleon. These results are consistent 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 7.6x$10^4$ years. Futhermore, the TIGER results, at energies greater than 500 MeV/nculeon, are consistent with the low energy, elemental observations from CRIS/ACE and the more precise isotopic observations from CRIS/ACE. We hope to develop our own interstellar propagation model with up-to-date cross sections in order to better constrain the model predictions. Finally, we anticipate an improvement in the statistical accuracy of the TIGER observations with the addition of the 2003-04 data.

## Acknowledgements

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