Upturn in the ratios of nuclei of Z=16-24 and abundant heavy nuclei to iron as observed in the ATIC experiment above 50 GeV/n and the Local Bubble

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ATIC (Advanced Thin Ionization Calorimeter)

ATIC collaboration:

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2. Marshall Space Flight Center, Huntsville, AL, USA
3. University of Maryland, Institute for Physical Science & Technology, College Park, MD, USA
4. Purple Mountain Observatory, Chinese Academy of Sciences, China
5. Max-Planck Institut for Solar System Research, Katlenburg-Lindau, Germany
6. Southern University, Department of Physics, Baton Rouge, LA, USA
7. Louisiana State University, Department of Physics and Astronomy, Baton Rouge, LA, USA
The ATIC spectrometer

At the start position

Protons and nuclei — 30 GeV - 100 TeV

$e^- + e^+ — 30$ GeV - 2-3 TeV

In the flight
ATIC (Advanced Thin Ionization Calorimeter)

1 — Silicon matrix
80 x 56 pixels, 1.5 x 2 cm

2 — Scintillator hodoscopes

3 — Carbon target
(1.5 $X_0$)

4 — BGO-calorimeter (thin)
Top view:
50 x 50 cm
BGO crystal:
2.5 x 2.5 x 25 cm
8 layers in ATIC-2 (18 $X_0$)
10 layers in ATIC-4 (22 $X_0$)
Prehistory — HEAO-3-C3: Ar/Fe, Ca/Fe

19th ICRC, 1985, V.2, p. 28-31
20th ICRC, 1987, V.1, p. 330-333

Ca, Ar: points above 150 GeV not shown
Possible systematics (?)
Prehistory: ATIC, Ti/Fe

No sings of systematics, but too low statistical significance
Heavy nuclei (S-Cr) to iron ratio in ATIC experiment (energy per nucleon spectra)

HEAO-3-C3: Ar/Fe, Ca/Fe
Heavy nuclei (S-Cr) to iron ratio in ATIC experiment (energy per nucleon spectra)

The statistical significance is

\[ p = 0.997 \]

"Naive expectation" - all primary nuclei have same rigidity spectra in the source, leaky box model
Different charge regions

Z, E > 20 GeV

H3
Entries 1505626
Mean 22.67
RMS 3.913

S Ar Ca Ti Cr Fe

S-Cr/Fe

Data, (15.5<Z<24.5)/Fe
Leaky box (16<=Z<=24)/Fe

Data, (20.5<Z<24.5)/Fe
Leaky box (21<=Z<=24)/Fe
Is actually the origin of the upturn is an unusual behavior of nuclei spectra from S (Z=16) to Cr (Z=24)?

May it be that the iron spectrum was measured by ATIC incorrectly?

How it can be verified?
Ratio of abundant nuclei to iron in the ATIC experiment

«naive expectation»:
all nuclei have same rigidity spectra in the source, leaky box model
Ratio of abundant nuclei to iron in the ATIC experiment. Various nuclei and nuclei groups.
The ratio of nuclei from sulfur to chromium to irion
From sulfur to chromium (Z=16-24) - ATIC-2 experiment;
Iron fluxes — from other experiments (TRACER, CREAM)
Absolute spectra of TRACER
Ratio $S+Ar+Ca/Fe$ and ratios $C/Fe$, $O/Fe$ from TRACER I и II, calculated from absolute spectra.
The 'standard' model of propagation in a uniform media together with power-law spectra in the sources could not explain the data.

But how it can be understood?

