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# Observations of geomagnetically trapped light isotopes by NINA

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**Abstract.** The detector NINA aboard the satellite Resurs-01-N4 detected hydrogen and helium isotopes geomagnetically trapped, while crossing the South Atlantic Anomaly. Deuterium and tritium at L-shell$<$1.2 were unambiguously recognized. The $^3$He and $^4$He power-law spectra, reconstructed at L-shell=1.2 and B$<$0.22 G, have indices equal to 2.30±0.08 in the energy range 12–50 MeV/n, and 3.4±0.2 in 10–40 MeV/n respectively. The measured $^3$He/$^4$He ratio bring to the conclusion that the main source of radiation belt light isotopes is the interaction of trapped protons with residual atmospheric helium.

## 1 Introduction

The trapped helium component was discovered at the beginning of the 60’s (Krimigis and Van Allen, 1967). Its isotopic composition was studied many years later with the ONR-604 instrument on board CRRES satellite, in the energy range 50–100 MeV/n (Wefel et al., 1995) and with the spectrometer MAST on board SAMPEX in the interval 5–15 MeV/n (Selesnick and Mewaldt, 1996). It was found that $^3$He is more abundant than $^4$He in the inner radiation belt, at least for L-shell$<$1.5. The CRRES measured $^3$He/$^4$He averaged ratio in the energy interval 51–86 MeV/n was 8.7±3.1 at L-shell 1.1÷1.5, and 2.4±0.6 at L-shell 1.5÷2.3 (Wefel et al., 1995); this ratio decreases as a function of energy in the first L-shell range and increases in the second. At L-shell 1.1÷1.5 the power-law fit gives spectral indices equal to 5.9±0.4 for $^3$He and 4.1±0.3 for $^4$He. The $^3$He/$^4$He ratio obtained on board SAMPEX at L-shell=1.2 is about 1 at energy E$\simeq$9 MeV/n and increases with energy (Selesnick and Mewaldt, 1996). This ratio was measured for L-shell up to 2.1, where it was about 0.1. No other measurements of the isotopic composition of trapped helium are available up to now.

Information about hydrogen isotopes is poorer. In the work of Freden and White (1960) the observation of 4 trapped nuclei of tritium in the energy range 126–200 MeV was reported. In the same experiment, which utilized a small stack of nuclear emulsions, helium and deuterium nuclei were not observed, and that was ascribed by the authors to the different cross section of isotope secondary production, and to a high deuterium break-up rate. The first observations of real geomagnetically trapped deuterium in the inner radiation belt were presented by Looper et al. (1996), performed by PET on board SAMPEX in the energy range 18–58 MeV/n. In this work it was shown that, at the same energy per nucleon, the deuterium flux is about 1% of the proton one. The following work (Looper et al., 1998) reported observations of trapped tritium between 14 and 35 MeV/n at L-shell$<$1.2, with a flux equal to 1/8 of the deuterium one. At higher L-shell values it was not possible to identify tritium nuclei due to the increasing of the instrument noise.

The first explanations about the origin of rare light isotopes in radiation belts deal with the interaction of high energy trapped protons with the residual atmosphere (Freden and White, 1960). This source is at least one order of magnitude greater than that coming from cosmic ray interactions with air nuclei. To explain the significant difference between the $^3$He/$^4$He ratios measured by CRRES at different L-shells it was suggested in Wefel et al. (1995) that the interaction region of protons lies at a lower atmospheric altitude for L-shell$\simeq$1.2 than for L-shell$\simeq$1.9, and therefore it is necessary to take into account not only proton interactions with nuclei of helium in the upper atmosphere, but also with nuclei of oxygen which dominate at lower altitudes.

