SOURCES OF NUCLEAR PARTICLES

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Keywords: Accelerators, cosmic rays, cyclotron, isotopes, nuclear particles, radiation

Contents

Summary

This paper describes the physical principles of operation of various sources of nuclear particles. Using natural and artificial radioactive sources one can easily obtain low-intensity electron, positron, and α-particle beams with energies in the range of 0.1 MeV to l5 MeV. Much greater energies for these particles can be achieved by arranging for their acceleration in machines of various types. Radioactive sources can also serve as a source of neutrons. Higher neutron fluxes can only be obtained in nuclear reactors.

1. Introduction

There are just three elementary particles that we can identify as the "building blocks" of our world—protons, neutrons, and electrons. Protons and neutrons form atomic nuclei, and electrons and nuclei are the components of atoms that form the chemical compounds of the various natural objects. A great many short-lived particles that are not constituents of atoms are generated as a result of the interactions (collisions) of particles.

In nature we deal with two types of sources of particles: cosmic rays and radioactive elements. Both of these sources were involved in the earliest investigations of the structure of matter, and are still an essential part of modern science. However, in reality, progress toward understanding nature has been more connected with artificially produced particles. Two particles are easy to obtain in a free state: protons and electrons. The protons are hydrogen nuclei, while electrons, the outer part of atoms, can escape easily from the atom. For these reasons, the most common way for producing other elementary particles is by accelerating protons and electrons to high energies and causing their subsequent interactions with matter.

2. Cosmic Rays

Penetrating radiation coming from the cosmos has been known about for a long time, and it is difficult to say who was the original investigator of cosmic rays. It has long been known that a charged gold leaf electroscope, if left standing for some time, will discharge even if it is heavily shielded. Since such shielding can stop radiation from radioactive materials, it was felt that these rays originated somewhere in interstellar space.

Cosmic rays are unique natural sources of particles of high and superhigh energies. During their travel to the Earth's surface cosmic rays pass through thick (10^3 g per cm^3) layers of matter, i.e. the atmosphere, and undergo a complicated chain of transformations. As a result, the primary radiation approaching the Earth from outer space suffers significant modification at the Earth's surface, the product being referred to as secondary radiation. The primary radiation comprises protons, amounting to 90% of the total number of particles, about 7% helium nuclei (α-particles), and a further 1% are heavier nuclei, such as C, N, and O.

The essential characteristic of cosmic rays is found in the energy distribution of its components. The energy of the major part of cosmic rays—of protons—extends from 0.1 GeV up to 100 GeV, and their intensity decreases by an approximate order of magnitude with every order of magnitude decrease in energy. The energy behavior of the intensity of cosmic rays is also a common characteristic of other cosmic particles.

In general terms, the energy of primary particles is expended in the Earth's atmosphere in two stages: first the energy of the primary particle is transformed in creating a number of secondary particles, and then the kinetic energy of the latter is lost in causing ionization of the atmosphere. The secondary radiation consists of hadrons (pions, protons, neutrons, and so on), muons, electrons, photons, and neutrinos. The secondary radiation is divided into nuclear active (hadronic, including protons), hard (muonic), and soft (electron-photonic) components. The reason for making such a division will be discussed later. First, however, we consider the way in which the different components of the secondary radiation are created.

When a high energy nucleon (a proton, for example) collides in the atmosphere with one of the nuclei of nitrogen or oxygen nuclei, it partially splits these nuclei and produces a number of unstable elementary particles, i.e. the creation of numerous secondary hadrons takes place through the act of interaction of high energy particles. These are mainly pions—charged π^+ and π^- with the lifetime $\tau = 2.5\times10^{-8}$ s and neutral π^0 with $\tau = 0.8\times10^{-16}$ s. *K*-mesons have about one-fifth to one-tenth as much probability of being created, with less probability, about 1%, accruing to hyperons and antiprotons, while few electrons and muons are born. The energy of the primary particle is mainly transformed into momentum of secondary particles in the direction of propagation, and therefore they come off close to the forward direction.

