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# Entering a new era: beams of radioactive nuclei

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We are entering an era where it will be possible to produce beams of a wide range of radioactive nuclear species. This will transform nuclear physics and nuclear astrophysics and open up new avenues of research in condensed matter science and medical physics.

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Our knowledge of the microscopic world is summarized in figure 1. The matter of our everyday world is made up of atoms and molecules, which are electrically neutral. The configurations of the electrons in the atoms dictate their properties, and an understanding of the full panoply of these configurations constitutes our knowledge of chemistry and gives the subject its power to transform the material world around us.

In simple terms, we see the atom as having a tiny ($10^{-14}$ m in diameter), positively charged nucleus at its heart. This nucleus is surrounded by negatively charged electrons in orbit, and is neutral overall. The central nucleus, in turn, is made up of neutrons and protons, generically called nucleons. The nucleons themselves have a substructure of three quarks, with protons being made up of two up quarks and one down, and the neutrons having one up and two down quarks. A substructure for the quarks is actively sought, but, at the time of writing, no convincing evidence for it has been found.

Our theoretical understanding of the various layers of matter shown in figure 1 varies in the solidity of its foundations and in its predictive powers. In principle, we believe that we have a theory, quantum electrodynamics, which encompasses all of atomic physics. Many of the calculations involved are very difficult, but, in principle, we have a theory which works. In particle physics we have the Standard Model. Despite the fact that the model has too many ad hoc parameters, it has been extremely successful and encompasses a wide range of phenomena. There is an intensive search for experimental observations which will provide the secure foundation for a more satisfactory model, but to date the Standard Model still prevails.

The most intractable of these problems is the structure of the nucleus. Here there is no unifying theory, although the shell model encompasses much of what we know. Instead, we have a variety of models that describe various aspects of nuclear behaviour. This situation has its roots in the fact that we do not know the form of the force between the nucleons and that, if we did have such a knowledge, we are unable to solve the resulting many body problem exactly.

Thus in nuclear physics we have models that give a good description of particular phenomena over a restricted range of parameters, but have very limited predictive powers. If these models are to be improved, then it is essential that we have observations over a much wider range of the key descriptive parameters such as excitation

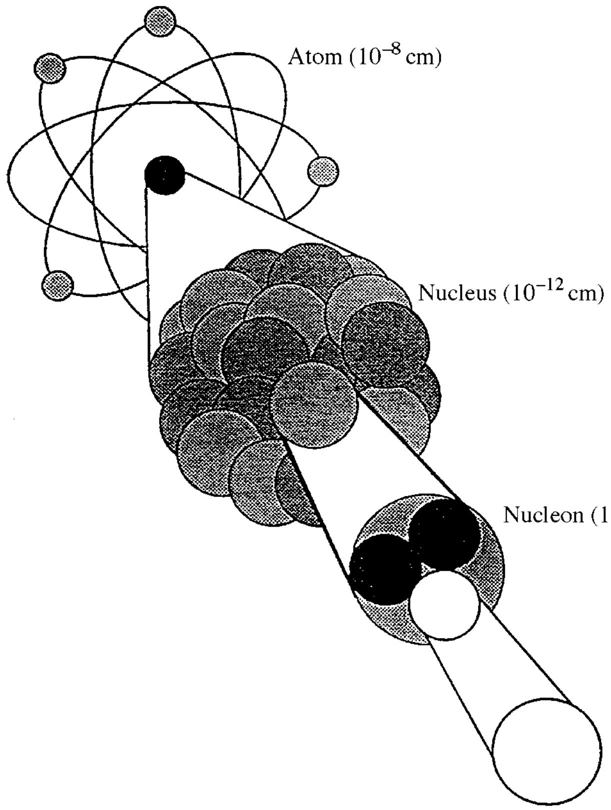


Figure 1. A simple picture showing our present view of the microscopic world.

energy ($E_{\text{exc}}$), angular momentum ($J$) and isospin ($N/Z$, the ratio of neutrons to protons). There are exciting developments on each of these fronts, but the present volume is concerned with the last of them; the extension of our observations to nuclei with every possible combination of neutrons and protons.

Every so often parts of science are transformed, either by a new idea or by technical developments. Two examples, taken from astronomy, will make the point. Until the 1940s our view of the heavens was confined to the visible part of the electromagnetic spectrum. The development of radio astronomy after World War II changed this, and now we have extended our observations to the ultraviolet, infrared, X-ray and $\gamma$-ray regions of the spectrum, etc. These observations have completely altered the range of phenomena observed and hence our perceptions and understanding of astronomical objects and events. More recently, it has become possible to put instruments into orbit beyond the Earth's atmosphere. We now have instruments free from the distorting effects of the atmosphere, and we can already see that this is again a great leap forward in the quality of the data obtained.

