SOURCES OF PARTICLES AND RADIATION, DETECTORS AND SENSORS

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Contents

Summary

The sources of particles and radiation are reviewed. Because most unstable particles and radiation have to be created with the use of accelerated stable particles special emphasis is put on the description of accelerators. To detect the generally high energetic particles and radiation special detectors were constructed. These rely on the interaction of radiation with matter which is briefly described. The most common detector types are reviewed. Some applications of particles and radiation are mentioned throughout the text.

1. Source of Particles

The term particles are used here to classify all entities which have sizes equal to or smaller than atomic nuclei. They include the basic constituents of matter: the proton, the neutron and the electron; all atomic nuclei; but also some exotic particles: muons, positrons, antiprotons, etc. Many particles are unstable and need to be created by a source. Among unstable particles is the neutron, which is only stable when bound in an atomic nucleus. The kinetic energy of the particles is an important quantity for a source of particles. The energy is expressed in electron-volts which is the energy of an electron accelerated by a potential of one volt (1 [eV] = 1.602 10^{-19} [joule]), using standard abbreviations: neV, μeV, meV, eV, keV, MeV, GeV, TeV each of which differ by a factor of 1000. An omnipresent but rather unpractical source of all the above mentioned particles are the cosmic rays, which are composed of ultrarelativistic particles, mainly protons, from outer space that hit the earth`s atmosphere with energies attaining hundreds of TeV. In the early 20th century the study of cosmic rays permitted the discovery of many new particles, amongst which is the antiparticle of the electron: the positron. Since the 1930, the development of particle accelerators has permitted scientists to have reliable sources of energetic particles at their disposal. These particles are often used for fundamental research but also for many other applications, for instance trace analysis or cancer treatment. An important property characterizing the source is the distinction between electrically charged particles which can be relatively easy manipulated and uncharged particles like the neutron. As a result of this fundamental difference we will discuss neutron sources separately.

1.1 Particle Accelerators

Most charged particles are accelerated to the desired energy or are obtained by creating them using nuclear reactions induced by accelerated particles (note that this is needed to overcome the Coulomb repulsion between the positively charged atomic nuclei). The devices which perform this task are called accelerators. Many types of accelerators exist and they can be very small (the television tube) to extremely large (the SPS accelerator at CERN (Geneva) has a diameter of 2.2 km). For electron accelerators, a heated filament provides the free electrons which are then extracted under vacuum using an applied electric field. For the other stable particles one ionizes the atoms either negatively or positively, in what is called the ion source. Positive ionization makes it possible to obtain highly charged atoms and is preferred whenever possible. As the particles are charged they may be guided using electric and magnetic fields toward the accelerating devices. The most simple electron accelerator consists of a cathode made by the filament and an anode put at a positive high voltage U. The liberated electrons are then accelerated from the cathode towards the anode and attain an energy of eU [eV]. Many different types of anode are used. Some anodes are made such that the electrons are completely stopped (television tube or X-ray tubes) or they might form the sample to be studied like in the electron microscope. Mostly, the particles are further accelerated and they pass easily through the anode, which is made of a grid, to enter a second accelerating device.

It is clear that the high voltage determines the final energy of the particle. Electrostatic accelerators work simply by establishing a constant high-voltage difference. The most widely used accelerators in the MeV domain are based on the Van de Graaff generator which can provide a stable positive voltage U of several megavolts on what is called the terminal, which contains the ion source. Using positively charged ions with charge +q, the end energy is then qU [eV]. In the Tandem accelerator the ion source is not installed at the terminal which leads to technical complications. Instead, the terminal is charged by a Van de Graaff generator to a positive voltage U. By using a negative ion source at the ground and a stripper foil installed at the terminal which transforms the negative ions into positive ions with charge state +q by removing the outer electrons, a final energy of (1+q)U [eV] can be reached. Van de Graaff generators are relatively cheap and easy to use. Therefore they can be operated at universities or small research facilities. They are mainly used to accelerate light ions to some tens of MeV and heavy ions to about 100 MeV. One of their most important properties is the stability of the terminal voltage, which make them very well suited for atomic mass spectroscopy.