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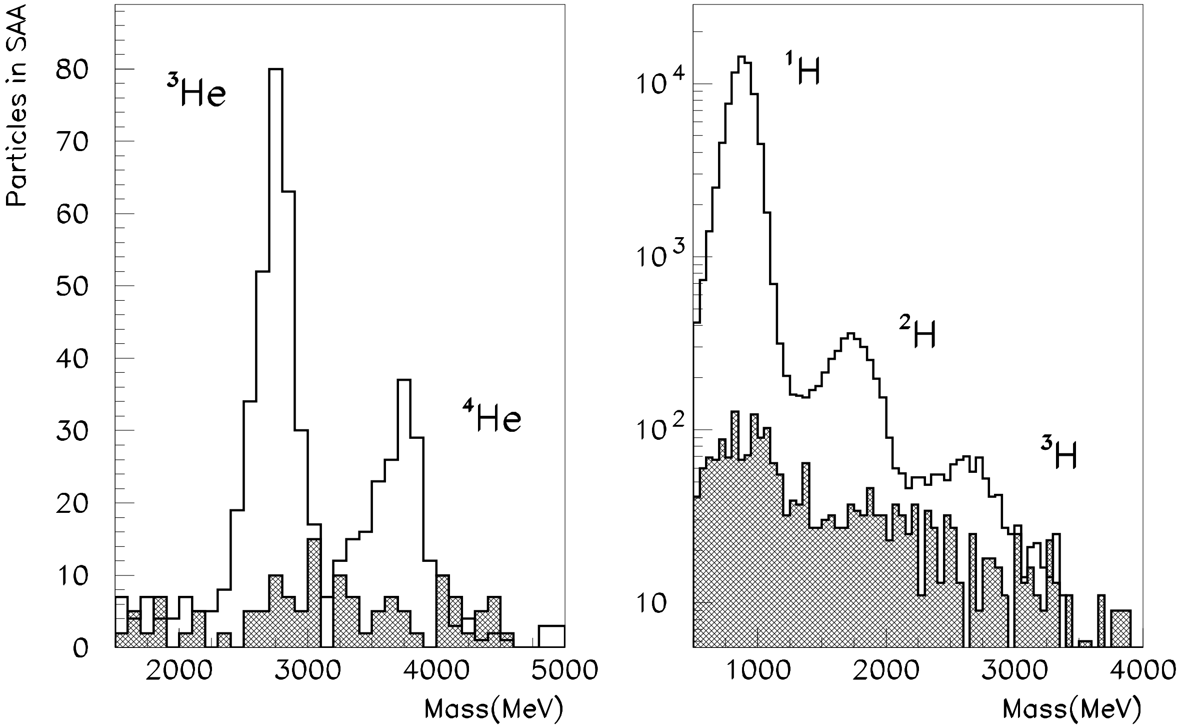

**Fig. 1.** Mass distributions for geomagnetically trapped He (left) and H (right) isotopes measured at L-shell<1.2 and B<0.22 G. The shaded area represents the estimated background. Arbitrary units on Y axis.

The first detailed calculation of production and trapping of secondary nuclei was done by Selesnick and Mewaldt (1996), where it was shown that the residual atmosphere is a significant source of $^2$H, $^3$He and $^4$He in the inner radiation belt. The results of calculations, however, depend on the detailed knowledge of some parameters, such as the radiation belt models and the solar cycle phase. Another possible mechanism discussed in literature is a radial diffusion of nuclei inside the magnetosphere. In the work by Spjeldvik et al. (1997) the secondary production rate for $^2$H and $^3$H in the upper part of the atmosphere was compared with radial diffusion, and the first appeared to dominate at L-shell in the interval 1.2÷1.6.

The instrument NINA presented in this article was put in orbit aboard the Russian satellite Resurs-01-N4 on July the $10^{th}$, 1998, and during its lifetime it performed measurements of Galactic Cosmic Ray fluxes (Bidoli et al., 2001) and isotopic composition of Solar Energetic Particles between 10 and 200 MeV/n. NINA stopped to be operational at the middle of the year 1999. On July the $14^{th}$, 2000, a second detector, NINA-2, was placed in orbit housed into the Italian satellite MITA, in order to extend NINA measurements in a different phase of the solar cycle (Casolino et al., 2001). In this article we report observations of geomagnetically trapped hydrogen and helium isotopes, performed by NINA during passages over the South Atlantic Anomaly (SAA) in the period November 1998–April 1999.