Nuclear physics is on the threshold of just such a change. Our knowledge of the structure and behaviour of atomic nuclei comes from studies of radioactive decay and nuclear reactions. The study of radioactive decay is invaluable and has many practical applications as well, but it is limited because radioactive decay is essentially immutable and gives us no control over our key parameters. Nuclear reactions, on the

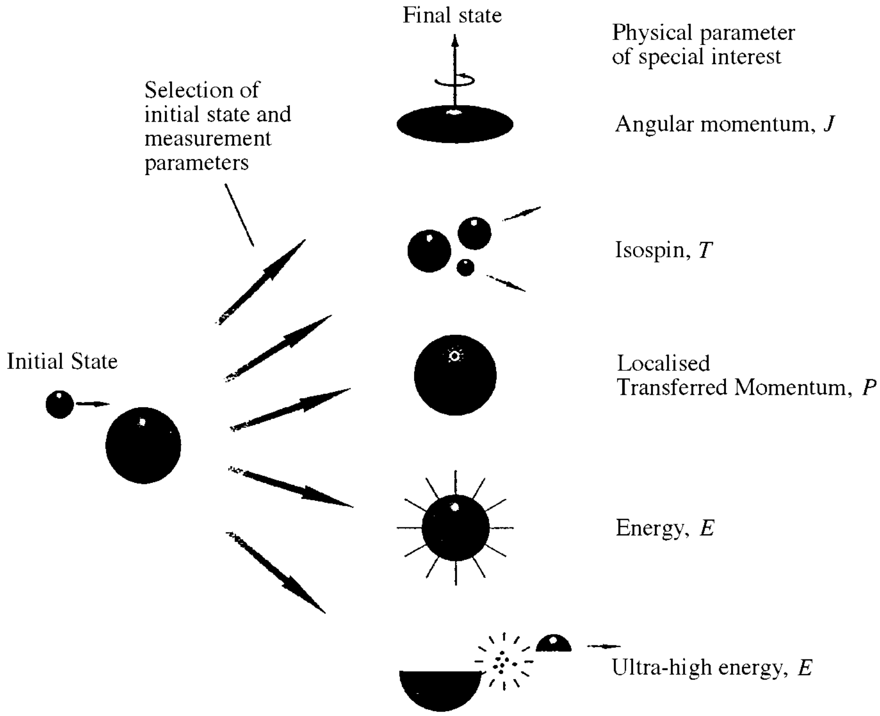


Figure 2. The figure shows a few of the things which can happen in nuclear reactions and suggests a physical parameter of special interest which governs the nature of the reaction in each case.

other hand, allow great variation. In essence almost any type of event we can imagine will actually occur in nuclear reactions: elastic and inelastic scattering, transfer, fusion, fission, etc. (see figure 2). For any given pair of nuclei and energy of interaction it is only a question of which of these processes predominates. By the choice of the projectile and the bombarding energy we can control $E_{\mathrm{exc}}$, $J$ and $N/Z$. However, two constraints remain.

Firstly, the nuclei are positively charged and repel one another. Accordingly, one of the projectiles, or both, must be accelerated to a high velocity to overcome this repulsion. In simple terms, the kinetic energy of the projectile must be greater than the Coulomb barrier, the electrostatic potential energy at a distance equal to the sum of the radii of the two nuclei. To produce nuclear projectiles with sufficient kinetic energy we require an accelerator, which is costly to build and operate. It is, however, now possible to produce beams of nuclei of the stable isotopes of all the elements and accelerate them to any energy required for nuclear physics.

These beams, however, are limited to the isotopes of the elements we can find on Earth; we are constrained to beams and targets of stable nuclei. As a result we have only been able to study nuclei with a very limited range of $N/Z$. There are only 283 stable or long-lived nuclei found on Earth compared with the *ca.* 7000 nuclear species that could live long enough to be created and then be accelerated. It needs little imagination to see that if beams of all 7000 of these species were available they would transform not only nuclear physics but have applications to a much wider range of sciences.

The present volume addresses this topic. Two methods have been found to produce beams of radioactive nuclei. The methods are complementary, as can be seen from the articles by Ravn and Morrisey & Sherrill. The former deals with beams produced by on-line isotopic separation, and the latter with beams produced in the fragmentation of stable, heavy nuclei at high energy. Our present knowledge of nuclear properties suggests some quite dramatic changes far from the line of stable nuclei. The article by Dobaczewski & Nazarewicz outlines some of the effects we might expect to see. Most of the other articles explore how various aspects of nuclear physics will be transformed by the availability of radioactive beams. It is not just nuclear physics which will benefit, however, and the articles by Forkel-Wirth and by Wiescher *et al*. show how they can be used for the study of solids and nuclear astrophysics, respectively.

No such volume can be exhaustive in its coverage and the ideas put forward here are inevitably limited by the experience and imaginations of the authors. No doubt the most exciting uses of radioactive beams are as yet undreamed of, but even without a crystal ball there is great excitement as we step over the threshold into an era where beams of radioactive nuclei are routinely available and we can attack a wide range of problems currently beyond our reach. The reader can hardly fail to feel this excitement.





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