The Alpha Magnetic Spectrometer (AMS-02)

Seminar Ib

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ABSTRACT

The Alpha Magnetic Spectrometer (AMS-02) is a large particle physics detector mounted at the International Space Station. It consists of many different sub-detectors. For the determination of properties of charged particles the Time of Flight detector, the Transition Radiation Detector and the Silicon Tracker are used. Each of these detectors contributes to the measurements of charge sign, mass or momentum of the incoming charged particle.
INTRODUCTION

The Alpha Magnetic Spectrometer (AMS-02) is a large particle physics detector mounted at the International Space Station at an altitude of about 300 km. It has been operating since 2011 and will continue operating until 2020 or even longer [1, 2].

\[\text{Figure 1. The Alpha Magnetic Spectrometer at the International Space Station [3].}\]
The main task of AMS-02 is to search for cosmic antimatter and dark matter and to study the properties of cosmic rays. The spectrometer can detect charged particles and nuclei as well as γ rays over large energy range (from a few hundred MeV up to the TeV energies). The detector is designed also for searching anomalies in antiparticles and photon spectra in order to find indicators of (so far) unknown matter in the Universe [2].

2 ALPHA MAGNETIC SPECTROMETER DETECTOR

The Alpha Magnetic Spectrometer consists of many different detectors as seen in Figs. 2 and 3.

![Figure 2. The AMS detector](image)

The detector system includes [2,5]:

- Transition Radiation Detector (TRD);
- Time of Flight Detector (TOF);
- Silicon Tracker (Tracker);
- Anti-Coincidence Counter (ACC);
- Magnet (MG);
- Ring image Cherenkov Counter (RICH);
- Electromagnetic Calorimeter (ECAL);
- Tracker Alignment System (TAS);
- Star Tracker and GPS;
- Electronics.

All but the last three parts are shown in Fig. 3.
Figure 3. The detailed scheme of split AMS detector system [6]. The size of the detector system is 5 m $\times$ 4 m $\times$ 3 m.

The magnet in the detector is important to bend the track of opposite charged particles into different directions which helps to separate between matter and anti-matter. Particle charge sign is then detected in Silicon Tracker.

The Time of Flight detector triggers the measurements of all other sub-detectors in the system. Transition Radiation Detector can distinguish massive and light particles. For measuring the energy of incoming electrons, positrons and $\gamma$-rays, the Electric Calorimeter is used. For measuring the velocity of cosmic-rays, AMS-02 uses the Ring-Imaging Cherenkov Detector.

Also the other parts of the detector system are important. Electronics transform detected signals into digital information, Star Tracker and GPS define position and orientation of the AMS-02 system and the Tracker Alignment System checks the Tracker alignment stability [5]. The Anti-Coincidence Counter is used to reject cosmic rays that leave or enter the AMS-02 through inner shell of the magnet, and protects the detector system against misidentification of matter nuclei as antimatter nuclei [4].
3 IDENTIFICATION OF CHARGED PARTICLES IN AMS

Different particles leave different tracks in the detector system as seen in Fig. 4.

The most important sub-detectors for the detection of charged particles in AMS-02 are the Transition Radiation Detector (TRD), the Time of Flight (ToF) detector and the Silicon Tracker.

The trajectory of charged particles passing the AMS detector system. The parts of the detector: a) the TRD, b) the ToF, c) the magnet, d) the Silicon Tracker, e) the RICH, f) the ECAL [4].

Figure 4. The tracks of different particles in the AMS-02 sub-detectors [7].

Figure 5. The trajectory of charged particles passing the AMS detector system. The parts of the detector: a) the TRD, b) the ToF, c) the magnet, d) the Silicon Tracker, e) the RICH, f) the ECAL [4].
3.1 Time of Flight Detector

3.1.1 Operation of Detector

The Time of Flight detector's main goal is to warn the other sub-detectors about the incoming cosmic rays. It can also measure the transit time of particles with high precision. For charged particles the ToF represents the trigger that warns all other detectors to start measuring signals.

Other important task of the ToF detector is distinguishing between upward going electron and downward going positron. Both of these particles give same trajectory in a magnetic field so there is a need of a system that can tell the difference in the direction of the particle and consequently of the charge sign. This distinction is important for antimatter detection.

The ToF system can also be used to determine the absolute charge of the particle which is used for the determination of nuclei of different chemical elements.

The ToF system measures two signals - the initial time when the particle enters the detector and the final time when the particle leaves the detector. The difference of these two times is used for the calculation of particle velocity. The ToF system in AMS can reach the accuracy of time measurement of 150 ps. As seen in Fig. 3, the two ToF detectors lie above and under the main detector system. Their distance is around 1.2 m; as a consequence, the system can measure particle velocity up to 98% of the speed of light [8].

3.1.2 Detector Design

The ToF detector at AMS-02 consists of 4 planes of scintillator counters. In Fig. 3 one can see that two of these scintillation counters are above and two below the magnet.