In the atmosphere a primary proton will undergo more than 10 collisions with nuclei, thereby creating nuclear active particles, the cumulative result being a cascade or nuclear shower (Figure 1). Charged pions and in particular kaons in decay produce muons and neutrinos. If the energy of charged pions is sufficiently high ($>10^{12}$ eV), then due to relativistic time dilation they have insufficient time for decay and, together with nucleons, continue in the branching cascade of interactions, producing nuclear-active components of the secondary cosmic rays.

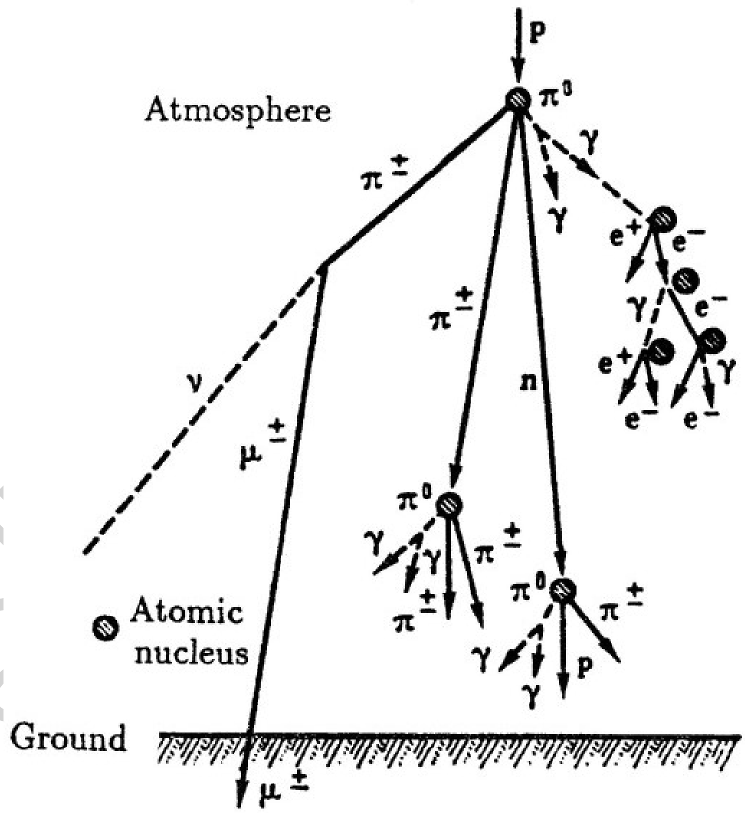

Figure 1. Schematic illustration of the interaction of a primary proton with the Earth's atmosphere

In parallel with the generation of nuclear-active components is the excess production of soft and hard components. Neutral pions (π^0) are the main source of the electron-photon component. Because of their limited lifetime, these rapidly decay, and two high energy γ-quanta result: $\pi^0 \to \gamma\gamma$. In turn, the γ-quanta, in collisions with atomic nuclei, produce electron-positron pairs, which then emit *bremsstrahlung* and so on.

Growth in the number of electrons, positrons, and γ-quanta takes place until ionization energy losses incurred by the electrons and positrons are comparable with their radiative losses, i.e. approximately at the energy 70 MeV (in air).

In the end the charged pions decay through the reaction

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\tilde{\nu}_{\mu}) \qquad (1)$$

and generate the hard muonic component of the secondary cosmic radiation.

The intensity of different components of the secondary radiation is dependent upon the thickness of the atmospheric layer through which this passes, as shown in Figure 2.

