Exotic Atoms: Elementary Particles Go into Orbit

Electrons are not the only negatively charged particles that are captured by the positively charged nuclei of atoms. Other elementary particles can go into stable atomic orbits and form "exotic atoms." The first such atom was discovered in 1952 by nuclear physicists who observed x-rays that were produced when negative pi mesons (mass 273 times that of the electron) cascade from one stationary energy level to another in atoms. Since then physicists have studied atoms formed with mu mesons and negative K mesons, the latter with a mass 966 times that of the electron. In 1968, an x-ray spectral line attributable to sigma-minus particles (with mass 2340 times that of the electron) was detected at the University of California at Berkeley. Researchers working on the 28 Gev protron synchrotron located at CERN in Geneva, Switzerland, have now found additional evidence that the massive sigma-minus forms exotic atoms. They have also added a fifth atom to the list by showing that antiprotons can be captured in atomic orbits. Experiments with exotic atoms provide powerful methods for investigating the size and shape of nuclei and the composition of nuclear surfaces; they also make possible very precise determinations of the mass of the orbiting elementary particles *(1)*.

When captured by the nucleus, each particle has its own characteristic energy levels, which are different from those of electrons. This is because the positions of the energy levels depend on the orbiting particle's mass. The heavier ones orbit closer to the nucleus; their "Bohr radius" is smaller, being inversely proportional to the elementary particle's mass. Some of the orbits actually penetrate the nucleus and thus give rise to techniques for probing its structure. All of the exotic atoms are "hydrogen-like" since only one exotic particle is captured per nucleus. Furthermore, the introduced particle is not identical to the electrons surrounding the nucleus; thus its stationary orbits are not restricted by the electrons according to the Pauli exclusion principle. These simplifications help theorists to calculate the expected energies of the x-rays emitted during the atomic cascades, and therefore also allow experimenters to readily identify the lines on their x-ray spectra.

Mu mesons are 200 times heavier than electrons but appear to be identical in every other respect. They primarily interact with the nucleus via the electromagnetic Coulomb force. Thus mu mesic atoms provide information about the distribution of electric charge within the nucleus—that is, about how the protons are arranged. The energy levels observed with mu mesic atoms do not agree with those predicted from models which depict the nucleus as a point charge. This is because some of the orbits are within the nucleus. In bismuth-209, for example, mu mesic x-ray data give a charge radius of 6.63 ± 0.03 fermis (1 fermi $= 10^{-13}$ cm) with a surface thickness of 2.40 ± 0.08 fermis.

The nuclear charge distribution can also be explored with probes of fast electrons, which make close collisions with the nucleus. The observed proportion of large-angle elastic scattering from heavy nuclei is much smaller than would be expected if all the charge were concentrated at a point. The bismuth-209 charge radius determined by elastic electron scattering, 6.74 ± 0.08 fermis, agrees with that derived from mu mesic atoms. However, the surface thickness, 2.00 ± 0.016 fermis, is smaller. This difference can be explained if the charge distribution has a tail extending out to 10 fermis and containing 0.4 percent of the charge. Such a halo would affect the mu mesic data more than the electron scattering measurements.

The particles—other than the mu meson—which participate in the known exotic atoms interact strongly with the nucleus and reveal additional information. The particles are captured in relatively high-energy levels. In times of the order of 10^{-10} second, they cascade preferentially through circular orbits to lower levels where the strongly interacting particles are absorbed by the nucleus and lose their identity. The nuclear absorption takes place in about 10^{-19} second, leading to extreme reduction in the intensity of x-rays corresponding to the lower levels. Knowledge of the particular orbit in which the x-ray cascade disappears reveals information about nuclear size and about the distributions of particles within the periphery of the nuclear surface. In 1969 Clyde Wiegand of the Lawrence Radiation Laboratory in Berkeley did a systematic study of K-mesic x-ray spectra for 24 elements ranging from atomic number 17 (chlorine) to 92 (uranium) *(2)*. His results for the sudden cutoff of the x-ray cascade suggested that the neutron distribution in heavy nuclei probably extends beyond that of the protons. Other nuclear experiments support Wiegand's surprising conclusion. Thus the evidence from K mesic atoms suggests that the proton halo discovered with mu mesic atoms has a large excess of neutrons.

Pi mesons prefer interactions with pairs of nucleons (protons and neutrons). They were used to determine the effect of adding two neutrons to oxygen-16 from studies of the x-ray transitions in pi mesic atoms of both oxygen-16 and oxygen-18. Another advantage of the pion's "double vision" is that we can learn about correlations between the motions of pairs of nucleons within nuclei.

Gerhard Backenstoss and his collaborators at CERN used a beam of K-minus mesons to produce the sigma-minus particles *(3)*. Wiegand had earlier identified a single sigmic x-ray line in potassium during his K meson experiments. The European physicists observed three lines in chlorine and three lines in zinc. In addition to this work on sigmic atoms, the CERN group observed x-ray spectra from antiprotons in several elements between phosphorus and thallium. From the good agreement between the calculated and the experimental values for the energy levels, they were able to deduce the mass of the antiproton to within 5 parts per 10,000. As is expected from elementary particle theories, the mass of the antiproton is identical to that of the proton within experimental error.

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References

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