The TRACER detector for cosmic-ray nuclei

PhD in Experimental Physics – High energy physics seminar

Alberto Arzenton

Università degli Studi di Siena

October 19, 2023

Overview

Overview

Transition Radiation Detectors

Transition Radiation Detector (TRD)

Particle IDentification (PID) detector based on the **Transition Radiation (TR)** emitted by charged particles with high Lorentz factor γ at the interface between materials with different dielectric constants.

Let us define $\xi_i^2 \equiv \omega_{Pi}^2/\omega^2 = 1 - \varepsilon_i(\omega)$, where ω_{Pi} is the plasma frequency of the i-th medium. Then, the double differential **energy spectrum** for a single interface is:

$$\left.\frac{d^2W}{d\omega d\Omega}\right|_{interface} = \frac{\alpha}{\pi^2}\left(\frac{\theta}{\gamma^{-2}+\theta^2+\xi_1^2} - \frac{\theta}{\gamma^{-2}+\theta^2+\xi_2^2}\right)^2 \quad (1)$$

in the $\gamma \gg 1$, $\theta \ll 1$ and $\xi_i^2 \ll 1$ limit.

Transition Radiation Detectors

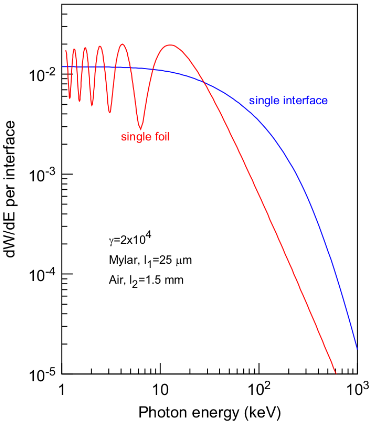
A single foil of material will have two interfaces, implying the presence of an **interference** factor:

$$\left.\frac{d^2W}{d\omega d\Omega}\right|_{foil} = \left.\frac{d^2W}{d\omega d\Omega}\right|_{interface} \times 4\sin^2\frac{\phi_1}{2} \qquad (2)$$

The phase $\phi_i \simeq (\gamma^{-2} + \theta^2 + \xi_i^2)\omega l_i/(2\beta c)$ depends on the medium thickness l_i. It is common to use a **stack** of N_f foils l_1 thick separated by gas layers l_2 thick, obtaining:

$$\left.\frac{d^2W}{d\omega d\Omega}\right|_{stack} = \left.\frac{d^2W}{d\omega d\Omega}\right|_{foil} \times e^{\frac{1-N_f}{2}\sigma} \times \frac{\sin^2\frac{N_f\phi}{2} + \sinh^2\frac{N_f\sigma}{4}}{\sin^2\frac{\phi}{2} + \sinh^2\frac{\sigma}{4}} \qquad (3)$$

where $\sigma \equiv \sigma_1 + \sigma_2$ is the absorption cross-section for the radiator materials and $\phi \equiv \phi_1 + \phi_2$.



[Andronic and Wessels (2012)]

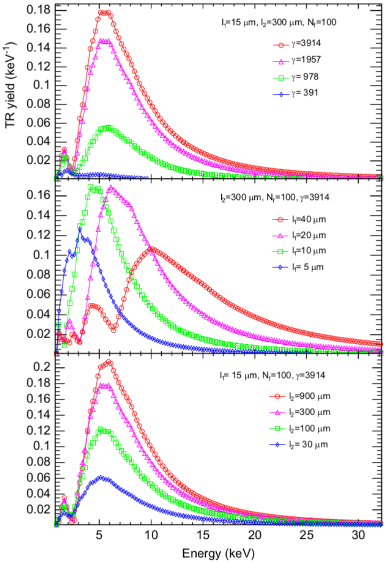
Transition Radiation Detectors

Some qualitative features:

1. The **formation zone** $z_i = \frac{1}{\gamma^{-2}+\xi_i^2}\frac{2\beta c}{\omega}$ is the distance beyond which the electromagnetic field readjusts; the photon yield is suppressed at $l_i \ll z_i$.
2. The spectrum has its **maximum** at $\omega_{max} = \frac{l_1 \omega_{P1}^2}{2\pi\beta c}$.
3. For $l_2/l_1 \gg 1$, the spectrum is mainly determined by single foil interference.
4. If $\gamma > \gamma_s \equiv \frac{1}{4\pi\beta c}\left[(l_1 + l_2)\omega_{P1} + \frac{1}{\omega_{P1}}(l_1\omega_{P1}^2 + l_2\omega_{P2}^2)\right]$, multiple foil interference causes **saturation**.

