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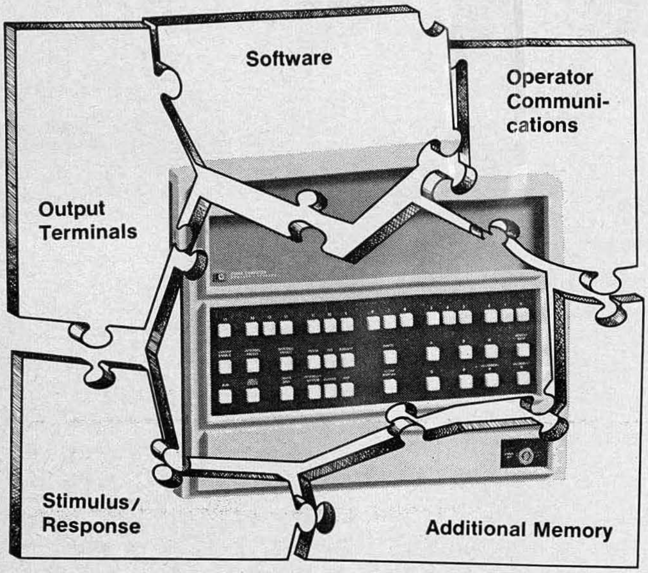

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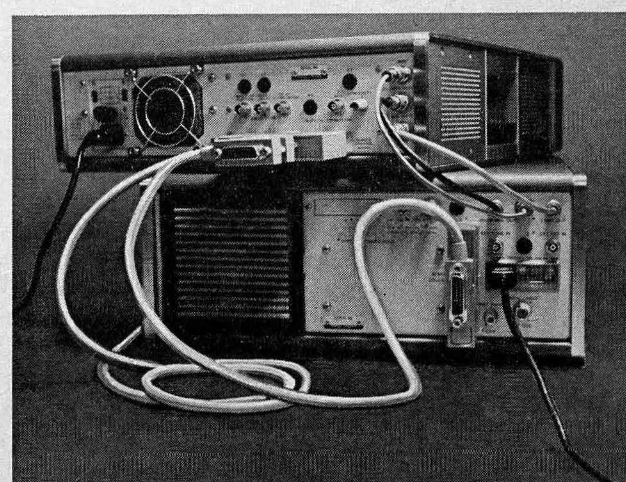
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EXOTIC ATOMS

An electron in an atom can be briefly replaced with another particle. The resulting new atom yields information on the nature of the nucleus

by Clyde E. Wiegand

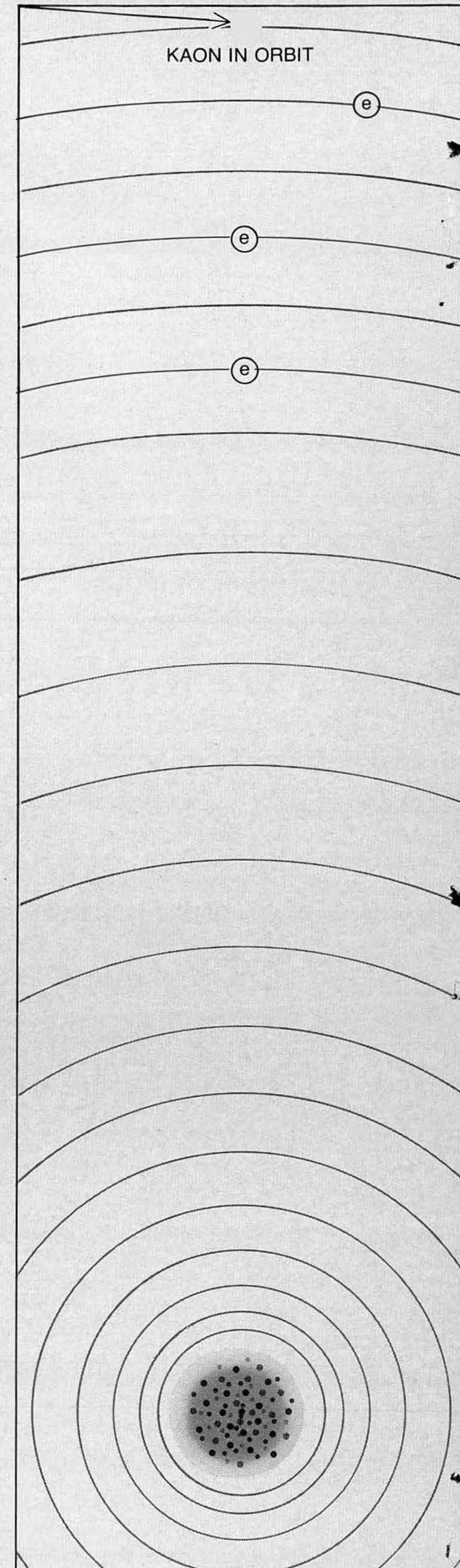
The atoms of ordinary matter consist of a cloud of negatively charged electrons surrounding a positively charged nucleus. The simplest of these atoms is hydrogen, with one electron and a nucleus consisting of one proton; the most complex is the latest element synthesized by nuclear chemists, which has 105 electrons and a nucleus made up of 105 protons and 157 neutrons. Most atoms are stable in the sense that they do not spontaneously change their properties. The exceptions are the natural and man-made radioactive atoms and what are called exotic atoms. In an exotic atom one of the electrons is artificially replaced with an entirely different negatively charged particle. Seven negative particles are capable of substituting for the electron, and so far five of them have been successfully implanted in ordinary atoms.

Although practically all the mass of an atom resides in the nucleus, the atom's chemical properties are determined by the number and configuration of the electrons. Until some 30 years ago the only elementary particles known were the proton, the neutron, the electron and the positron (a positively charged particle with the same mass as the electron). In the 1940's studies of cosmic rays revealed another class of charged particles: the mesons. Mesons are short-lived particles whose mass ranges between the mass of the electron and the mass of the proton (1,840 times the mass of the electron). The first man-made mesons were the pions, or pi mesons, created in the 184-inch cyclotron at the University of California at Berkeley in 1948. It was several years—and several cyclotrons—later that negative pions were successfully substituted for electrons in atoms.

