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MEASUREMENT OF THE ABSOLUTE PROTON AND HELIUM FLUX AT THE TOP OF THE ATMOSPHERE USING IMAX

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ABSTRACT

The balloon-borne experiment "IMAX" launched from Lynn Lake, Canada in 1992 has been used to measure the cosmic ray proton and helium spectra from 0.2 GeV/n to about 200 GeV/n. The IMAX apparatus was designed to search for antiprotons and light isotopes using a superconducting magnet spectrometer with ancillary scintillators, time-of-flight, and aerogel cherenkov detectors. Using redundant detectors an extensive examination of the instrument efficiency was carried out. We present here the absolute spectra of protons and helium corrected to the top of the atmosphere.

INTRODUCTION

Though protons and helium nuclei are dominant in cosmic rays (about 98%), their abundances are still not known precisely. Even at energies below 100 GeV/n, where direct measurements with balloon-borne magnet spectrometers are possible, published data show differences by a factor of two in the absolute fluxes. The main reason for these differences are most probably the uncertain detector efficiencies of the experiments. We will show that due to the redundant instrumentation of the IMAX experiment we can derive the detector efficiencies with high precision. Additionally solar modulation has a significant effect on particle fluxes at low energies. There is still great uncertainty how to describe this effect in full detail.

IMAX was launched from Lynn Lake, Manitoba, Canada on 16 July 1992. Float duration was ~16 hours at an average altitude of 36 km, with an atmospheric overburden of about 5 g/cm^2. Landing was near Peace River, Alberta, Canada. Over $3.5 \cdot 10^6$ events were recorded during float.

INSTRUMENT DESCRIPTION

IMAX measured the magnetic rigidity using a superconducting magnet spectrometer with drift chambers (DC) and multiwire proportional chambers (MWPC) as the trajectory measuring devices with the possibility of analyzing both detectors independently (Hof et al. 1994, Golden et al.1991). Using only the driftchambers, the MDR of the spectrometer was 180 GV for protons (240 GV for helium). Charge and velocity are determined with time-of-flight scintillation counters TOF1 and TOF2 (Mitchell et al. 1993). The time resolution was 130 psec for protons and 90 psec for helium. Further charge information is obtained with the two scintillation counters S1 and S2, using the dE/dx-β technique. The Cherenkov detectors C1, C2 and C3 were not used in this analysis. The IMAX instrument was triggered by a four-fold coincidence of photomultiplier (PMT) signals from the two TOF layers: two top PMT's and two bottom PMT's.

SELECTION CRITERIA

The data was recorded onboard and then sent to the control station on ground via telemetry; about 7% of the data were lost due to telemetry errors. Quality cuts were applied to this data to create a set of single, non interacting particles having either charge Z=1 or Z=2. Events with multiple tracks or particles undergoing inelastic interactions should be rejected. The following cuts were applied.:

- Tracking quality cuts: A minimum of 9 (out of 12) measurements in the X-coordinate and 6 (out of 8) in the Y-coordinate, $\chi^2 < 4$ for the X- and Y-coordinate (to remove low quality fits and events with inelastic interactions). To remove multiple tracks, a cut on the number of hits outside the track was applied.
- Single paddle hits in top and bottom TOF. This removes showers and multiple tracks.
- Three-fold charge selection with ToF1, S2 and ToF2. (S1 is only used for cross checks).

With the surviving events a raw rigidity spectrum is derived. We convert it to an energy spectrum (in GeV/n), taking all Z=1 particles as protons and all Z=2 particles as ^{4}He.

CALCULATION OF THE FLUXES „TOP OF INSTRUMENT"

The Z=1 data sample consists of hydrogen isotopes and the light particles μ, π and e^+. To get the pure proton spectrum, we corrected for this background, based on the spectrum of the light negative particles and the results of the IMAX ^{2}H/^{1}H analysis of Reimer et al. (1995). If the contamination of the light particles and deuterium is neglected, the proton flux will be overestimated by about 10-15 % at low rigidities. Above 5 GeV/n the ^{2}H/^{1}H ratio is assumed to have a constant value of 1.5%. Because we measure the rigidity (not energy/n), this converts to a ratio of ~5% for high rigidities.