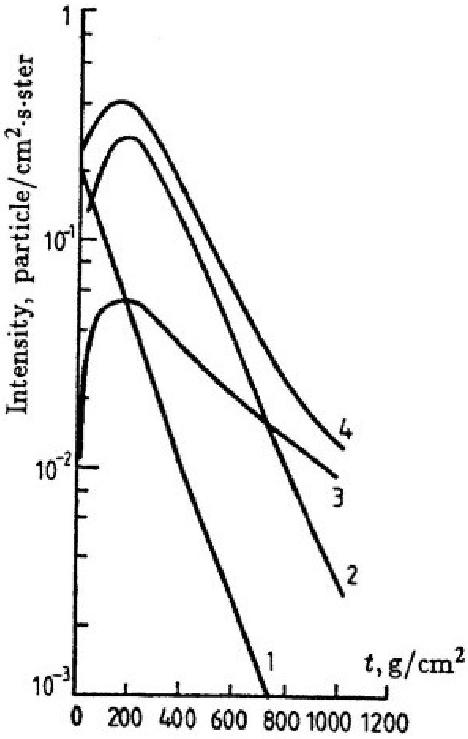

Figure 2. Composition of cosmic rays as a function of height

In Figure 2, line 1 represents the nuclear-active component, line 2 the electron-photon component, line 3 the muon component, and line 4 the total intensity of cosmic rays; *l* is the thickness of the atmosphere measured from the upper boundary. As can be seen, the intensity of the nuclear-active component sharply decreases with atmospheric depth and practically disappears at sea level. Similarly, the electron-photon component predominates at high altitudes but is rapidly absorbed so that at sea level it plays a much lesser role than that played by muons.

Thus, cosmic radiation at sea level consists of two components that differ significantly in their features. The particles of the one component, the electron-photon (electrons and, to a lesser extent, photons), are intensively absorbed by matter, it also being known that their absorption factor essentially depends on the atomic number of the absorbing atmosphere *Z*. This component of cosmic rays is called *soft*. The soft component can be absorbed, to practically insignificant intensities, by 20 cm of lead. Particles of the other component, the muons, are poorly absorbed by matter, and absorption is approximately the same in all substances (comparing of course absorbers with equal quantities of matter). To emphasize the great penetrating power of particles of this component of cosmic rays, they are called the *hard* component.

What is the basis for such a strong difference in the penetrating power of the soft and hard components? Ionization losses of particles with the same energy are approximately equal, and the difference in losses can only be caused by radiation (*bremsstrahlung*) whose generation is inversely proportional to the mass of the particle squared. This means that for muons radiation losses are practically absent, and this is the main cause of the different penetrating capabilities of the particles of the soft and hard components of cosmic rays.

2.1. Radiogenic Elements in the Earth's Atmosphere

Under natural conditions minor activation of some nuclides occurs through exposure to secondary neutrons from cosmic rays. This process is most intense on the boundary between the troposphere and the atmosphere, the main reaction being the production of radiocarbon from nitrogen $^{14}N(n,p)^{14}C$. On the basis of this reaction, Libby in 1955 developed radiocarbon dating.

The chemical behavior of radiocarbon is the same as that of ordinary carbon (^{12}C), and it therefore forms heavy carbon dioxide, which mixes with the ordinary carbon dioxide of the atmosphere. Atmospheric carbon dioxide enters the oceans as dissolved carbonates, while plant life grows by photosynthesis of atmospheric carbon dioxide and in turn animals live off the plants. An equilibrium amount of ^{14}C exists on the Earth, since while ^{14}C is produced at the rate of about 8 kg per year by cosmic ray neutrons, ^{14}C, with a half-life of 5730 years, disintegrates to ^{14}N, emitting a 160 keV β-particle. Consequently ^{14}C is distributed throughout the atmosphere, the biosphere (i.e. the realm of animal and plant life), and the oceans, with the ratio of ^{14}C atoms to ^{12}C atoms being approximately 1 to 8×10^{11}.

Living wood, for example, contains the above equilibrium proportion of ^{14}C. However, dead wood, which no longer takes in carbon dioxide from the atmosphere, suffers depletion of ^{14}C by radioactive decay and therefore its concentration slowly decreases—by approximately 1% every 80 years. Consequently by measuring the ^{14}C to ^{12}C ratio in a piece of dead wood and comparing it with the ratio in living wood, the age of the dead wood can be calculated using the laboratory measured half-life for ^{14}C.

Certainly, carbon-14 is not the only radionuclide produced by cosmic rays. As an example, chlorine-36, which is used in hydrology, is also formed in the atmosphere by the spallation reaction $^{40}Ar(p,n\alpha)^{36}Cl$, 40% of production occurring within the troposphere and the remainder in the stratosphere. The dominance of the stratospheric production results in a strong dependence of the fallout rate on geomagnetic latitude with a marked maximum corresponding to injection in middle latitudes via the tropopause.