Transition Radiation Detectors

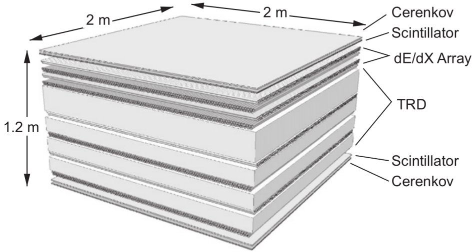
- For a given particle energy, the γ **dependence** of the spectrum makes it possible to discriminate the **mass**: TRDs usually combine TR and $\frac{dE}{dx}$ measurements.
- The TR yield saturates quickly with l_1 and slowly with l_2, since here $z_2 \gg z_1$.
- TR and $\frac{dE}{dx}$ signals scale like Z^2, so the **fluctuations** decrease for higher Z.



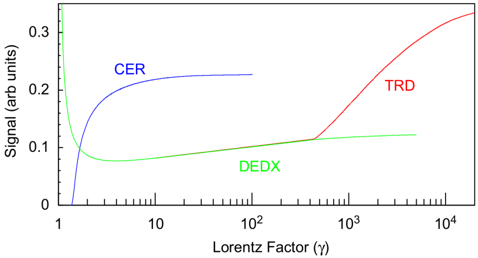
Overview

General features

TRACER (TR Array for Cosmic Energetic Radiation): balloon-borne detector meant for the PID of **cosmic-ray nuclei**.



- Two pairs of **scintillation and acrylic Cherenkov counters** for E below 10 GeV/amu and Z.



- Z measured top and bottom to control possible charge-changing nuclear reactions with the detector.
- $\frac{dE}{dx}$ **array and TRD** for E at 10–400 GeV/amu and above.
- Saturation at 3×10^4 Gev/amu ($\gamma_s \sim 10^4$).

General features

- The device was built to float at 36–40 km of altitude in the polar regions (Long Duration Balloon flights, **LDB**).
- Electric power granted by **photovoltaic solar arrays**.
- **Thermal protection** ensured by foam insulation and Mylar sun shields.
- $Z \leq 2$ nuclei were not studied due to statistical fluctuations.

General features

After a short test flight in 1999 (**T99**), two LDBs were performed at Antarctic and Arctic latitudes: **LDB1** in 2003 and **LDB2** in 2006.

Table 1
Some technical parameters of the TRACER instrument.

Year of flight	1999	2003	2006
Gondola height (m)	3	3	2.5
Detector height (m)	1.1	1.1	1.2
Geometric factor (m^2 sr)	5.04	5.04	4.73
Mass (lbs)	4044	4000	4000
Power consumption (W)	220	250	250
Voltage (V dc)	28	32	24
Battery type	Lead-Acid	Li-Ion	NiMH
Flight CPU	Intel 486	Intel 486	PC-104
Linux OS	QNX	QNX	Debian
On-board storage (TByte)	0.1	1.0	0.5
LOS Telemetry (kb/s)	2×455	2×455	1×1000
Float altitude (km)	34–38	36–39	36–40
Flight duration (h)	28	250	108
Residual atm. ($g\,cm^{-2}$)	6.1	3.9	3.5
Geomagnetic cutoff (GV)	4.6	0	0

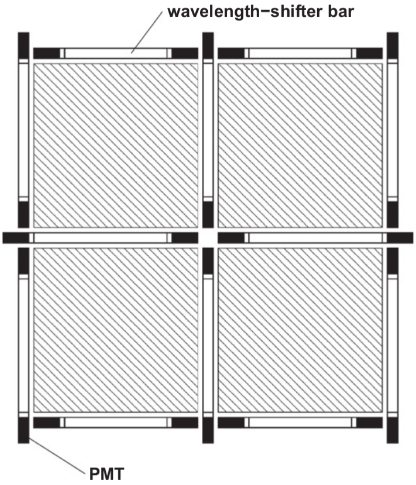
Detector subsystems

Scintillator and Cherenkov active area: 2 m × 2 m, split into 4 quadrants.

- 24 **PMTs**, 12 **waveshifter bars**.
- In T99 and LDB1 the coupled system was only in the bottom; in LDB2, a replica was added on top.

Table 2
Components used in the scintillator and Cherenkov counters.