At high energies we have a distortion of the measured spectra due to the limited spectrometer resolution. We corrected for this („Deconvolution"), though the effect was found to be small (about ± 5% between 50 GV and 250 GV) due to our high MDR of ~200 GV.

The flighttime was 55800 sec with a livetime of 74±1%. The geometry factor was derived with a Monte-Carlo simulation to 142±2 cm²sr at high rigidities (getting smaller for slower particles)

The most important part for the calculation of absolute fluxes is the knowledge of the detector efficiencies. IMAX with its various instruments has the big advantage that we are able to derive the efficiency of a device by using redundant detectors: We define a reference data sample with single, non interacting particles and then test the response of the specific device. The efficiency of the drift chamber was obtained using the MWPC to select particles. We show the response of the DC in figure 1. The efficiency is roughly 50%, with a decrease for low energies both for protons and helium. This is caused by the effect of multiple scattering, which increases the deviation from the fitted track and therefore χ^2. For protons one can see an additional dip at about 2 GeV. We explain this by energy dependent ionization which effects the efficiency of the single driftcell (with the ionization minimum at 2 GeV). This driftcell efficiency is directly reflected by the distribution of the number of hits in the DC, and the quality cuts applied to this distribution will reproduce the energy dependent shape of the driftcell efficiency. For Z=2 particles the efficiency was at its upper level due to the

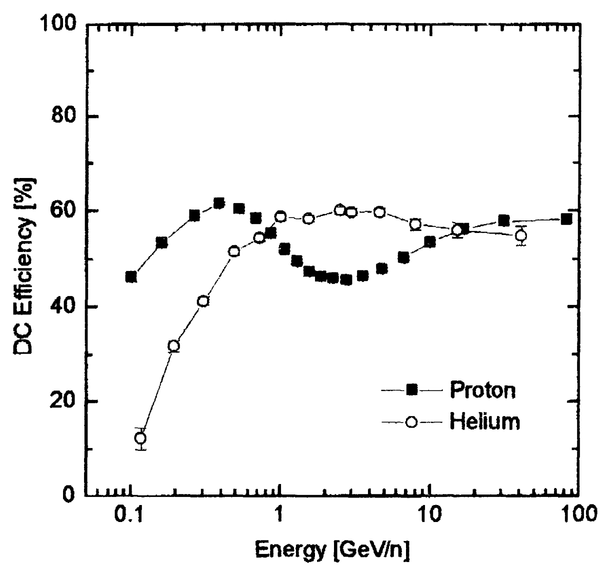

Fig. 1. The detection efficiency of the DC for protons and helium

higher ionizaton rate of Helium and did not show significant variations. Additional checks ensured us that the error in the presented DC detection efficiency is not larger than ±5%.

The efficiency of the charge selection is derived by selecting Z=1 or Z=2 with a three fold consistency using only three of the four scintilllators. (misidentification probability only ~10^{-4}). Now the fourth scintillator is checked for its response. We derived energy dependent detection efficiencies of around 95%-98%, with slightly different values for each detector.

The effects of inelastic interactions in the instrument (mass-changing spallation, scattered flightpath without producing new particles, etc.) are complex, because the various IMAX detectors will respond to these interactions in a different manner. We estimated the rejection power by making the reasonable assumption that all inelastic interactions are recognized and vetoed by our quality cuts. The interaction probability was then calculated using the total inelastic cross sections for protons (and helium) on nuclei with the IMAX detector material as an input. The highest probability with all the material above the lower TOF (16.8 g/cm²) is used as an upper limit, the lower limit is set by the amount of material above the spectrometer(11 g/cm²). For further calculations we use the average of these two values (~20% loss for protons, ~40% loss for helium) and use the limits to estimate the uncertainties (± 3% for protons, ± 7% for helium).

