Building exotic atoms

Substitution of heavier particles for electrons is reaping results

by Dietrick E. Thomsen

CERN

Heavy equipment produces atoms, measures X-ray output.

As everyone knows, a normal atom consists of a positively charged nucleus surrounded by negatively charged electrons. The electrons are held in their orbits by an electromagnetic, or Coulomb, force, which attracts them to the nucleus. The force attracts rather than repels because of the opposite polarity of the charges of the nucleus and electron.

In principle any negatively charged particle could replace the electron and, bound to the nucleus, orbit it in similar fashion. In practice the substitution is difficult to make for a number of reasons. The possible candidates for substitution, negative mesons, hyperons and others, are all in one way or another unstable and hard to handle. They must be delivered to the neighborhood of the nucleus with just the right energy to be captured. When they are captured, they tend to form unstable structures: Unlike electrons, the substitute particles are quickly absorbed by the nuclei.

In spite of the difficulties such exotic atoms are made and studied. The first of them, which substituted negative pi mesons for electrons, were produced in 1952. Mu mesons followed in 1953 and K mesons in 1967.

The latest results bring exotic atoms into a new domain; for the first time electrons have been replaced with particles at least as heavy as the particles of the nucleus itself. The substitutes are negative sigma hyperons, first seen at the Lawrence Radiation Laboratory in Berkeley in 1968 and confirmed this summer at the CERN laboratory in Geneva, and antiprotons, which were achieved in the same series of experiments at CERN.

The CERN experiments were performed by a group of 13 scientists from the Max Planck Institute for Nuclear Physics at Heidelberg and the University of Karlsruhe in Germany, the Swiss Federal Polytecnic Institute in Zurich, the University of Sussex in England, the Institute of Nuclear Research in Warsaw and the University of Warsaw. The Berkeley experiment was done by a team led by Dr. Clyde E. Wiegand of the University of California.

Exotic atoms are made and studied for two reasons—to learn more about the detailed structure of the nucleus and to determine certain properties of the particles that cannot be easily investigated when they are flying free.

The substitute particles are all heavier than the electron. The lightest, the mu meson, is 200 times as heavy as the electron; the heaviest, the sigma, 2,400 times as heavy. They all, therefore, orbit more closely to the nucleus than the electron—200 times as close for the mu meson, 2,400 times as close for the sigma. At this point it becomes a little unreal to talk of the orbits since the heavier particles spend most of their time inside the spatial limits of the nucleus. This makes them more sensitive to the details of nuclear structure than the electron.

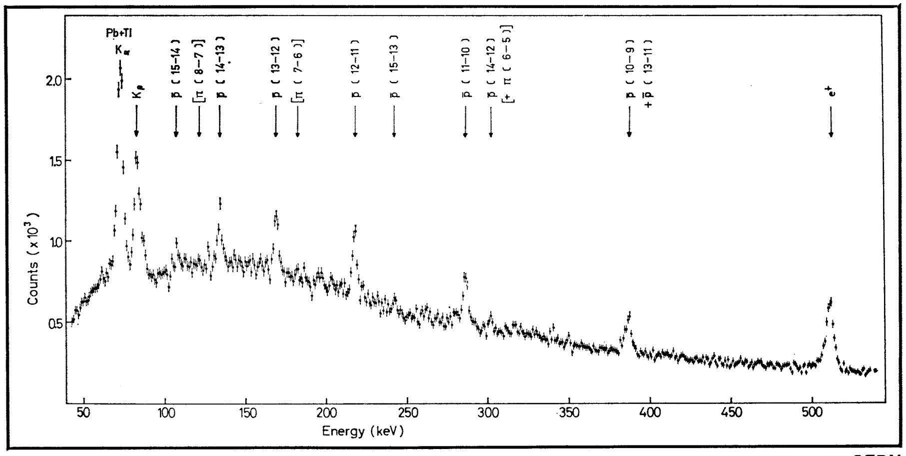
The substitute particles are captured at relatively high-energy levels. Gradually they drop down the scale of energy levels until they are absorbed—until they interact with part of the nucleus in such a way that their identity is lost. As the exotic particles drop from one energy state to another, they give off X-rays, and a description of their behavior can be determined from the X-rays.