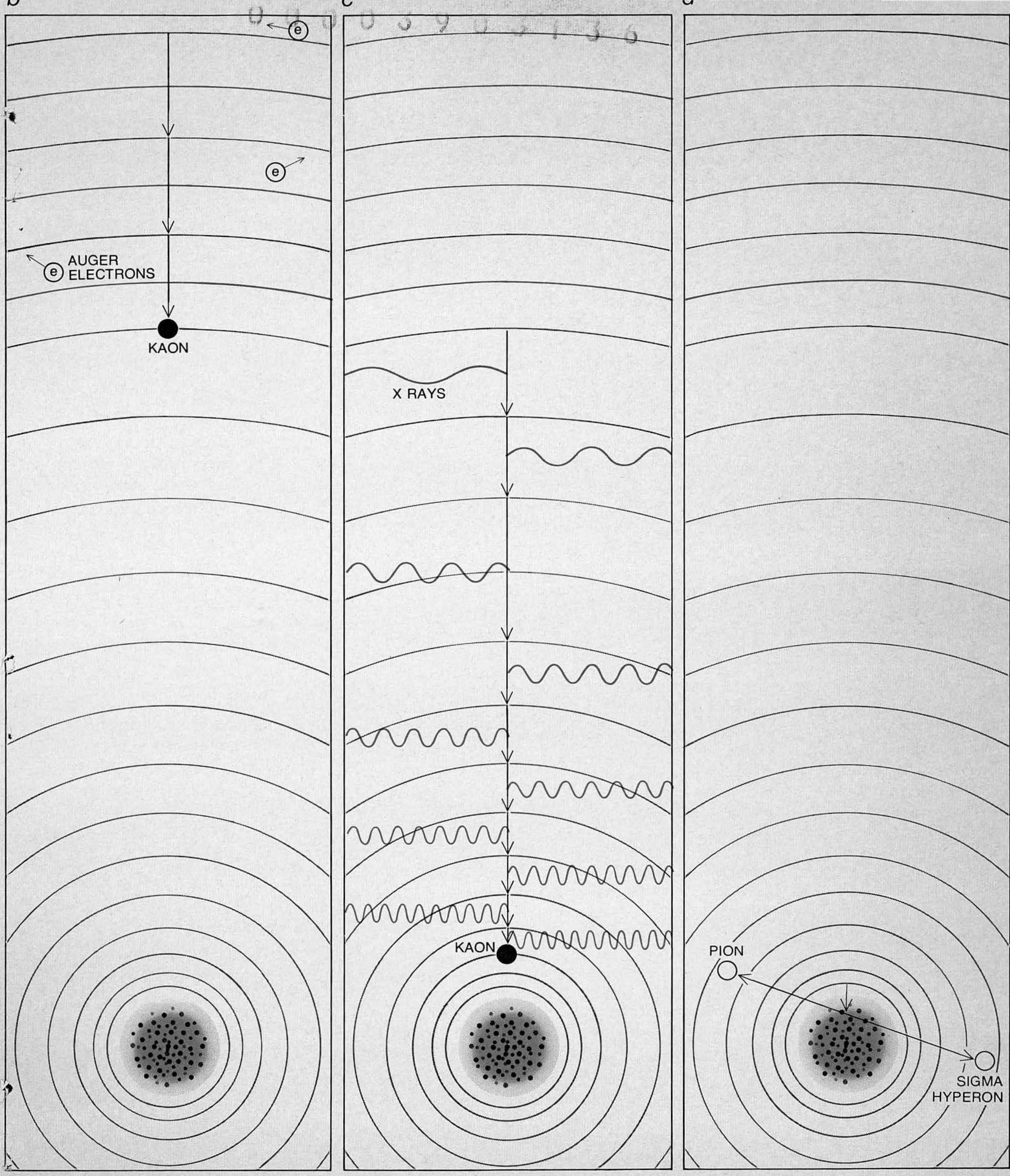
Except for some special modifications all the exotic atoms resemble the hydrogen atom, and it will therefore be useful to briefly consider the properties of the hydrogen atom. The model of the atom proposed by Niels Bohr in 1913 puts the electrons in discrete orbits around the nucleus. An electron can occupy any one of these orbits but not the space in between. Each orbit is given a number called the principal quantum number and designated n. When a hydrogen atom is in its ground state, that is, its state of lowest energy, its electron occupies the first Bohr orbit, whose principal quantum number is 1. The radius of the orbit is 5×10^{-9} centimeter. The atom can be excited to higher energy states by absorbing a photon, or quantum of electromagnetic radiation, from an external source. The electron jumps to another Bohr orbit, and in 10^{-8} second the atom spontaneously emits a photon of its own and the electron returns to the ground state.

The orbit to which the electron jumps depends on the energy of the photon absorbed by the atom: a more energetic photon will cause the electron to jump to a higher Bohr orbit (for example, to one where $n = 4$ or $n = 5$) than a less energetic photon will. When the energy of the photon is sufficiently great to remove the electron completely, the atom is said to be ionized. For hydrogen the energy of ionization is 13.6 electron volts, corresponding to the energy of a photon in the far-ultraviolet region of the electromagnetic spectrum. A lone proton will ultimately attract a free electron or steal one from another atom. The new hydrogen atom will emit photons as the freshly attracted electron cascades down to the ground state from the orbits with large principal quantum numbers.