3. Natural Radioactive Sources

A number of radioactive nuclei are naturally occurring, namely nuclei that because their genesis with the formation of the earth continue to exist in spite of their decay or those nuclei that are continuously being created through bombardment by cosmic rays. Radioactive nuclei can also be obtained artificially by the bombarding of stable nuclei with energetic particles. Here is to be noted that there is no physical difference between natural and artificial radioactivity even though the circumstances of their origin are different.

Minerals or rock containing long-lived radioactive nuclides are capable of acting as radioactive clocks or geochronometers in the full sense of these words and can therefore be used for dating of geological events. Such geological events can be mineral crystallization or hardening of a rock, or, strictly speaking, cooling of a rock down to the temperature at which losses of daughter products of radioactive decay due to diffusion become negligible. The well-known example is potassium-argon dating of geological events.

Another natural radioactive tracer is the most abundant of the uranium isotopes, namely ^{238}U, undergoing spontaneous fission with a decay constant of 6.9×10^{-17}y. As a result, in a mineral containing just 1 ppm of uranium, some 2000 fission fragments would cross 1 cm^2 of any inner surface in a period of one million years. Provided all of these fragments manifested in the formation of tracks within the mineral, simple counting of the track density coupled with measurement of uranium content would allow the possibility of determining the age of the sample.

Natural isotopes have become powerful indices of subsurface waters. The isotope concentration in subsoil waters is governed by hydrological processes and interaction between the atmosphere and the hydrosphere. Stable nuclides, whose properties do not change with time, are used as a rule for identification of the origin of subsoil waters and processes of their mixing. Radioactive nuclides, in their turn, are used to study the subsoil water dynamics.

One of the major problems in most countries is to supply good quality water to the population. With the identification of new water resources becoming increasingly difficult, major efforts need to be directed toward the protection and rational use of existing resources. Nuclear techniques using isotopes can provide an adequate solution to the problem of the origin, distribution, and properties of water in a given region. An ideal water tracer should have a behavior that is as similar as possible to that of the water and, at the same time, it should be easily detectable—possibly *in situ*—and easily injectable over large regions of a hydrological system.

An important point of interest is the residence time of water in an aquifer, also called the “age” of the water. Several radioactive isotopes can play a role—depending on their half-lives—in settling the question of how long ago the water under consideration was in contact with the atmosphere. Young groundwater means that replenishment can depend on the rainfall in a certain year, so that a dry season can be followed by a lack of groundwater. The other extreme, of old groundwater, can imply replenishment, and therefore, mining of the ground water can be indicated.

It is clear from the foregoing that isotope techniques can help scientists in seeking solutions to many significant problems of hydrology. Other examples include:

- origin of saline water intrusion
- pollution from industrial and urban releases and from agricultural practices
- consequences of exploitation upon groundwater
- consequences of deforestation on groundwater
- general groundwater assessment and pollution risks

These form part of the global problem of aquifer vulnerability and the risk of exposure to contamination.

Another example of usage of natural radioactive elements is radon mapping for locating geothermal energy sources. Geothermal energy sources are usually associated with volcanic regions where hot water springs exist and vapor emanations occur. They can also be used in indicating potential geothermal energy reservoirs. However, to define an anomaly, one must perform geochemical and geophysical surveys, heat flow measurements in shallow holes, and deepwell drilling for flow testing. After making a discovery of a potential geothermal energy source, step-out wells have to be drilled to determine the extent of the reservoir. Experience has shown that alternative methods, prior to drilling, have to be applied to reduce the number of wells. Among these methods is radon mapping which provides an additional parameter for geothermal source assessment.

4. Accelerators

Practically the only way to investigate nuclei and elementary particles is to arrange for the collision of one sort of particle with others and then to record the number and energies of the products of these interactions. In the absence of the study of both collisions and decays, it is possible to investigate only static nuclear characteristics of the nuclei and particles, such as spin, magnetic moment, electric quadrupole moment, and so on. To investigate collisions it is first necessary to know how to produce particle beams.

