Into the nucleus

Higher-energy probes lead to fine details of structure

by Dietrick E. Thomsen

Backenstoss checks pi and mu meson experiment.

CERN

The nucleus of an atom is a complex entity. Any number from one to 200 or more neutrons and protons may be moving around in it, affecting each other and the world around them by their motions and the forces they generate.

The study of nuclear structure has been difficult, painstaking and slow. Much of it in the past has concerned the nucleus as a whole, how much energy a whole nucleus possessed and how that energy is radiated, for example. Theoretical models tended to be gross; one such regards the nucleus as similar to a drop of liquid.

"People used to go to the laboratory and make movies of drops of liquid nitrogen," says Dr. Michael Danos of the National Bureau of Standards, "how they twisted, vibrated and split apart, to see how a nucleus behaved."

This is no longer the case.

"Nuclear physics today," says Dr. Danos, "has come of age," and researchers are looking for the first time at the detailed structure of nuclei, how the individual neutrons and protons behave and how they affect one another.

A nucleus appears to be more than just the sum of a certain number of neutrons and protons. Its properties are not always what one would expect from adding up its constituents.

It seems, say the nuclear physicists, that the protons and neutrons are not the same particles inside a nucleus as they are when flying free: The presence of other particles nearby and of the forces between them distorts the protons and neutrons and alters their properties.

The sort of thing that this distortion can do is illustrated by an old problem involving tritium, hydrogen 3, one of the simplest of nuclei. When theorists predicted the magnetism of a tritium nucleus, they figured it should be the same as that of a free proton since the tritium nucleus has two neutrons and a proton and the neutrons should cancel each other out.

"But it isn't," says Dr. Danos, "it's bigger."

Something in the interrelationship of the three particles alters them so as to give the extra magnetism.

The problem is further complicated because it appears that the force that does the distorting, the so-called strong nuclear force, does not behave the same way inside a nucleus as it does when it acts between two isolated particles.

Nuclear physicists were unable to explore this and other similar phenomena adequately when their techniques and equipment limited them to the study of gross nuclei. But they are now able to, and are beginning to probe this complex pattern of distorted particles and altered forces. They are beginning to see how the protons and neutrons are distributed inside nuclei, how they may be distorted and how the force between them behaves. From such data they hope to get an understanding of how these details affect the properties and behavior of atomic nuclei and of the matter built of them.

The problem has been that there have not been intense enough sources of high-energy probes available. The low-energy probes available to nuclear physicists tend to see the nucleus as a whole undifferentiated blob and give information about its state as a whole.

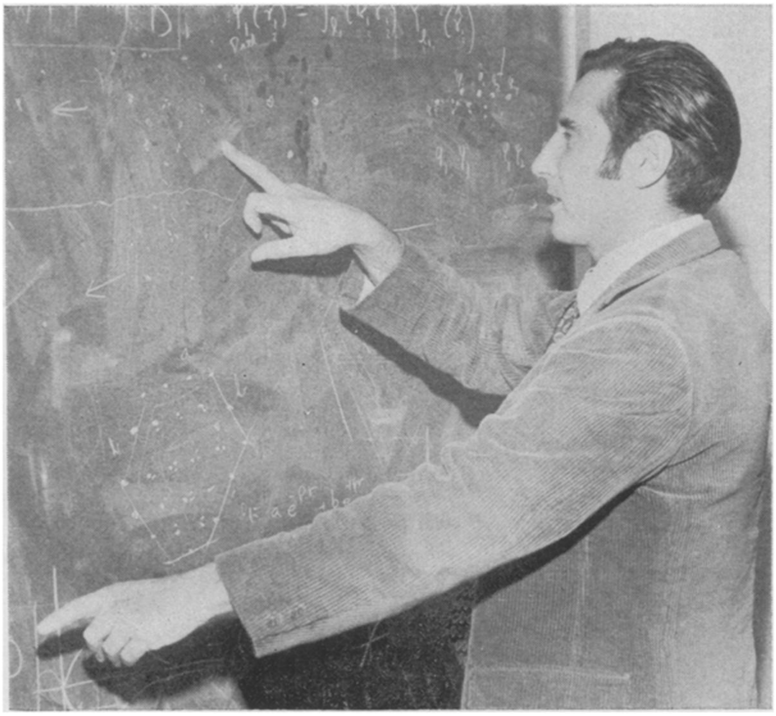
To get the detailed information nuclear physicists need to probe nuclei with particles of higher energies. The high-energy probes interact with individual neutrons and protons as they go through a nucleus and thus come out with information about the structure.

To provide the high-energy particles, physicists in several parts of the world are now building a new generation of particle accelerators, the meson factories (SN: 10/11, p. 332). These are designed to provide copious beams of protons and mesons at energies between 100 million electron volts and a billion electron volts.

The energy range that the nuclear physicists consider high is considered modest by particle physicists. There are numerous accelerators around the world that will provide protons or electrons in this energy range—from 100 million to one billion electron volts—but not in the numbers desired by nuclear physicists. For optimum performance, the nuclear physicists would like particle beams between 10 and 100 times as dense as those commonly used for particle physics.