An exotic atom created by replacing the electron with another negatively charged particle behaves in much the



EXOTIC ATOM IS FORMED when one or more electrons of an ordinary atom are artificially replaced with an entirely different negatively charged particle. In this illustration the capture of a kaon (K meson) by a target atom to form an exotic atom is depicted schematically. The kaon is captured near the 100th energy level of the kaonic

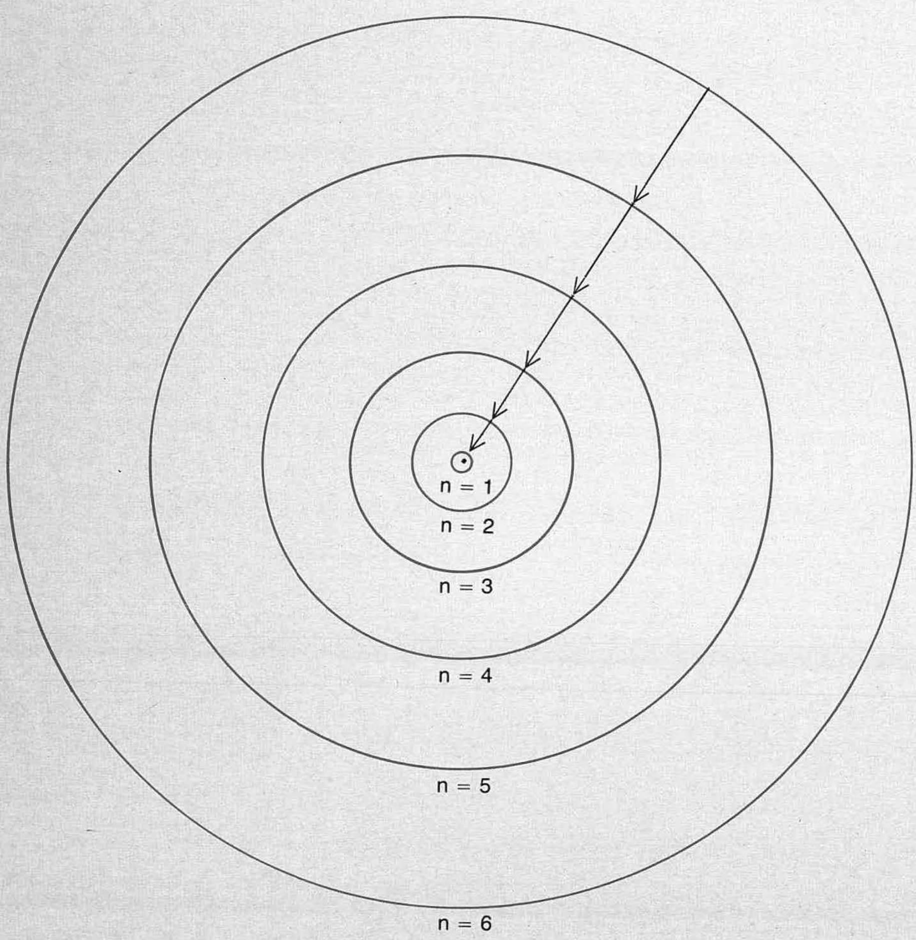


atom (*a*). As the kaon drops from one energy level to the next (*orbits in gray*), it falls within the electron orbits of the atom (*orbits in color*). The energy that the kaon releases during its fall ejects electrons from the outer reaches of the atom (*b*). These electrons are called Auger electrons. At each succeeding jump toward the nucleus the amount of energy lost by the kaon increases. Below the lowest energy level (ground state) of the electrons the energy is released in the form of X rays (*c*). The more energetic the X-radiation, the shorter the wavelength. Sometimes the kaon jumps more than one orbit at a time. Finally it enters a region near the nuclear surface, where it encounters a nucleon (a proton or a neutron). Both the kaon and the nucleon disappear, creating two new particles: a pion (pi meson) and a sigma hyperon (*d*). The distances of the drawing are exaggerated. If the atom were drawn to scale and the nucleus were represented by a dot one millimeter in diameter, orbit of the first electron would be almost one meter away.

same way. Exotic atoms have two important characteristics. First, for the same quantum numbers the radii of the orbits are inversely proportional to the mass of the orbital particle. Second, the energy levels of the orbits are directly proportional to the mass of the orbital particle. For example, the pion is 273 times as heavy as an electron; therefore the diameter of the pionic atom is 1/273rd the diameter of the hydrogen atom, and the energy required to make the pion jump from one orbit to another is 273 times the energy required for an electron to make the same jumps in the hydrogen atom.

In order to make exotic atoms with negative mesons the mesons are created in an accelerator and directed at a suitable target. The mesons are slowed down and brought to rest by their interaction with the atomic electrons that are bound to the target nuclei. Ultimately the strong attraction of a positive nucleus draws the negatively charged meson toward it. In order for the atom to remain electrically neutral one of the atomic electrons is ejected as the meson is incorporated into the atom. The meson falls from one Bohr orbit to another as it approaches the nucleus that captured it. Mesons are generally caught in orbits larger than about $n = 30$, depending on the specific meson involved. The replacement process takes about 10^{-11} second; the capture time must of course be shorter than the lifetime of the meson. As the meson cascades through the orbits, it radiates photons in the form of X rays. It is by measuring the X-ray photons that we study exotic atoms.

In our experiments the mesons were produced in the Bevatron, the 6.2-billion-electron-volt accelerator at the Lawrence Berkeley Laboratory. X-ray detectors, the heart of the apparatus, were placed near the target. One of the most successful detectors was a single cylindrical crystal of ultrapure germanium two centimeters in diameter and four millimeters thick. The detectors and the associated electronic apparatus were perfected in the Lawrence Laboratory by the nuclear instrumentation group under Frederick Goulding, Richard Pehl and William Hansen. When an X ray is absorbed in the lattice of germanium atoms that make up the crystal, it excites many electrons in the lattice to higher energy levels. A vacancy in the lattice left by an excited electron can be regarded as a hole. The electron-hole pairs act as carriers of electric charge. In our experiments the X rays deposited their energy within the crystal in the form of electron-hole pairs, and the number of charges was proportional to the energy of the X rays. Electrical pulses produced by the charges were amplified and converted to digital numbers. The numbers, whose magnitudes were proportional to the energy of the X rays, were recorded on magnetic tape. A computer sorted the energies and tabulated them into the spectrum of the exotic atom [*see illustration on page 108*]. The excellent resolution of these spectrometers allowed a wealth of information to be recorded from the exotic atoms produced by the Bevatron.