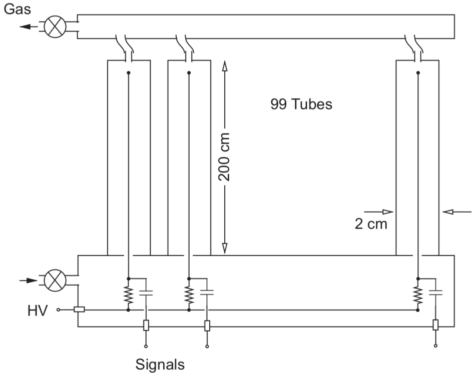
Component	Type	Dimensions
Scintillator	BICRON 408	4 m^2; 0.5 cm thick
Cherenkov	Polycast Acrylic	4 m^2; 1.3 cm thick
Waveshifter bars	BC 482A	1 m long
PMT	Photonis XP1910	19 mm diameter



Detector subsystems

$\frac{dE}{dx}$ **array and TRD** belong to a single **proportional tube array**, made by 8 double layers of single-wire cylinders.

- Each layer contains 99 tubes and a **manifold** for the signal collection.
- Manifolds oriented in alternate x and y directions to reconstruct the particle's **trajectory**.
- Smaller manifolds containing the gas are connected via flexible hoses, to get around the tubes' **thermal expansion**.



[Ave et al. (2011)]

Detector subsystems

The upper half of the layers measure $\frac{dE}{dx}$, while the lower $\frac{dE}{dx} + TR$ (X-rays).

- In the lower half, **radiators** are located above each double layer to produce TR.
- The top radiator (17.80 cm) is thicker than the others (11.25 cm) to compensate for the lower yield of X-rays.
- Radiators are made of blankets of thick and thin fibers.

Table 3
Summary of major parameters of the proportional tubes.

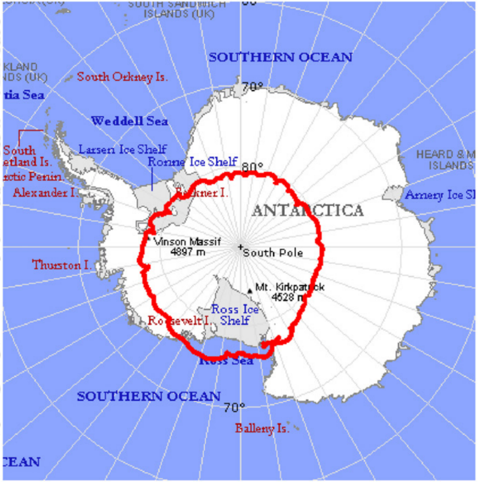
Tube dimension	Length 200 cm; diameter 2 cm
Wall material	Mylar; 3 layer, thickness 76 µm
Cathode	Aluminization on inner Mylar layer
Anode wire	Stainless steel; diameter 50 µm
Gas mixture	$Xe:CH_4$ (50:50) (T99 and LDB1) $Xe:CH_4$ (90:10) (LDB2)
Gas pressure	0.5 atm (T99 and LDB1) 1.0 atm (LDB2)
High voltage	1000 V (T99 and LDB1) 1150 V (LDB2)

Table 4
TRD fiber radiator parameters.

Parameter	Thick fibers	Thin fibers
Supplier	Hercules, Inc.	3 M Company
Material	Herculon 101	Thinsulate M400
Density (mg cm^{-3})	40	45
Average fiber thickness (µm)	17	4.5

Overview

LDB1

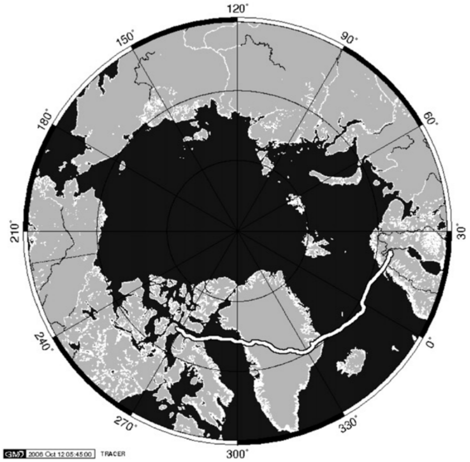


[Ave et al. (2008)]

LDB1 flew over Antarctica for 14 d, starting on 12/12/03.

- A counting rate of 60 events/s allowed to measure 5×10^7 events.
- The **gas mixture** used was Xe:CH_4 50%:50% by volume at 0.5 atm (as in T99).
- Elements **from O to Fe** were studied.

LDB2



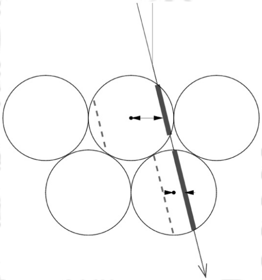
[Obermeier et al. (2011)]

LDB2 was launched from Kiruna, Sweden on 8/7/06 and lasted only 4.5 d due to the lack of permission to fly over Russia.

