Astroparticle Physics

Ad van den Berg & Olaf Scholten
Kernfysisch Versneller Instituut
NL-9747 AA Groningen

Exam, November 2, 2010.
5 problems (total of 130 points).
Write the solution of every problem on a separate piece of paper with name and student number.

Write clearly, it should be readable.

Problem 1 (40 pnts in total)
In Cosmology one distinguishes four different terms in the total energy density; namely the matter, the radiation, the vacuum, and the curvature terms.

10 pnts a. Give for each of the 4 types of energy density their scaling with red-shift z and their distinguishing features.

8 pnts b. What is the experimental evidence that a large fraction of the total energy content of the Universe has to be attributed to dark energy?

2 pnts c. How large is the fraction of dark energy?

5 pnts d. Describe how Zwicky proved evidence for the existence of dark matter, in particular the role played by the virial theorem in this proof.

5 pnts e. Describe the DAMA experiment.

5 pnts f. Give an estimate for the count rate in the DAMA experiment using the numbers given in the table at the end of this exam. Assume for the dark matter particles a mass of $m_{DM}c^2 = 22$ GeV, for the molecular weight of NaI=150 g, and an interaction cross section of dark matter particles of $\sigma_{DM} = 10^{-39}\,\mathrm{cm}^2$. Make reasonable estimates for numbers that are not given.

5 pnts g. What will be the fate of the Universe?

cooling down, flat : everything moving to a point

Problem 2 (20 pnts in total)
After the Big Bang, the Universe expanded and cooled.

7 pnts a. Name at least seven consecutive phases after the Big-Bang.

7 pnts b. Give the temperature or energy scale for each of these phases.

6 pnts c. What happened 300,000 years after the Big Bang and why then.

matter - radiation / decoupling
equality

$m^{-3} \cdot m^2 \cdot ms^{-1}$

Problem 3 (20 pnts in total)
The formation of nuclei in an early phase in the development of the Universe helps to determine some crucial cosmological parameters.

7 pnts a. Why are the primordial nuclei limited to isotopes of hydrogen, helium and lithium?
temperature dropping, freeze-out

7 pnts b. Which primordial nucleus is the most sensitive probe for the baryon density of the Universe and why?
deuterium

6 pnts c. How does one determine the relative abundance of this nucleus?

Problem 4 (30 pnts in total)
High-energy cosmic rays must be related to some of the more violent astrophysical processes. The flux of cosmic rays changes over many orders of magnitude as function of the energy.

8 pnts a. Give an approximate relation between flux and energy of cosmic rays. Sketch the flux spectrum and give an indication of the units on the axes and their orders of magnitude.
$E^{-2.7}$ 10^{15}eV $E^{-3.0}$ $4\cdot10^{18}$eV $E^{-2.6}$ $4\cdot10^{19}$eV $E^{-4.0}$

8 pnts b. Describe the generic process which is used to model the acceleration mechanism of cosmic rays.
Fermi acceleration

4 pnts c. Where could this process occur in the Universe?
shock fronts of super novae

7 pnts d. What is the GZK process? Describe which particles interact in this process and which reaction products can emerge from this process.
$p^+ \gamma \rightarrow n + \rho$

3 pnts e. What part of the cosmic ray flux spectrum will be affected by the GZK effect and how.
$> 4\cdot10^{19}$ eV

Problem 5 (20 pnts in total)
At a certain stage in the evolution of the Universe matter starts to dominate over anti-matter.

4 pnts a. Name the Sakharov criteria.
B violation
non-eq. processes
CP and C violation

8 pnts b. Give the importance of each of these criteria.

8 pnts c. Name two different experiments tailored to the detection of cosmological anti-matter and describe how they work.
AMS Moon
Satellite with big magnet

Some numbers
Proton mass: $m_p c^2 = 0.938\,\text{GeV}$ where $1\,\text{eV/c}^2 = 1.78 \times 10^{-36}\,\text{kg}$
Boltzmann's constant: $k = 8.62 \times 10^{-11}\,\text{MeV/K}$
Avogadro's number: $N_A = 6 \times 10^{23}\,/\text{mol}$
Solar Mass: $\text{M}_\odot = 1.99 \times 10^{30}\,\text{kg}$
Parsec: $1\,\text{pc} = 3.1 \times 10^{16}\,\text{m}$
Velocity of Sun w.r.t. center Milkyway: $V_\odot = 270\,\text{km/s}$
Velocity of Earth in orbit around the Sun: $V_\oplus = 30\,\text{km/s}$
Typical galactic dark matter density: $\rho_{DM} = 9\,\text{k}\,\text{M}_\odot/\text{pc}^3$