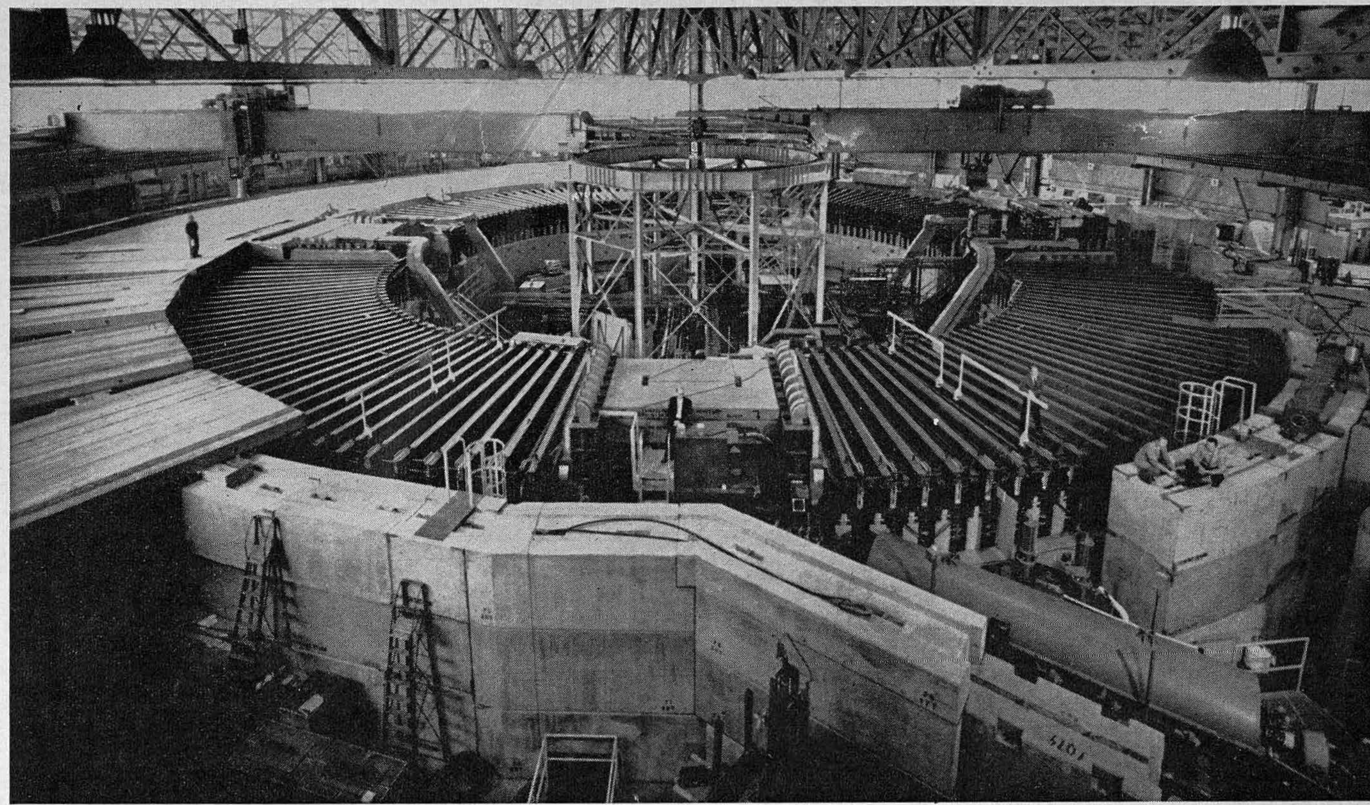


BOHR MODEL of the atom assigns the electrons to discrete orbits around the nucleus. Each orbit is given a principal quantum number (n). The ground state of the atom is $n = 1$; higher levels are $n = 2$, $n = 3$ and so on. The radius of each orbit is proportional to n^2. Where n is large, the electron can easily be stripped from the atom. Radius of the $n = 1$ orbit of hydrogen is 5×10^{-9} centimeter. The Bohr model also applies to an exotic hydrogen-like atom except that all the radii are smaller in proportion to the mass of the orbital meson. For kaonic hydrogen the radius of the $n = 1$ orbit is 5×10^{-12} centimeter.

Two kinds of exotic atom have been known for almost 20 years. One is the pionic atom; the other is the muonic atom, made with muons, or mu mesons. X rays from pionic atoms were first studied by Morton Camac, A. D. McGuire, Joseph B. Platt and Harry J. Schulte at the University of Rochester in 1952. A year later Val L. Fitch and James Rainwater conducted experiments on muonic atoms at Columbia University. In more recent years interest in such atoms has been rekindled.

The behavior of muonic atoms has provided much information about the structure of the nucleus, particularly about the distribution of protons within nuclei. Muons are particularly valuable for probing the interior regions of nuclei because they interact only with the electric charge of the protons and do not "feel" the strong nuclear force that binds the nucleons (neutrons and protons) together. Since the size of the orbits is inversely proportional to the mass of the orbiting particle, some of the muonic orbits of low principal quantum number are so small that they actually lie within the nucleus [see "Mesonic Atoms," by Sergio DeBenedetti; SCIENTIFIC AMERICAN, October, 1956].