CORRECTION TO „TOP OF ATMOSPHERE"

After calculating the fluxes at the top of the instrument we have to correct for interactions in the residual atmosphere (5 g/cm²). Both for protons and helium there are losses due to inelastic interactions. With a similar calculation to that for the instrument we find a 5% loss for protons and 12% for helium.

There is an enhancement in the proton flux due to atmospheric secondary protons, we used the theoretical calculations of Papini et al. (1996). We assumed a solar modulation of 750 MV (estimated by using the results of other experiments and the actual neutron monitor counts) to find the appropriate secondary fluxes for the IMAX flight. The secondary to primary proton ratio is small (around 1%) for higher energies, but rises dramatically for lower energies. Below ca. 200 MeV the secondary protons even dominate the proton sample. We applied an uncertainty of 20% to the secondary/primary ratio and finally present the IMAX fluxes "Top Of Atmosphere" in figure 2, the actual values are shown in Table 1. In figure 3 we compare the IMAX fluxes with the results of Seo et al. (1992) and Webber et al. (1987). While these measurements represent the lower and upper bounds in the proton flux, the IMAX flux is right between these limits.

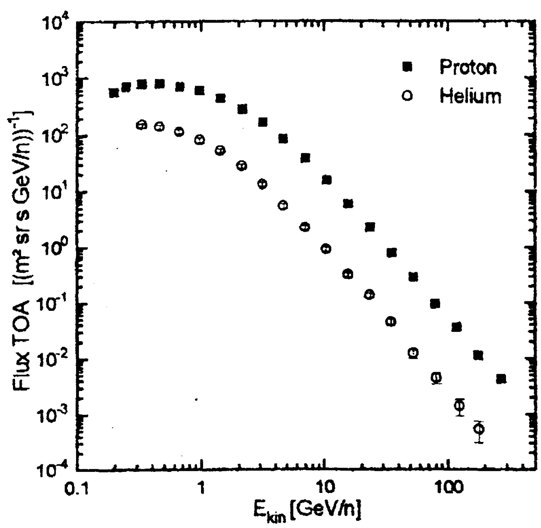

Fig. 2. IMAX proton and helium fluxes TOA

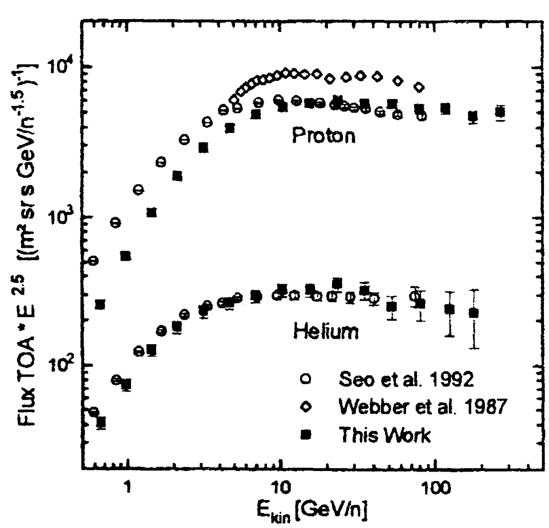

Fig. 3. IMAX proton and helium fluxes TOA compared with other balloon measurements

It is a difficult task to present a reliable result for the interstellar spectral index, because even at energies around 20 GeV/n the influence of the solar modulation is not negligible. Therefore the IMAX TOA energy spectra were demodulated using the „Force-Field" method by Axford and Gleeson (1968), and then converted to rigidity spectra. The best agreement with a pure power law proton spectrum in rigidity is derived using ϕ=800 MV for the solar modulation parameter (in good agreement with our estimate above). The results are presented in figure 4. Both spectra are in good agreement with a pure power law, with only small differences at low rigidities for the helium spectrum. If we fit the data between 20 GV and 150 GV, we get a spectral index of 2.70±0.06 for protons and 2.76±0.10 for helium.