Each of the particles interacts with the nucleus in a different way so that each variety of exotic atom adds its own piece to the total picture. Mu mesons respond to the electromagnetic forces of the nucleus as electrons do. But since the mu mesons are much closer to the nucleus, their behavior is strongly affected by the distribution of electric charge within the nucleus. Studies of muonic atoms have yielded much information about the distribution of positive charges—protons—within nuclei.

The pi meson is subject to both electromagnetic forces and the strong nuclear forces that hold the nucleus together. It interacts particularly with pairs of nuclear particles, says Dr. Wiegand. The application of this behavior is exemplified by experiments in which X-rays from pionic atoms of oxygen 16 and oxygen 18 were studied to determine the effect of adding two neutrons to the nucleus.

The newer exotic particles—K's, sigmas and antiprotons—also respond to both forces, and they will be especially

. . . antiprotons



CERN

Peaks in X-ray spectrum of thallium 81 show that antiprotons are present.

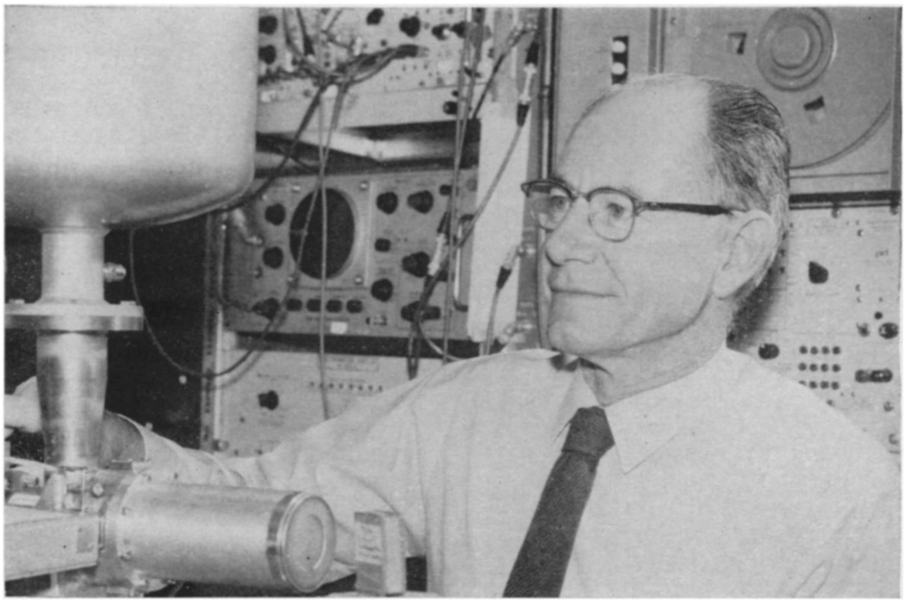
useful in investigating the outer layers of the nucleus. K mesons, says Dr. Wiegand, interact about equally with protons and neutrons. They have already shown that neutrons seem to predominate in the outer parts of nuclei.

Kaonic and sigmic atoms tend to go together, since experiments aimed at making kaonic atoms make sigmic ones too. When a beam of K mesons strikes a target, some of the K's, instead of being drawn into orbit, may interact with protons or neutrons to form sigmas, and the sigmas then orbit. This is the way that sigmic atoms were made at both CERN and Berkeley.

"Sigma-minus and K should fit together to give some picture of the surface of the nucleus," says Dr. Wiegand. More theoretical work is needed to understand atoms of these types, he adds. He has been trying to interest theoreticians in the subject since kaonic atoms were first made, but with little success. Now that there are also sigmic and antiprotonic atoms, he believes the theoreticians will pay more attention.

Studies of sigmic and antiprotonic atoms could also determine the magnetic moments of the sigma-minus and the proton and the mass of the antiproton. The magnetic moment of a particle measures its intrinsic magnetism. When a magnetic particle is under the influence of the magnetic field of an atom, the magnetic interaction splits energy levels. Several energy levels are possible where only one would exist if the particle were nonmagnetic. The different levels, in turn, yield different X-ray frequencies.

The magnetic moment of the sigma-minus is expected to be different from those of its siblings, the sigma-plus and the sigma-zero. But for protons and antiprotons theory requires that the masses and magnetic moments be the same. "Experiment will see if that's true," says Dr. Wiegand. ☐



Berkeley

Dr. Wiegand: Exotic atoms help in investigating the surface of the nucleus.