![Figure 6. The Position of the scintillator paddles in the ToF detector of the AMS detector system [9].](image-url)
The upper two planes contain 8 scintillator paddles. The lower two contain 10 and 8 scintillator paddles aligned along the x and y coordinates respectively [8]. The position of scintillator paddles in each counter is shown in Fig. 6.

Figure 7. The construction of scintillator paddle in ToF detector in AMS detector system. The length of paddle is 12 cm [10].

3.1.3 OPERATION OF THE SCINTILLATOR PADDLE

A charged particle passing through a scintillator causes molecular excitations in the medium. Molecules come to the ground state very quickly and emit fluorescence light. This light is detected by a photo-multiplier tube (PMT) that converts it into electrons through the photo effect. Produced electrons are multiplied in a series of electrodes, so called dynodes. At the end of the electrode chain the initial signal is multiplied by a factor of up to $10^8$.

In the AMS-02 ToF system a special type of PMTs are used. They are called fine-mesh PMT and have a compact dynode structure that reduces the influence of the stray magnetic field. The angle between PMTs and magnetic field is optimized so that the effect on multiplication is minimal [8].

3.2 THE TRANSITION RADIATION DETECTOR (TRD)

3.2.1 TRANSITION RADIATION

Transition radiation is the electromagnetic radiation emitted when a charged particle passes the boundary of two media with different indices of refraction. The emission rate becomes important at the Lorentz factor $\gamma \sim 1000$. Electrons therefore start to emit X-rays at an energy of 0.5 GeV. For TRD detectors stacks of thin foils or porous materials are used because the emission probability per single boundary is low, approximately $\alpha = 1/137$. The emission angle for transition radiation is about $1/\gamma$ and the energy of X-rays is about 10 keV.

For detection of emitted X-rays a wire chamber with a high Z gas (with high probability for photo effect) in the gas mixture is needed. The X-rays produce photoelectrons in gas, which, in turn, ionize molecules of gas that trigger the ionization cascade. The hits from transition radiation photons are separated from ionisation losses by using two thresholds - the lower threshold for ionisation losses and higher threshold for X-ray detection. The ionisation losses
are spread out along the track and the X-ray hits deposit high energy on one place [11]. The principle of detection is shown in Fig. 8.

3.2.2 Operation of Detector

A disadvantage of most particle identification detectors is that they cannot separate light particles at very high velocities. Also the Time of Flight and the Ring-Image Cherenkov Counter cannot separate between these particles. The Transition Radiation Detector sensor is sensitive to particles with a Lorentz factor gamma beyond 1000. A TRD detector can therefore be used for detection of light particles by emission of transition radiation X-rays.

These measurements are most important in searches for dark matter where we are looking for positrons from dark matter annihilation. Since we are looking for positrons, it is important not only to separate between electrons and positrons but also between positrons and protons [12]. The principle of operation is shown in Fig. 8.

![Figure 8. Principle of operation of the Transition Radiation Detector (TRD) in the AMS Spectrometer [13].](image)

At high energies electron (or positron) emits and proton does not emit X-rays while crossing the TRD detector. X-rays are detected in straw tubes filled with a Xe-CO₂ mixture as seen in Fig. 8. The X-ray ionizes molecules of gas and they trigger the ionization cascade in the gas mixture, and an electric signal occurs that indicates the detected X-ray. The signal is significantly higher if a charged particle and the X-ray pass through the tube instead of only a charged particle [12].

3.2.3 Detector Design

A TRD detector is placed on the top of the detector system as seen in Fig. 3. It is made up of 328 modules arranged in 20 layers supported by a conical octagon made of aluminium and carbon-fibres. Each module consists of 16 tube straws filled with a gas mixture of 80% of xenon and 20% of carbon dioxide with a high efficiency for X-ray conversion. Straw tubes operate at voltages up to 1600 V. Another part of the TRD system is a 20 mm thick radiator made of a plastic foam with a very low density of 0.06 g/cm³. The radiator has many interfaces with a different index of refraction which increase the probability for production of X-rays.
The straw tubes are made of about 10 000 separate pieces and need to be gas-tight in a vacuum, representing a challenge for their production. Another need for accuracy presents the gas mixture. The ratio between the two gases must be very accurately regulated with a deviation of less than 1 %. Furthermore, the gas mixture has to be extremely clean - the contamination limit is 1 ppm\textsuperscript{1}. To ensure that there is no leakage, the pressure is monitored at all times.

To ensure that the detector is constantly filled with a clean gas mixture, the AMS spectrometer has a gas circulation system that can decant 7 litres of gas mixture per day which is a bit more than 2 % of the detector volume. Within the TRD, the gas mixture is flowing in a monitored closed circuit that controls its properties continuously \cite{12}.