- The counts were increased to 120 events/s, obtaining 3×10^7 data points.
- To reduce intrinsic signal fluctuations and improve the energy resolution, Xe was increased by a factor of 4 (95%:5% at 1 atm).
- This improvement was fundamental for the **inclusion of B, C and N**.

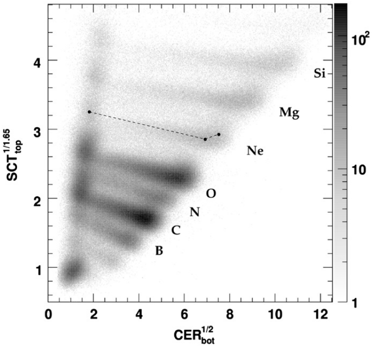
Overview

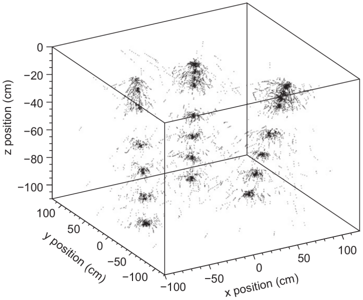
Data analysis



The **trajectory** is determined fitting the crossed tube centres and considering that the signal is proportional to the path. $\Delta x, \Delta y \approx 2\,\text{mm}$ was reached.

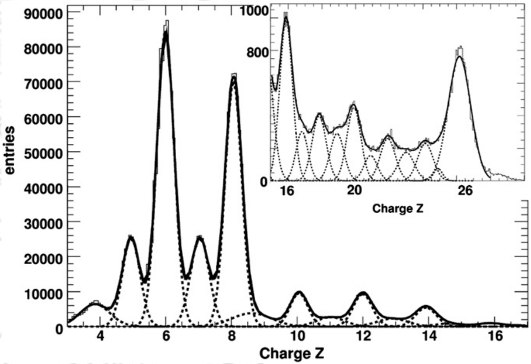
Z is studied with the **correlation** of scintillation and Cherenkov, scaling as $\sim Z^{1.65}$ (due to saturation) and Z^2.



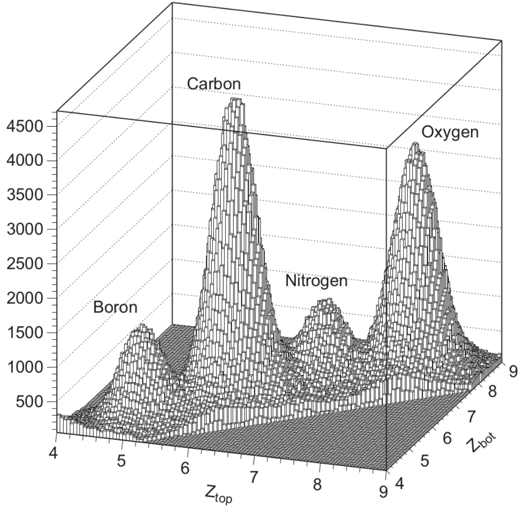


GEANT4 MC simulations were used to quantify the influence of ***δ*-rays** on the signal.

Data analysis



LDB1 had a **resolution** of 0.3–0.6 charge units; LDB2 improved to 0.23–0.55 thanks to the 2nd scintillator/Cherenkov installation.



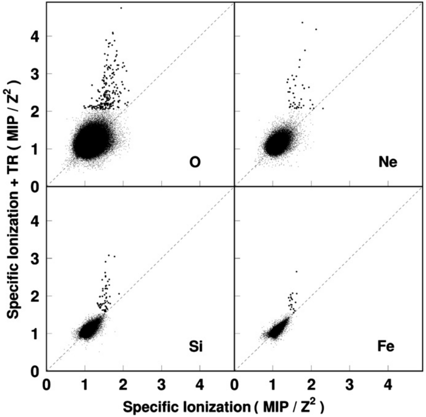
Data analysis

Regarding ***E***, in the *i*-th tube layer:

$$\left\langle \frac{dE}{dx} \right\rangle = \frac{\sum_{i=1}^{i=8} \Delta E_i}{\sum_{i=1}^{i=8} \Delta x_i}, \quad \left\langle \frac{dE}{dx} + TR \right\rangle = \frac{\sum_{i=9}^{i=16} \Delta E_i}{\sum_{i=9}^{i=16} \Delta x_i}$$

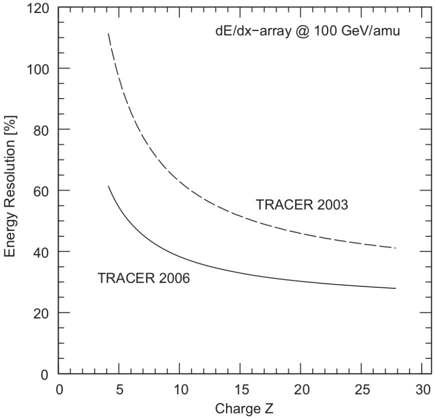
The **correlation** of these signals can be investigated for each element.