In principle, there are not that many types of particle sources. The first type of source is radioactive nuclei, suffering the restriction that the energy region of the emitted particles does not exceed a few MeV. In response to this challenge one might consider using cosmic rays. However, the cosmic rays' spectrum is extraordinarily diverse and their intensities are extremely small. The result is that in practice one cannot use them. Therefore, the only sources of charged particle beams of great energy are accelerators. Only stable charged particles can be accelerated. Beams of other particles, including neutral ones, are produced as a result of target reactions, and these are used as secondary sources. The most common powerful source of neutrons is the nuclear reactor. Reactor neutrons arise from nuclear fission, and hence, they, too, are classified as secondary particles.

Accelerators are of two types. In electrostatic accelerators the particles are accelerated by applying a constant potential difference U, determining the energy of the particle by the relation $mv^2/2=eU$, where e is the charge of the particle. The problem reduces simply to the production of high voltages by using techniques involving electrostatic machines and/or electronic circuitry. The voltages that are produced, and, as a consequence, the energies, are limited by the occurrence of corona discharges from the high voltage terminal and other such practical difficulties. In practice, while particles can be accelerated to only about 4 MeV or 5 MeV, by using the tandem principle, as explained later, one can achieve energies of, at the most, up to 25 MeV.

To overcome this limit, one must avoid the use of electrostatic forces, which are essentially conservative and which always have zero circulation. This means that the kinetic energy gained by the particle, whatever its trajectory might be, cannot be greater than the potential energy acquired due to free fall through the maximum voltage created by the machine. A variable nonconservative electric field, which is necessarily associated with a variable magnetic field by the equation

$$curl \quad E = -\partial B/\partial t$$

provides other interesting possibilities for charged particle acceleration. One could think of other closed paths along which the circulation of E and hence the kinetic energy gained by a particle will differ from zero. If the particles are made to follow such a path many times, then one achieves a process of acceleration that is not limited by the maximum voltage drop existing in the machine. Machines that use the principle of repeated accelerations of the same particle in cyclic paths are called cyclic accelerators. The accelerating voltage is only a small fraction of the maximum energy that can be achieved. The trajectories of the particles can be straight, as in linear accelerators, or curved, as in the cyclotron or synchrotron.

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Biographical Sketches

David A. Bradley graduated Bachelor of Science (Physics) from the University of Essex in 1975. He has a Masters of Science (Radiation Physics) degree, awarded by the University of London in 1976, and a Ph.D. awarded by the University of Science (Penang) in 1985. His career, which began with work as a radiotherapy physicist at Charing-Cross Hospital (London), has encompassed long periods of teaching and research at universities in Malaysia. He is a senior lecturer and member of the biomedical physics group at the School of Physics, University of Exeter. His research interests concern the general area of interactions and consequences of radiation in industry and medicine; a specific interest has been the elastic photon-atom scattering process. Journal publications number some 100 papers. In addition, he has been the editor of a number of books and special issues of journals on ionizing radiation. Bradley is a fellow of three professional Institutes, the Institute of Physics (IOP), the Institute of Physics and Engineering in Medicine (IPEM), and the Malaysian Institute of Physics (IFM). He is an editor of the journal *Applied Radiation and Physics* and a Council Member of the International Radiation Physics Society (IRPS).

Yuri Mikhailovich Tsipenyuk graduated from the Moscow Institute of Physics and Technology (MIPT) in 1961, becoming a candidate of sciences in 1969, and a doctor of physico-mathematical sciences in 1979. From 1961 until the present he has worked at the P.L. Kapitza Institute for Physical Problems, Russian Academy of Sciences, now as the leading scientist of this Institute. In addition he is Professor of Physics of the Moscow Institute of Physics and Technology. His scientific interests include: electron accelerators, fission of atomic nuclei, activation analysis, investigation of the solid state by neutron scattering, and superconductivity. In 1997 he was made Soros professor, and in 1997 he became a Member of the New York Academy of Sciences. Tsipenyuk has published more than 120 papers in scientific journals and is the author of three monographs, *Physics of Superconductivity* (in Russian, 1995, Moscow: MIPT Publishing), *Nuclear Methods in Science and Technology* (IOP Publishing, 1997), and *The Microtron: Development and Applications* (Harwood Academic Press, 2001), in addition to being the coauthor of the textbook on general physics for high school *Basics of Physics* (Moscow: Nauka, 2001).