Linear accelerators form a second class of particle sources. They rely on drift tubes across which a high frequency (100 MHz) high voltage is placed in AC mode either directly or via accelerating cavities filled with high power electromagnetic waves. Particles entering the first drift tube at the right moment can traverse all the drift tubes such that they always will find the next tube at a higher voltage and are accelerated further (the repulsive phase happened when they were shielded in the tube). In the non-relativistic regime the length of the drift tubes needs to be varied in order to compensate the increase in velocity. When reaching relativistic velocities this is not needed anymore, but the main problem is the need to use very high frequencies (10 GHz) in order to keep the dimensions of the accelerator small. They are in the microwave domain and are created in powerful klystrons or magnetrons. For electrons, which are about 2000 times lighter than protons, velocities close to the speed of light are very quickly reached (a 1-MeV electron attains already 94% of the velocity of light). The requirements of this technique make it clear that these particle sources produce pulsed beams of particles. The longest linear accelerators attain lengths of several kilometers. An advantage of linear accelerators is that there is no energy limitation, except the costs due to the increasing length.

An alternative is to accelerate the particles using a circular structure. In this case the particles pass several times through the same accelerating cavities and gain some energy each time until they reach the final energy and are extracted from the accelerator. The classical example of a circular machine is the cyclotron. A constant magnetic field keeps the particles in circular orbits with a radius proportional to their velocity and mass so that the time needed to make a complete turn stays constant. Therefore one can apply a high frequency electric field in between two D-shaped cavities placed inside the magnet, which allows to accelerate the particles twice during an orbit. Cyclotrons can accelerate light and heavy ions to several tens of MeV and deliver intense beams of the order of 100μA. They are extensively used for medical applications. The maximum end energy of a classical cyclotron is limited due to relativistic effects. When the particles are accelerated to several percent of their rest mass energy (932 MeV for a proton) their mass increases and this must be compensated by a radial increase of the magnetic field. This is attained in the isochronous and azimuthally varying field (AVF) cyclotrons, that can deliver intense proton beams up to 600 MeV. The high intensity is important because the proton beam may be used to create new particles that form secondary beams and because such beams might be needed for nuclear waste transmutation.

When higher energies are needed, the limit of magnetic field strength makes it necessary to increase the radius of the orbiting particles. It then becomes more practical to built the accelerator in the form of a ring containing straight accelerating sections and magnets which bend the beam. The radius of the accelerator being fixed, the magnetic field should vary synchronously with the increasing energy of the particles. In this case one speaks of a synchrotron. Synchrotrons can attain energies of TeV for protons and of several GeV for electrons. The energy of the latter is limited by the increasing energy loss due to synchrotron radiation (see synchrotron radiation). Once the final energy is attained the particles are often stored in storage rings in which they are held for further use. The LEP storage ring of CERN is the largest in the world with its length of 27 km.

Energetic stable particles enable the creation of unstable particles. Therefore accelerators often serve just to initiate this process. At low energies the particles bombarding a target provoke nuclear reactions which lead to the creation of unstable nuclei. These radioisotopes can be used as tracers, in nuclear imaging and for cancer treatment. Presently there is a strong scientific interest in accelerating these isotopes as a Rare Isotope Beam (RIB) and many RIB facilities are under construction. The interest of such a beam is that a RIB permits the study of nuclei still further away from stability, which are important for astrophysics and the understanding of the nuclear many-body problem. At higher energy the particle beams can be used to create more exotic particles: muons, pions, and antiprotons. These exotic particles are extracted using magnetic fields and guided to the experimental halls. Most of these particles are short lived. They have been extensively used as tools to study materials (muon spin resonance) and pion beams have even been used for cancer treatment.

Sources of the antiparticle of the electron, the positron, are a special case. Positrons are generally obtained from unstable nuclei undergoing beta decay, which transforms a proton into a neutron, neutrino and a positron. An example is ^{22}Na, which decays with a half life of 2.6 years and can be created by bombarding ^{24}Mg with 5.2 MeV deuterons. Another method relies on the pair-production process and requires a high-intensity photon source with energies well above 1 MeV (see bremsstrahlung). Positrons are used in imaging (see the PET camera) and solid state physics.