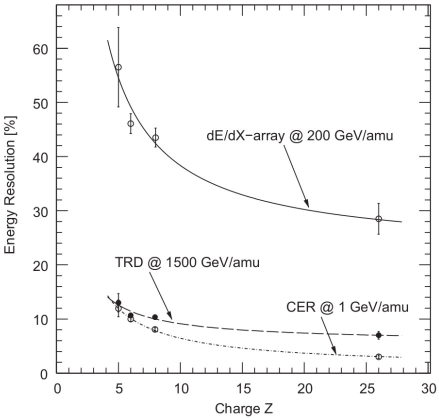
- Fluctuations decrease as $1/Z$.
- TR appears in the rare events above 400 GeV/amu (bold scatter).



MIP: minimum ionization level ($\gamma \sim 3$).

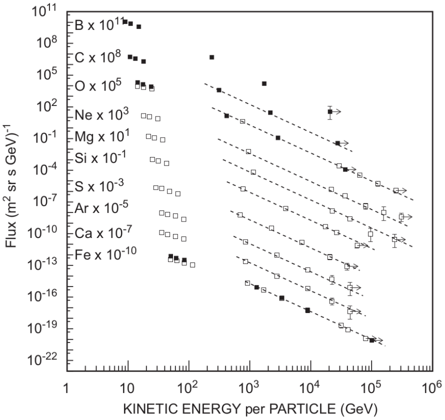
Data analysis

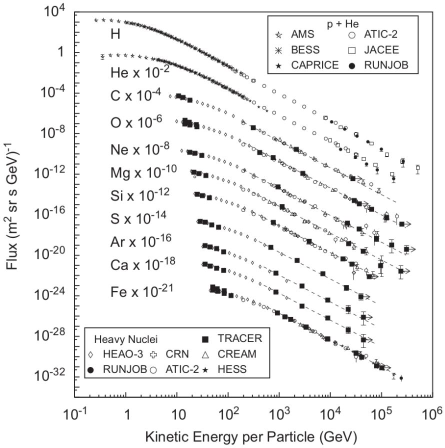




The LDB2 gas mixture significantly improved the $\frac{dE}{dx}$ **resolution** up to 33-40%, at the cost of a **higher TR threshold** (from $\gamma = 440$ to $\gamma = 785$).

Scientific results





The experiments produced a set of **new data** on cosmic-ray nuclei, extending also to the region above 10^5 GeV, previously **unexplored** for certain elements.

Overview

Summary and future prospects

The main achievements of the TRACER campaigns are probably two.

- ✓ The production of a **scientifically relevant dataset for cosmic-ray nuclei** from C ($Z = 5$) to Fe ($Z = 26$).
- ✓ The proof that the **novel instrumental configuration** chosen can provide clean results even at unexplored energies.

Finally, some possible upgrades were pointed out for future experiments.

- MC simulations suggested that **aerogel Cherenkov radiators** would produce higher signals than the acrylic ones.
- **Longer exposure times** would allow to investigate even higher energies.

Thank you for your kind attention!

References

A. Andronic and J. P. Wessels. Transition radiation detectors. *Nuclear Instruments and Methods in Physics Research A*, 666:130–147, 2012.

M. Ave, P. J. Boyle, F. Gahbauer, C. Höppner, J. R. Hörandel, M. Ichimura, D. Müller, and A. Romero-Wolf. Composition of primary cosmic-ray nuclei at high energies. *The Astrophysical Journal*, 678:262–273, 2008.

M. Ave, P. J. Boyle, E. Brannon, F. Gahbauer, G. Hermann, C. Höppner, J. R. Hörandel, M. Ichimura, D. Müller, A. Obermeier, and A. Romero-Wolf. The tracer instrument: A balloon-borne cosmic-ray detector. *Nuclear Instruments and Methods in Physics Research A*, 654:140–156, 2011.

A. Obermeier, M. Ave, P. J. Boyle, C. Höppner, J. R. Hörandel, and D. Müller. Energy spectra of primary and secondary cosmic-ray nuclei measured with tracer. *The Astrophysical Journal*, 742:14, 2011.