The most abundant of the particles that can make exotic atoms are still the pions. Like muons and electrons, pions feel the electromagnetic force of the nucleus, but in addition they are agents of the nuclear force. This force between



BEVATRON at the Lawrence Berkeley Laboratory of the University of California is one accelerator that has produced mesons for the study of exotic atoms. It is capable of accelerating particles up to an energy of 6.2 billion electron volts (BeV). At lower right is a linear accelerator that injects protons into a chamber within the huge circular magnet. The magnet is 120 feet in diameter and weighs 10,000 tons; the men standing on top of the machine indicate its scale. Particles circle the chamber four million times in 1.8 seconds, close to speed of light. In that time they travel some 300,000 miles, farther than the distance from the earth to the moon.

nucleons, and between pions and nucleons, acts only over a very short range: some 10^{-13} centimeter. It manifests itself in violent interactions that can cause particles to change from one species to another. Some 1,000 times stronger than the electromagnetic force, it is often called simply the "strong force." In this terminology many particles are said to react "strongly."

The precise energy levels of pionic atoms should be predictable from knowledge of the pion-nucleon interactions. Up to now, however, some of the calculated levels have not agreed very well with the levels observed in experiments. The study of pionic X rays has nonetheless yielded the most accurate value for the mass of the pion.

My own primary interest has been in exotic atoms formed with the particles known as kaons (*K* mesons) and sigma hyperons. The investigation of these atoms and the atoms formed with antiprotons (negatively charged protons) has begun only quite recently. After pions and muons had been put in orbit around nuclei, negative kaons were logically the next particles to be tried. Some evidence that kaonic atoms could be formed was provided by the tracks of kaons stopped in specially prepared photographic emulsions. Although the emulsion experiments did not reveal X rays, they did show that electrons and the reaction products of kaons were ejected from the silver atoms of the emulsion in a manner consistent with the formation of kaonic atoms. To the best of my knowledge the first attempt to observe the X rays from kaonic atoms was made by Joseph Murray and Nahmin Horwitz at the Berkeley Bevatron in 1958. They saw one line in the X-ray spectrum of carbon, but because the resolution of the detector was inadequate the experiment was discontinued. (Germanium semiconductor detectors had not yet been invented.) The first report on "K^--mesonic" X rays was published in 1965 by G. R. Burleson, David Cohen, Richard C. Lamb, Daniel N. Michael, R. A. Schluter and Thomas O. White, who were working at the Argonne National Laboratory. They used as a target helium: one of the most difficult but important elements to try. Again the results were not entirely convincing, mostly because the resolving power of the detector was inadequate and the level of background "noise" in the data was high. In 1966 Dick A. Mack and I, working with silicon semiconductor detectors at the Bevatron, succeeded in measuring several X-ray lines from kaons injected into targets of the light elements lithium, beryllium, boron and carbon.

Beams of kaons are much more expensive to make than beams of pions or muons. Pion and muon beams can be produced with cyclotrons of moderate energy; for all practical purposes negative kaons can be made only by machines that can accelerate particles to energies of more than five billion electron volts.

Negative kaons interact violently with both neutrons and protons. The investigation of kaonic atoms therefore yields information on the nature of the surfaces of nuclei. Are the surfaces smooth or granular? Do they show equal numbers of neutrons and protons? Or do they have more neutrons than protons, as was proposed by Montgomery Johnson and Edward Teller in 1953 on the basis of theoretical considerations [see "The Texture of the Nuclear Surface," by Chris D. Zafiratos; SCIENTIFIC AMERICAN, October]? We already know the distribution of protons from earlier investigations that showed how electrons are scattered by nuclei and how muonic atoms behave when the muons orbit within the nucleus. Electrons and muons do not, however, sense the presence of neutrons.

Observations of low-energy kaons in their encounters with neutrons and protons in bubble chambers suggested that the kaons could be used as probes because their behavior at the nuclear surface could be predicted. The number of reactions involving kaons at certain distances from the nuclei should in some way be proportional to the number of nucleons encountered at those distances. Whenever a kaon encounters a nucleon, both particles disappear and two new particles appear: a pion and either a sigma hyperon or a lambda hyperon. As in chemical reactions we must be careful to balance the equation: the electric charge and the pertinent quantum characteristics of the particles must be equal on both sides of the equation.

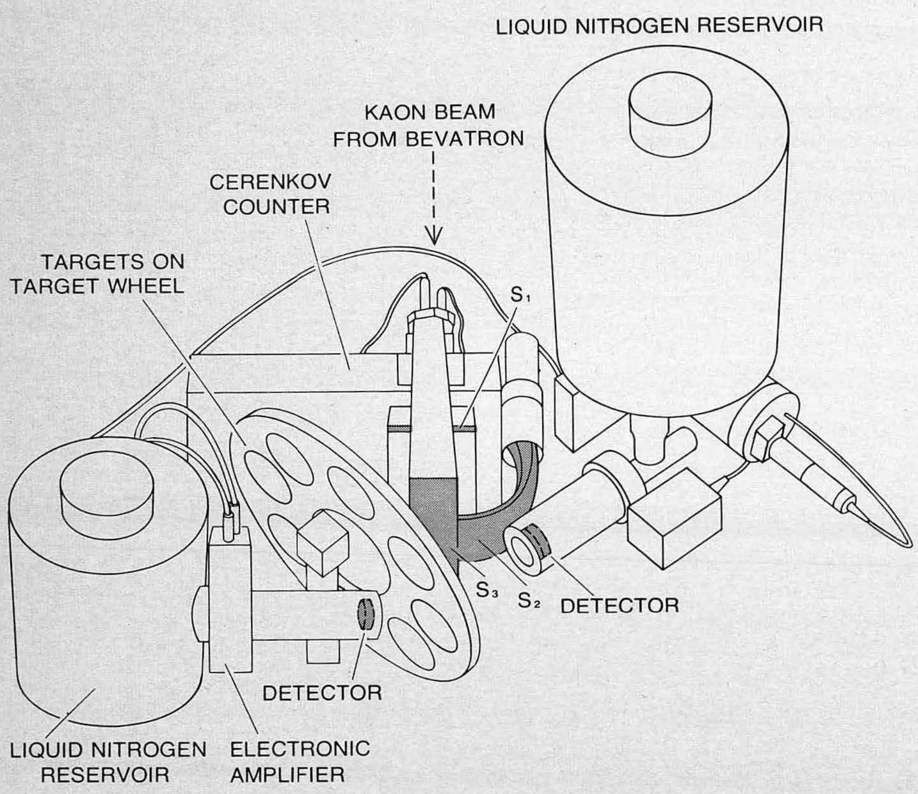
Let us imagine the sequence of events from the moment a negative kaon is captured by an atom. The kaon has replaced one of the inner electrons of the atom and is established in an orbit of about $n = 30$. The kaon is strongly attracted to the positively charged nucleus. It jumps down to a lower orbit, and at this stage of the process the energy liberated is most likely to eject additional electrons from the outer regions of the atom. These electrons are called Auger electrons. At each succeeding jump toward the nucleus the amount of energy lost by the kaon increases, until X rays become the dominant means of shedding the energy. Each jump of the meson between certain orbits results in the emission of an X-ray quantum of an energy and wavelength belonging to that transition. Finally the kaon enters a region near the nuclear surface, where it has a chance to encounter a nucleon in the "rarefied nuclear atmosphere" [*see illustration on pages 102 and 103*].