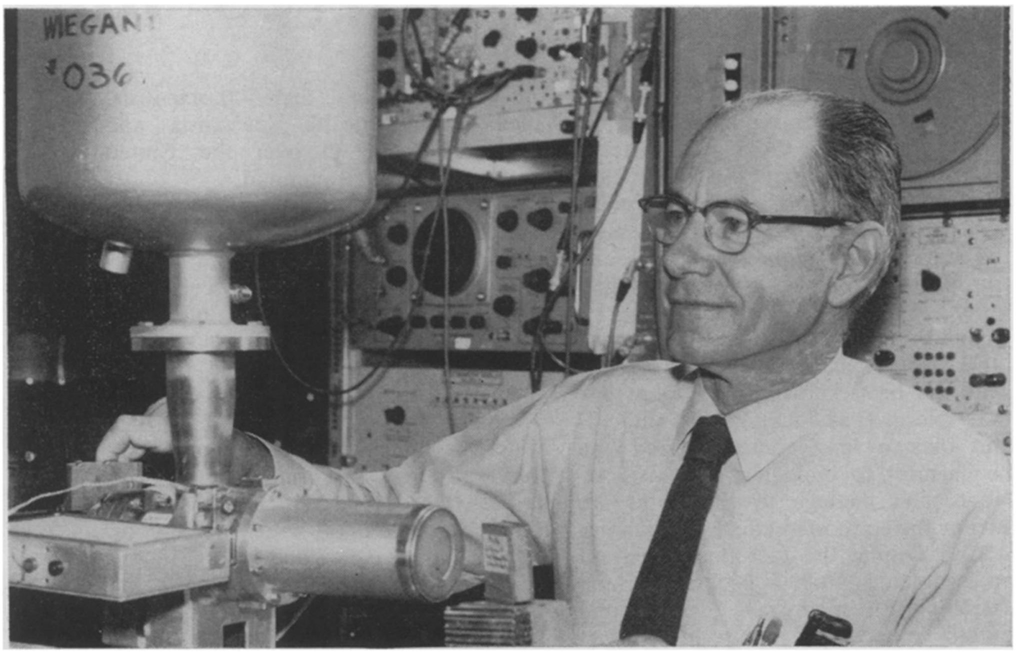
Nevertheless, nuclear physicists can and do make use of existing equipment, and since the energy requirements are, in absolute terms, modest, not only the big national and international laboratories like CERN in Geneva, Lawrence Radiation Laboratory and Argonne National Laboratory in the United States, or Saclay and Orsay in France, are in the field, but even smaller institutions like the College of William and Mary in Williamsburg, Va.

In the future, when the meson factories are finished, the geographical spread may narrow somewhat, but it will still be large compared to particle physics. The meson factories are cheaper than high-energy synchrotrons (tens of millions versus hundreds of millions of dollars), and economically small countries can and will build them. Switzerland and Canada are two



NBS

Danos (left) and Wiegand: Nuclear physics comes of age with brand-new techniques.



LRL

current examples of the trend.

The mesons are particularly interesting to nuclear physicists because they behave somewhat like electrons. A meson, if it has a negative electric charge, will be captured by the electric force of the nucleus and orbit like an electron, forming a so-called mesonic atom. But the mesons are heavier than electrons and therefore spend more of their time near the nucleus than electrons do. The mesons' behavior is thus more influenced by details of the nuclear structure than are the electrons'.

As the mesons move from orbit to orbit around the nucleus, they give off X-rays. By studying the spectra of these X-rays, nuclear physicists deduce information about the details of nuclear structure.

Different mesons are useful for different parts of the picture. For example, mu mesons (muons) are subject only to the electric forces while pi mesons (pions) are subject to both the electric and the strong nuclear forces. Comparing the X-ray spectra of these two kind of mesons can give details about the behavior of the strong nuclear force, still one of the biggest mysteries in subatomic physics inside a nucleus or out of it.

"Comparison of muonic and pionic atoms," says Dr. Gerhard Backenstoss of CERN and the Technical University of Karlsruhe in West Germany, "is a powerful tool to investigate the strong pion-nucleus interaction, which in its turn has significant bearing on the structure of the nucleus."

Theoreticians have had an orgy with pionic atoms, says Dr. P. C. Gugelot of the University of Virginia. Of 30 references to the subject, only 8 were experimental papers. In future the experimentalists hope to even the score.

Evidence from pionic atoms shows that the strong nuclear force is a very complex phenomenon. The force that the pion feels from the nucleus is a mixture of attractive and repulsive elements, and the nature of the mix and which part dominates under what conditions can cast interesting lights on details of the nucleus.

For example, when the pion is in certain high-energy states the relations between pion and nucleus are dominated by an attraction to the neutrons. "So here everything depends on neutron distribution in these nuclei rather than protons," says Dr. T. E. O. Ericson of CERN. The X-rays that the pions give off in these high-energy states can thus be used to deduce details of the neutron distribution.

That the neutrons and protons are not distributed in similar proportions is already apparent from studies of atoms that include K mesons (kaons). Kaons are especially useful for studying the outer reaches of nuclei since they spend most of their time in that neighborhood.

Studies of kaonic atoms of 29 different elements, says Dr. C. E. Wiegand of the Lawrence Radiation Laboratory, is leading to the conclusion that "nuclear matter, very probably neutrons, extends to greater radii than the electric charge distribution." Since the electric charge is tied to the protons, this means that there appears to be a greater concentration of neutrons than of protons in the outer skin of a nucleus.

This sort of study of the nucleus is only beginning, and Dr. Wiegand stresses that there is a great deal to be learned. "This is an infant subject," he says, "and this part of the baby is only a few months old."

For the future he foresees extending these mesonic studies to particles heavier and therefore more deeply probing than those now in use. Not only mesons, but any particle with a negative charge, might do. "We have the possibility of studying antiprotonic atoms," he says, employing a particle of the same mass as the proton, but with a negative charge, which would certainly relate most intimately to any nucleus that captured it. □