## 2 Instrument

The telescope NINA is a tower composed by 16 planes, each made of two silicon detectors, segmented in 16 strips orthogonally glued so as to provide the X and Y information of the particle track. The first two detectors are 150 $\mu$m thick, while the thickness of all the remaining is 380 $\mu$m, for a total of 11.7 mm of silicon.

NINA geometrical factor for helium and hydrogen isotopes is about 10 cm$^2$sr, decreasing as a function of energy. The mass resolution of the instrument is about 0.15 amu for He isotopes and about 0.1 amu for H isotopes. The energy resolution is about 1 MeV. A detailed description of the instrument and its performance in orbit are reported by Bakaldin et al. (1997); Bidoli et al. (1999, 2001).

## 3 Data observations and analysis

The satellite Resurs-01-N4 has a near-Earth polar orbit with inclination 98° and altitude 835 km. NINA is accomodated on Resurs so as to point always to the zenith. The spacecraft makes about 14 revolutions per day, and when the orbit crosses the South Atlantic Anomaly (about 7 times per day) NINA can measure particles trapped in the inner radiation belt. At L-shell $\leq$ 1.2, indeed, the local pitch-angle ($\alpha_{loc}$) distribution for particles detected by NINA is peaked at 90 degrees, that corresponds to an average equatorial angle $\alpha_0$