We interpret the disappearance of the X-ray lines in the spectrum of our measurements as a signal that the kaons have reacted with nucleons on the nuclear surface. For example, in certain elements the intensity of the X-ray lines for transitions between lower orbits (such as from $n = 4$ to $n = 3$) is less than the intensity for transitions between higher orbits (such as $n = 5$ to $n = 4$). This decrease in intensity means that some of the kaons were absorbed from the $n = 4$ orbit. If the intensity had dropped by half, we could say that half of the kaons were absorbed from the fourth orbit and thus could not make the jump from $n = 4$ to $n = 3$. For a transition starting from an orbit of a given principal quantum number the intensity had been predicted to drop quite suddenly as heavier nuclei (nuclei with more charge) were used as the target. Increasing the charge of the nucleus shrinks the kaonic orbits and brings the kaons closer to the nucleus; in addition the radius of the nucleus itself increases slightly. On the assumption that protons and neutrons are equally distributed on the nuclear surface, theory predicted that the termination of the series of X-ray lines would be a function of the number of protons. Our kaonic X-ray experiments of 1968 indicated, however, that kaons encountered nucleons at distances farther from the nuclear surface than had been anticipated. We theorized that the kaons reacted with a low-density halo of neutrons above the main nuclear surface.

There is no complete agreement among theoreticians concerning the interpretation of the experiments. At the European Organization for Nuclear Research (CERN) in Geneva, T. E. O. Ericson has devoted considerable effort to the understanding of pionic and kaonic atoms. He believes the observed decreases in X-ray intensity can be calculated on the assumption that protons and neutrons are present at the nuclear surface in equal numbers. On the other hand, the notion that nuclear surfaces are dominated by neutrons has been put forward by several physicists since Johnson and Teller made their original prediction. The theoretical calculations are based on the concept that the nucleons will arrange themselves in a configuration that allows the total energy of the system to be at a minimum. An analogy is the fact that a free drop of liquid takes the shape of a sphere if it is not disturbed by outside forces. When all the known properties of nucleons are applied to the picture of nuclear matter, the configuration that results is one in which the neutrons have a slightly larger radius of distribution than the protons.

There are further complications in the simplified conclusion that the observed kaonic X-ray spectra show that nuclei have a skin of neutrons. The negatively charged kaons and positively charged protons attract each other with particular strength under special circumstances. This effect might cause the kaons to react more strongly with protons bound in nuclei than had been anticipated.

The early demise of kaons might then



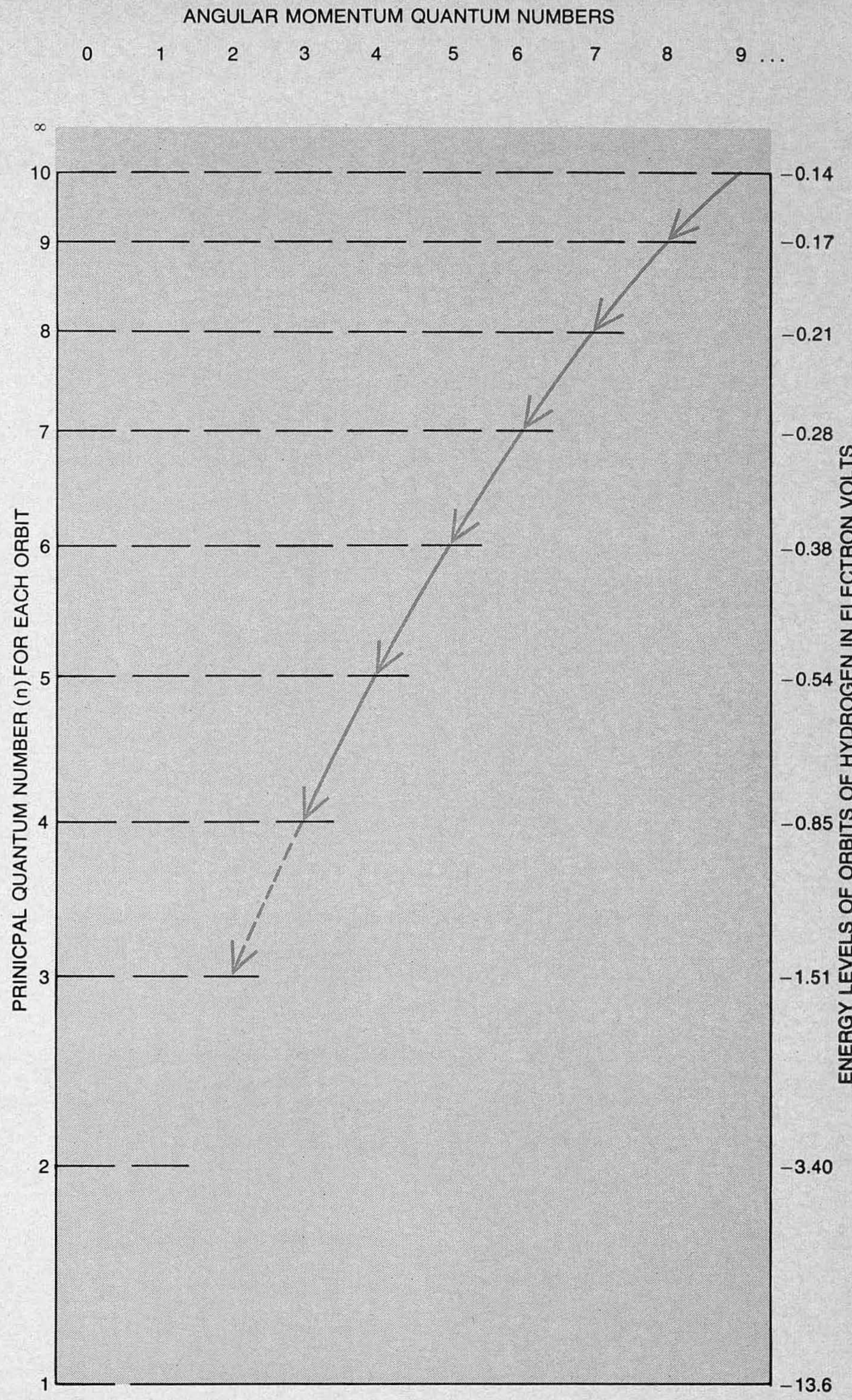
X RAYS FROM KAONIC ATOMS were detected by the apparatus depicted in this drawing. The targets were mounted on a wheel and could be selected at will. Two (sometimes three) germanium or silicon detectors were placed near the target. The detectors were cooled by liquid nitrogen to suppress background "noise" in the data. Beam counters (S_1, S_2 and S_3) signaled the arrival of the kaons at the target. Response from detectors was amplified electronically and recorded on a chart as the X-ray spectra shown on page 108.