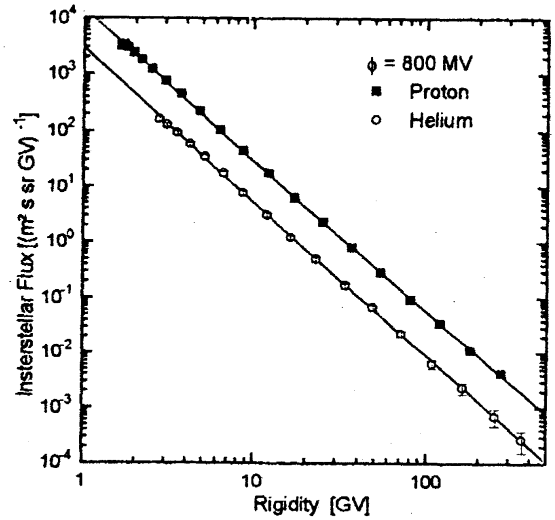

Fig. 4. Interstellar rigidity spectra for a solar modulation parameter of ϕ=800 MV

Table 1. IMAX proton and helium fluxes (particles / m² sr s GeV/n) „Top of Atmosphere"

E_k (GeV/n)	Proton Flux	Helium Flux	E_k (GeV/n)	Proton Flux	Helium Flux
0.20	$(5.64\pm0.66)\cdot10^{2}$	-	7.04	$(3.71\pm0.24)\cdot10^{1}$	2.27 ± 0.21
0.25	$(7.05\pm0.66)\cdot10^{2}$	-	10.5	$(1.54\pm0.10)\cdot10^{1}$	$(9.33\pm0.91)\cdot10^{-1}$
0.33	$(7.90\pm0.58)\cdot10^{2}$	$(1.50\pm0.14)\cdot10^{2}$	15.7	5.89 ± 0.38	$(3.25\pm0.34)\cdot10^{-1}$
0.46	$(7.87\pm0.52)\cdot10^{2}$	$(1.39\pm0.12)\cdot10^{2}$	23.6	2.24 ± 0.15	$(1.35\pm0.15)\cdot10^{-1}$
0.66	$(7.11\pm0.46)\cdot10^{2}$	$(1.14\pm0.10)\cdot10^{2}$	35.3	$(7.78\pm0.51)\cdot10^{-1}$	$(4.51\pm0.60)\cdot10^{-2}$
0.97	$(5.87\pm0.38)\cdot10^{2}$	$(8.01\pm0.72)\cdot10^{1}$	53.0	$(2.82\pm0.19)\cdot10^{-1}$	$(1.25\pm0.22)\cdot10^{-2}$
1.44	$(4.35\pm0.28)\cdot10^{2}$	$(5.21\pm0.47)\cdot10^{1}$	79.4	$(9.42\pm0.69)\cdot10^{-2}$	$(4.53\pm1.04)\cdot10^{-3}$
2.13	$(2.83\pm0.18)\cdot10^{2}$	$(2.78\pm0.25)\cdot10^{1}$	118.5	$(3.49\pm0.28)\cdot10^{-2}$	$(1.38\pm0.45)\cdot10^{-3}$
3.16	$(1.62\pm0.10)\cdot10^{2}$	$(1.31\pm0.12)\cdot10^{1}$	177.8	$(1.12\pm0.11)\cdot10^{-2}$	$(5.30\pm2.21)\cdot10^{-4}$
4.71	$(8.11\pm0.52)\cdot10^{1}$	5.53 ± 0.51	270.4	$(4.19\pm0.49)\cdot10^{-3}$	-

DISCUSSION AND CONCLUSION

We presented the absolute fluxes of protons and helium at the top of the atmosphere. The quality of the IMAX spectrometer is superior to former measurements. Using redundant detectors, we could determine the detector efficiencies with high precision. If the TOA spectra are demodulated with a solar modulation parameter of ϕ=800 MV, the proton and helium spectra can be represented by a power law in rigidity.

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