3.3 THE SILICON TRACKER (THE TRACKER)

3.3.1 OPERATION OF DETECTOR

The Silicon Tracker can determine the charge sign of incoming particle from its trajectory. This is important for the separation of matter from antimatter. It is also used for the determination of the direction and the momentum of the incoming particle.

The tracker is the main part of the AMS-02 detector. As seen in Fig. 3, it is positioned in the middle of the system and surrounded by a magnet. It measures the curvature of the incoming particles. With higher energy the curvature gets lower and vice versa. It is the only sub-detector in AMS-02 that can directly distinguish between particles and antiparticles from the direction of the curvature. A positive and a negative particle have opposite directions of curvature due to the deflection in the magnetic field. From the measured incoming direction and momentum it is possible to separate galactic cosmic-rays from particles trapped in the geo-magnetic field.

The tracker can also determine the absolute charge of the particle together with the ToF and RICH detectors by measuring its rigidity. This contributes to the detecting of different chemical elements \cite{13, 14}.

![Figure 9. The Silicon Tracker in AMS-02 \cite{16}](image)

\textsuperscript{1} part per million
3.3.1.1 MEASURING THE RIGIDITY

The rigidity $R$ is defined as the momentum of the particle divided by its absolute charge $q$: $R = p/q$. Rigidity can be determined from the curvature of the trajectory with relation $R = Br$, where $B$ is the magnetic field density and $r$ is the curvature. The absolute charge is measured in the ToF detector, and together with curvature measured in the tracker determines the particle momentum.

In reality $B$ and $r$ cannot be measured so simply. There are some anomalies in magnetic field that need to be taken into account. Another uncertainty comes from the fact that initial direction does not coincide with incoming direction because particles can scatter on different materials in AMS-02 detector [15].

3.3.1.2 MEASURING THE POSITION

The tracker measures 8 positions along the track. From these 8 points the best circular trajectory is determined. Each position is measured with a high precision of 10 μm. The maximum rigidity that can be measured in a detector system depends on the precision of measured positions. The Maximum Detectable Rigidity (MDR) at AMS-02 is very high, about 2 TeV.

As in many other detectors the double-sided micro-strip silicon sensors are used in the AMS-02 tracker to measure the position of the particle passing the detector. Detectors are made of high purity doped silicon and are 300 μm thick. When a charged particle crosses the strip detector, many thousands of electron-hole pairs are created. These particles start to drift in opposite directions due to electric field in the detector. When charges drift towards the electrodes, they generate an electric signal on the strips [13, 14]. The principle is shown in Fig. 10.

![Figure 10. The principle of measuring position with micro-strip detector. The detector is 300 μm thick and made of silicon [17].](image)
3.3.2 DETECTOR DESIGN

The AMS-02 silicon tracker is the largest precision tracker ever built for operating in space. The effective sensible area of the tracker is 6.2 m². It consists of 2264 silicon sensors with a surface of 72×41 mm² each. The read-out system is composed of 192 units that contain about 200,000 read-out channels. The electronics has a very low power consumption and noise and a large dynamic range. The problem of such a huge read-out system is a large quantity of heat which has to be removed. Therefore the read-out system is cooled with the Tracker Thermal Control System (TTCS) [13, 14]. The operating temperature of tracking system is between -10°C and +25°C [14].

For cooling in space there are again some limits. No atmosphere means that fans cannot be used for cooling. The most appropriate way is the transfer of heat from the electronics to a radiator. Two large radiators with a possibility of radiating about 10 times more heat than it is produced are installed at two positions in the detector system. As seen in Fig. 3, these radiators are not directly coupled to the tracker so the Tracker Thermal Control System is used for transferring the excess heat. For the cooling system the loops filled with high pressure liquid carbon dioxide are used. The gas in system transits between fully liquid and liquid/gas phase while transferring the heat from the detector to the radiator [15].

4 CONCLUSIONS

The Alpha Magnetic Spectrometer is a large detector system in the International Space Station. Its main goals are to search for antimatter and dark matter in the Universe.

The AMS-02 consists of many sub-detectors that all together present an accurate system to measure many properties of particles, such as mass, charge sign, velocity etc. Due to its complexity and the fact that it is positioned hundreds of kilometres above the surface of Earth the construction of the detector was very challenging.

So far the AMS experiment has measured billions of high energy cosmic rays. One of the results is the positron fraction (the ratio of positron and electron particles) in the energy range

![Figure 11. Positron fraction measured in different experiments [18].](image)

So far the AMS experiment has measured billions of high energy cosmic rays. One of the results is the positron fraction (the ratio of positron and electron particles) in the energy range...
from 0.5 to 350 GeV. As seen in Fig. 11, the results from the AMS are much more precise and accurate than results from previous experiments [18].

It will operate for many years to come and hopefully give much useful information to help us expand our knowledge and deepen our understanding of structure and evolution of the Universe.

5 LITERATURE