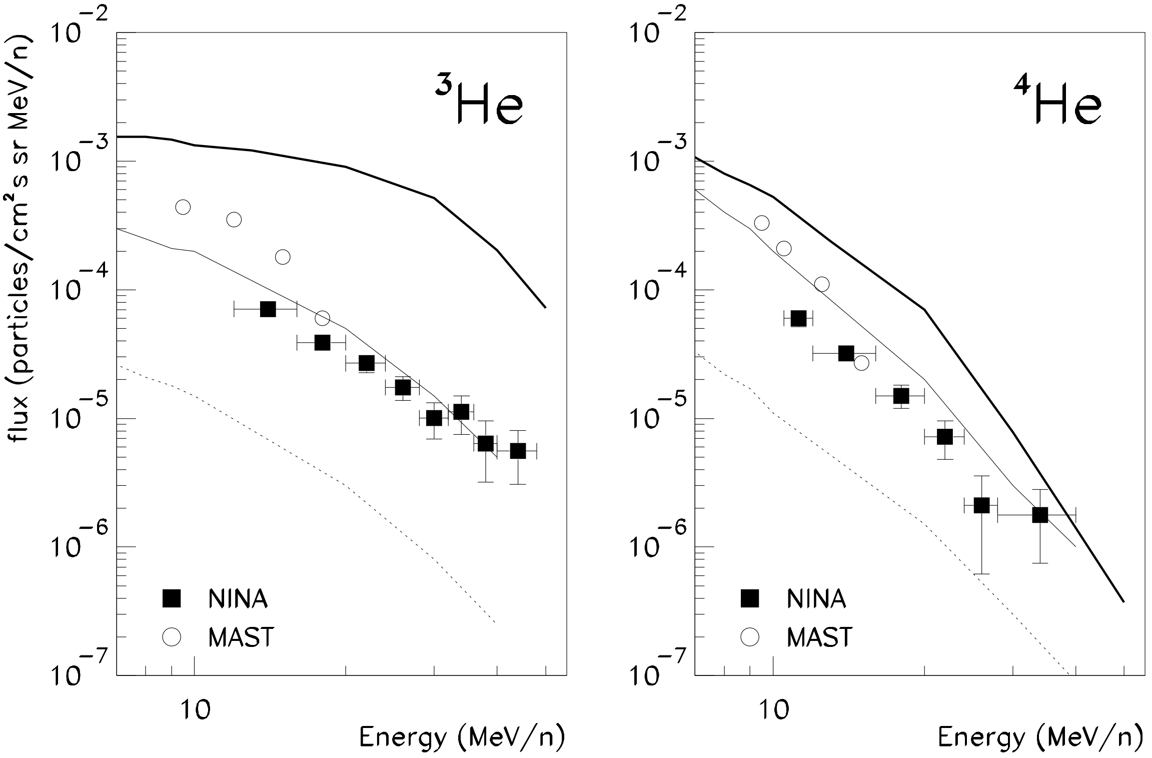

**Fig. 2.** $^3$He (left) and $^4$He (right) differential energy spectra measured inside the SAA by NINA (squares) and MAST (circles). The continuous and dotted lines represent the calculated helium flux at equatorial pitch angles $\alpha_0$=80° and $\alpha_0$=70° respectively, assuming atmospheric helium as the source of secondary production (Selesnick and Mewaldt, 1996). The thick line is the sum of the $p + He$ and $p + O$ contributions at $\alpha_0$=80°.

of about 75 degrees.

The period of observation taken under consideration ranges from November 1998 to April 1999; data include also particles collected during Solar Energetic Particle events, because even in conditions of intense solar activity the fluxes in the inner radiation belt remain practically constant.

The segmented structure of the detector, in addition to measuring the total energy released, allows a very precise determination of the topology of the particle's path inside the instrument. By a dedicated off-line track selection algorithm (Bidoli et al., 2001) upward moving particles, nuclear interaction patterns and multiple tracks events are rejected. Energy, incident angle, charge and mass identification procedures are applied to events which survive the track selection algorithm.

Figure 1 (left) presents the mass distribution for $^3$He and $^4$He in the SAA region, for data collected in the time period considered. It is possible to see the good isotope separation, and the higher abundance of $^3$He with respect to $^4$He, in agreement with previous observations (Wefel et al., 1995). Figure 1 (right) shows the mass distribution for hydrogen isotopes.

The most delicate point in analyzing rare isotope abundances is to clarify whether these nuclei are particles really trapped or are due to secondary production inside the instrument. The detector is installed into a special vessel having a 300 $\mu$m aluminum window in correspondence of the telescope aperture. Our data of Solar Energetic Particle events confirm that the interactions of low energy protons and heliums with the aluminum window cannot produce a number of secondary $^3$He nuclei such as that observed in the SAA. Our average $^3$He/$^4$He ratio measured during SEP events was $\sim$ 0.01 (Sparvoli et al., 2001). However, the energy of protons trapped in the inner radiation belt extends up to 1 GeV; since the interaction cross section increases with energy, the contribution of the high energy part of the proton spectrum could be important.

In order to estimate the secondary isotope fraction, we utilized a method similar to that proposed by Looper et al. (1996) for PET telescope on board SAMPEX. In this technique we consider the first detector of NINA as a silicon target, and therefore we do not include it in the algorithms of track selection and mass reconstruction. The ratio between the particles produced in the silicon target (150 $\mu$m thick) and in the aluminum window is finally 0.43. In Figure 1 the shaded areas represent the background contribution calculated in this way, for helium (left) and hydrogen (right). The comparison between this contribution and the measured abundances shows that NINA detected real hydrogen and helium isotopes geomagnetically trapped.