Most high-energy accelerators can only accept particles having attained a high energy. Therefore high-energy facilities operate a series of accelerators each adapted for their energy domain. An illustrative example of such a facility is given in Fig. 1 which shows the accelerators of the Paul Scherrer Institute. Two injectors, of which one is a fixed-energy cyclotron can be used either for low-energy experiments, radioactive isotope production, cancer treatment or to feed the AVF cyclotron. The AVF cyclotron can deliver 2mA proton beams of 590 MeV (the world`s most intense beam). They are used for experiments and cancer treatment or to generate subsequently pions, muons and finally neutrons, which are guided to their own experimental areas.

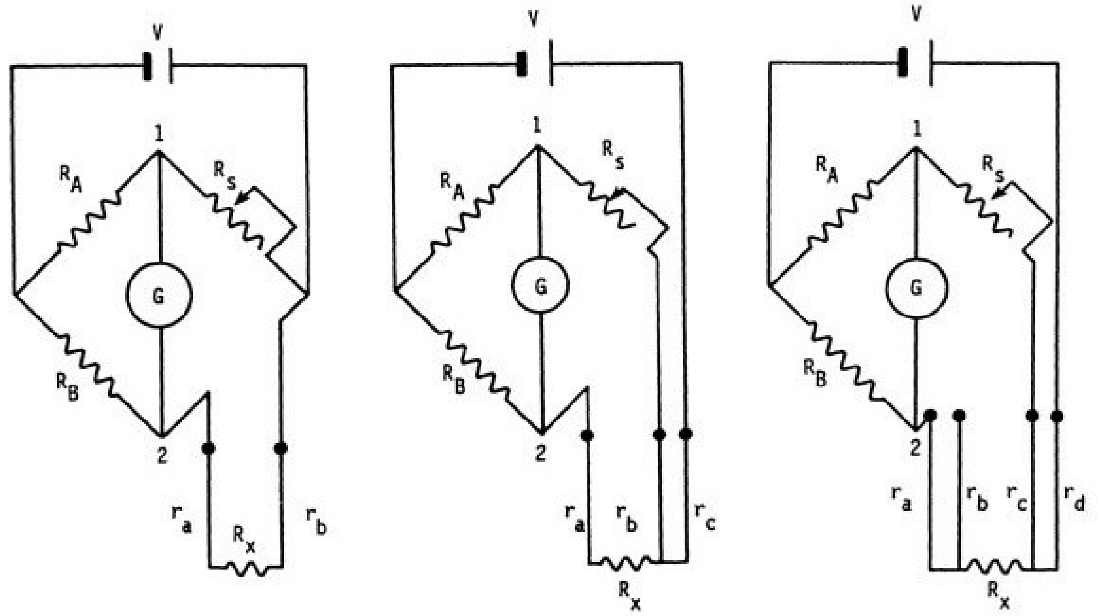

Figure 1: Accelerator complex of the Paul Scherrer Institute (Villigen, Switzerland).

(see: “*Radiation Therapy*”, bremsstrahlung, PET camera)

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Biographical Sketch

Jan Jolie is full professor at the University of Cologne (Germany). He received his degrees from the University of Gent in Belgium (PhD in 1986). He is working in the field of nuclear physics. His research interest were first in the theoretical description of atomic nuclei using dynamical symmetries and supersymmetries. After receiving his PhD in Gent he went for five years to the Institut Laue Langevin in Grenoble (France). There he started to work on experimental methods using the neutrons from the nuclear reactor. In 1992 he moved definitely to experimental physics by accepting a post as first assistant at the University of Fribourg (Switzerland). In his Swiss period he worked on in-beam gamma-ray spectroscopy and cold neutron capture at the Paul Scherrer Institute, on tunable gamma-ray sources and their applications to tomography at the Gent LINAC and ESRF, and on the study of interatomic potentials using ultra-high resolving-power gamma-ray spectroscopy using the double flat-crystal spectrometer GAMS4 at ILL. In 2000 he was nominated full professor at the university of Cologne were he leads the Institute for Nuclear Physics which operates a Tandem van der Graaff Generator. His main interests are fundamental and applied nuclear physics, from the theoretical models down to the development of new instrumentation. He has published approximately 100 scientific papers in international scientific journals and was awarded the Yale University 2000 Leigh-Page Prize for his work on dynamical symmetries and supersymmetries in atomic nuclei.