be attributed to a voracious appetite of some protons rather than an overpopulation of neutrons. Another factor that comes into play is that the affinity of kaons for nucleons is so strong the orbits of the kaons are pulled in closer to the nucleus than they would be for particles that do not react so strongly. These effects and others would modify the simple picture suggested by the exotic hydrogen atom.

Quantitative estimates of these effects are controversial. It is apparent that additional data and calculations will be needed to resolve the details of the structure of the surfaces of nuclei and the distribution of neutrons within the nuclei. Up to the present time most of the experiments on kaonic atoms have been done at Berkeley and at CERN, where an active group is directed by G. Backenstoss. Other groups at Argonne and at the Brookhaven National Laboratory have recently joined in the investigations. In spite of the complications physicists working on exotic atoms are confident that their studies will lead to a clearer picture of nuclei.

X-ray spectra of exotic atoms made with antiprotons were first observed by the CERN group in 1970. The antiproton was discovered with the Berkeley Bevatron, but the machine does not make a beam of antiprotons with sufficient intensity to produce antiprotonic X-ray spectra. Antiprotonic atoms emit X-ray spectra that are similar in appearance to kaonic X-ray spectra, but there is one significant difference that has recently been observed. If we could see all the lines at high resolution, we would almost certainly find that each line is a doublet, that is, it is made up of two separate lines. The lines are split because antiprotons and protons possess spin and magnetic moment. They behave as if they were spinning magnets. Some have their north pole "up" with respect to their orbital motion around a nucleus and some have it "down." In antiprotonic atoms the energy levels of the various orbits of the antiproton around the nucleus are slightly different depending on whether the spin is "up" or "down." The X-ray lines of the spinning particles are thereby split into two components, and the amount of splitting can be calculated.

The magnetic moments of protons and antiprotons are believed to be exactly equal except for their algebraic sign. This assumption is based on some of the most sacred symmetry principles in physics. The belief is that if all the