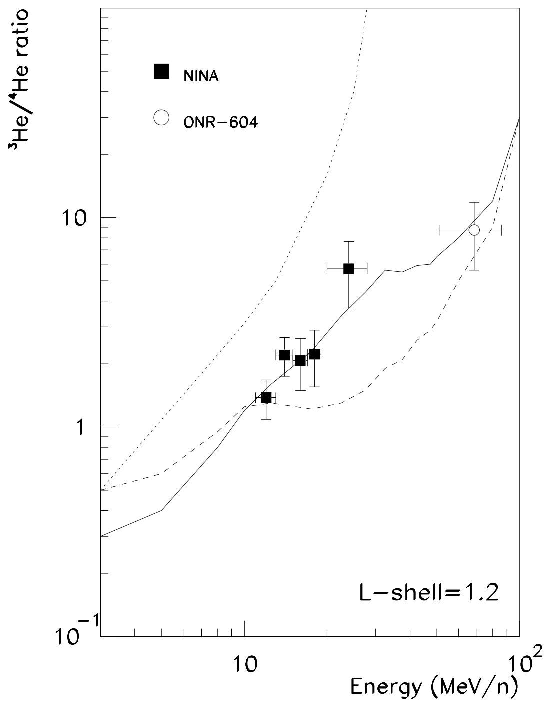

**Fig. 3.** $^3$He/$^4$He ratio measured by NINA (squares) at L-shell=1.2, and by ONR-604 (circle) (Wefel et al., 1995) for L-shell 1.1÷1.5. The dotted line represents the calculated ratio for the reaction $p + O$. The solid and dashed line represents the calculated ratio for the reaction $p + He$ at pitch angles $\alpha_0$=80° and $\alpha_0$=60° respectively (Selesnick and Mewaldt, 1996).

## 4 Results

The energy spectra of $^3$He and $^4$He obtained by NINA at L-shell 1.18÷1.22 and B<0.22 G are presented in Figure 2, together with the data of MAST on SAMPEX at L-shell=1.2. Fluxes are averaged over local pitch angles at $\sim$ 800 km and $\sim$ 600 km of altitude for NINA and MAST respectively. The $^3$He spectrum is fitted by a power-law with index equal to 2.30±0.08 in the energy range 12–50 MeV/n, while $^4$He has a spectral index of 3.4±0.2 in 10–40 MeV/n respectively. The NINA and MAST data have been gathered during quite different periods of the solar cycle; taking also into account the sharp decrease of the trapped particles flux near the edge of the radiation belts, they show a reasonable agreement.

The energy spectra of $^3$He and $^4$He presented in Figure 2 are in good agreement with calculations for atmospheric helium source (dotted and continuous line, for two different equatorial pitch-angles). The thick line is the sum of the $p + He$ and $p + O$ contributions, which seems to overestimate the $^3$He contents with respect to the experimental measurements. In figure 3 the ratio $^3$He/$^4$He as a function of energy is shown; the dotted line is the theoretical calculation for atmospheric oxygen source at $\alpha_0$=80°, as inferred from the work by Selesnick and Mewaldt (1996), while the solid and dashed lines correspond to the atmospheric helium source at two different equatorial pitch angles, $\alpha_0$=60° and $\alpha_0$=80°. From this picture it is possible to conclude that the model of proton interaction with oxygen in atmosphere overestimates the $^3$He production.

Our measured $D/p$ ratio is roughly equal to 1% at energy about 10 MeV/n, and it is close to that observed by PET instrument at 18–58 MeV/n (Looper et al., 1996). The calculation of Selesnick and Mewaldt (1996) predicts instead a ratio of about $10^{-3}$ at these energies, for L-shell=1.2. The deuterium flux computed by Spjeldvik et al. (1997) was also two times lower than that observed by SAMPEX. NINA measured $D/T$ ratio at 10 MeV/n is about 4.

## 5 Conclusion

Rare light isotopes represent a distinct component of the Earth's inner radiation belt. The data analysis performed by the detector NINA and the comparison with the available theoretical calculations bring to the conclusion that this component is originated from the interactions of high energy trapped protons with the residual atmospheric helium. At energy above 10 MeV/n the interaction with atmospheric oxygen is less important. The observed $D/p$ ratio at energy 10 MeV/n, however, is higher than calculated from atmospheric production models.

NINA-2 on board MITA is able to measure energy spectra of hydrogen isotopes in a broader energy interval (Casolino et al., 2001), and therefore can give important additional information about the sources of radiation belt light isotopes. NINA-2 analysis of geomagnetically trapped particles is in progress.

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