![Graphs showing data and model predictions for S-Cr/Fe and O/Fe ratios.](image-url)
Model of closed galaxy with super-bubbles embedded

"Closed" Galaxy

The Sun

Super-bubbles

B. Peters, N.J. Westergaard.
Cosmic ray propagation in a closed galaxy.
Mathematics for the closed galaxy with super-bubbles embedded

\[ \kappa \equiv 1/\lambda \]

\[ Q_{\text{bulk}}(\varepsilon) = \frac{\kappa_{\text{esc}}(\varepsilon)}{\kappa_{\text{esc}}(\varepsilon) + \kappa} Q(\varepsilon) \]

\[ \frac{I_{N_i}(\varepsilon)}{I_{Fe}(\varepsilon)} = \frac{\kappa_{N_i,Fe}}{\kappa_{\text{esc}}(\varepsilon) + \kappa_{N_i}} + K \frac{\kappa_{N_i,Fe}}{\kappa_{N_i}} \frac{\kappa_{Fe}^{\text{esc}}(\varepsilon)}{\kappa_{Fe}} \]

\[ 1 + K \frac{\kappa_{\text{esc}}(\varepsilon)}{\kappa_{Fe}} \]

\( K \) represents the fraction of the bulk flux in the total flux.

\( K \) should be fitted to the data to obtain correct minimum position.
Model of closed galaxy with super-bubbles embedded - the description of the data

\[ K = 0.2 \]
Model of closed galaxy with super-bubbles embedded - oxygen to iron ratio description

\[ K = 0.2 \]
Diffusion coefficient in the Local Bubble

\[ D \sim \frac{H^2}{\tau_{esc}} = q c \frac{H^2}{\lambda_{esc}} \]

\[ \lambda_{esc} = 34.1 \times R^{-0.6} \text{g/cm}^2 \]

\[ D = D_0 R^{0.6} \]

\[ H = n \times 1 \text{kpc} \]

\[ D_0 = \left[ \frac{\rho}{0.5 \text{cm}^{-3}} \right] \times n^2 \times 0.7 \times 10^{28} \text{cm}^2/\text{s} \]

For the Local Bubble:

\[ H \sim 100 \text{ pc} \ (n \sim 0.1) \]

\[ D_0^{\text{bubble}} \sim (10^{-2} - 10^{-4}) \times D_0^{\text{Galaxy}} \]

\[ D_0^{\text{bubble}} \sim 10^{24} - 10^{26} \text{ cm}^2/\text{c} \]

Very small diffusion coefficient or reflection from the Local Bubble shock?
What about B/C? **B/C - before Rio-2013**

Situation at high energies is unclear
No upturn at high energies
A challenge: how it could be understood?
Conclusions

1. The upturn in the ratio of heavy nuclei to iron and abundant nuclei to iron are statistically significant and should be considered seriously, however independent direct experimental confirmation is needed.

2. Super-bubble model may be relevant to understanding of the phenomenon, However further work is needed

3. How B/C and (S-Cr)/Fe could be reconciled in one uniform model?
Thank you for attention!
The ATIC flights

Test flight, 0.6 m² sr days

First science flight, 2.5 m² sr days

ATIC-3 2005
failed to reach altitude

Second science flight,
2.2 m² sr days
Fit of the universal hardening of spectra by the Closed Galaxy + Super-bubble model

\[ \gamma_{\text{source}} = 2.55 \]

\[ \gamma_{\text{source}} = 2.45 \]
Dependence of the charge distribution of the energy
The statistical significance of the upturn.

1. Naive (incorrect) approach.

\[ R = \frac{m}{n} \]

\( m, n \) - random Poisson numbers

There is no statistical distribution for \( R \)!

With non-zero probability \( n = 0 \) and \( m/n \) does not exist.

How to use maximum likelihood method?
The statistical significance of the upturn.

2. Correct solution.

\[ \gamma_R - \gamma_L > 0 \] above \( E = 50 \text{ GeV/n} \) ⇒
Ratio of Left charge region to the Right charge region energy spectra is a rising function above \( E = 50 \text{ GeV/n} \)
The statistical significance of the upturn.

3. Result

The statistical significance is $p = 0.997$ (the probability to obtain $\gamma_R > \gamma_L$)

Monte Carlo simulation of $\Delta \gamma = \gamma_R - \gamma_L$ for Poisson statistics of events count.