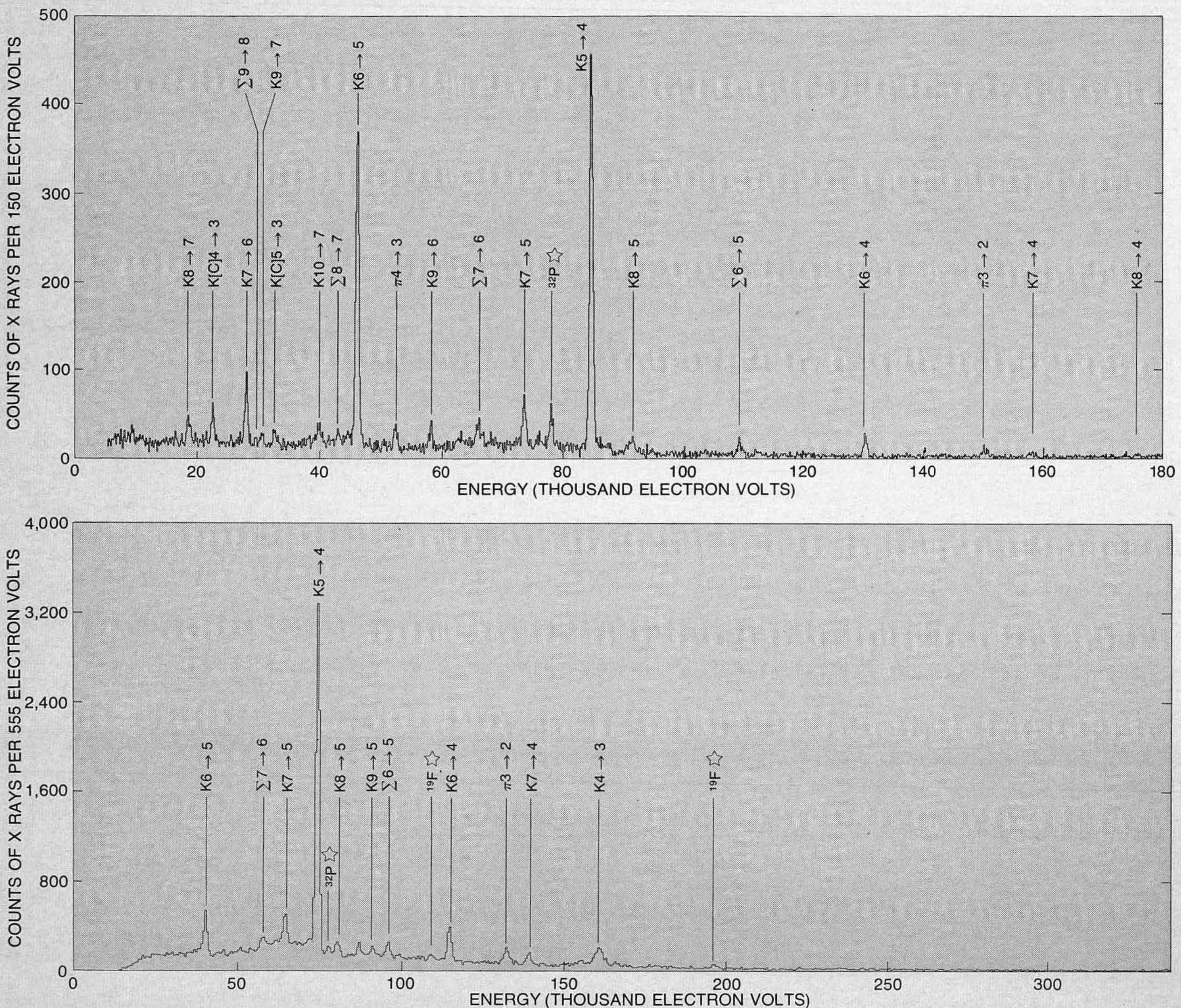


ENERGY LEVELS and angular-momentum quantum numbers of a hydrogen-like atom are shown. The principal quantum number (n) for each orbit is indicated in the vertical scale to the left. The vertical scale to the right shows the energy level of each orbit in hydrogen; for example, it would require an energy of 13.6 electron volts to take an electron in the ground state ($n = 1$) completely out of the hydrogen atom. Exotic atoms can be considered hydrogen-like systems. The arrows show the main transitions a meson makes as it falls toward the nucleus after being captured. Some 10 percent of the particles skip an orbit as they fall, say from $n = 6$ to $n = 4$ without pausing at $n = 5$. The energy in electron volts of each orbit of an exotic atom is given by the relation $-13.6(Z^2/n^2) \times$ mass of the orbital particle divided by the mass of the electron. Z is the number of protons in the nucleus and n is the principal quantum number. For example, mass of a kaon divided by mass of the electron is 966. The $n = 4$ orbit of a kaon around a chlorine nucleus has an energy of 237,000 electron volts. For the $n = 5$ orbit the energy is 152,000 electron volts. The difference between these two energies is 85,000 electron volts. There is a tall peak in the X-ray spectrum of chlorine at this energy, corresponding to the transition from the $n = 5$ orbit to the $n = 4$ orbit (*see the carbon tetrachloride spectrum on the next page*).

charges were interchanged (negative for positive), all the position coordinates were interchanged ($-x$ for $+x$ and so on) and time ran backward, the results of all experiments in the "negative" world would be the same as those in the "positive" one. Physicists like to test the theorem of invariance at every opportunity. A split X-ray line in the spectrum of antiprotonic uranium was observed last summer by a group of physicists at Brookhaven. They found that the magnetic moment of antiprotons was opposite in sign to the magnetic moment of the protons and agreed with the predictions of symmetry. It will probably be some time, however, before measurements are accurate enough to afford an ultimate test of the theorem by this method. Meanwhile antiprotonic atoms are expected to take their place alongside pionic and kaonic atoms as probes of the nucleus.

As I have mentioned, kaons react with nucleons to form pions and hyperons. Many of the hyperons are ejected from the nuclei in which they are formed. Their kinetic energy is sufficiently low for them to have a high probability of staying in the target in which they originate. They are slowed down, come to rest and are captured in the same way that kaons are captured by nuclei. Thus X-ray lines from hyperons were expected to appear along with the X-ray lines from kaons.

In a kaonic X-ray spectrum of potassium obtained in the Berkeley experiments of 1968 there was a line at 136,000 electron volts that corresponded to the transition energy of a sigma-minus hyperon when it jumps from the $n = 6$ orbit to the $n = 5$ orbit. Some two years later the CERN group confirmed the formation of sigma-minus hyperonic atoms by identifying several spectral lines of the transitions of sigma-minus hyperons in chlorine and zinc. The X-ray lines of sigma-hyperonic atoms have appeared in the kaonic spectra of elements as light as lithium and in the medium-heavy ele-



SPECTRA OF X-RADIATION from kaonic atoms are shown for targets of carbon tetrachloride (*top*) and sulfur (*bottom*). The energy of the spectrum in each case increases toward the right, and the intensity of the X-ray lines increases toward the top. K stands for a transition made by a kaon, Σ for a transition made by a sigma hyperon and π for a transition made by a pion. The numbers indicate which orbits were involved in the transition. For example, $K8 \rightarrow 7$ means that the transition was made by a kaon jumping from its $n = 8$ orbit to its $n = 7$ orbit. In the carbon tetrachloride target most of the transitions occurred in chlorine atoms. Transitions in carbon atoms are labeled $[C]$, for example $K[C]4 \rightarrow 3$. The stars stand above the spectral lines that were created not by kaonic X rays but by gamma rays that were emitted by excited phosphorus or fluorine nuclei returning to their ground-state energy level.

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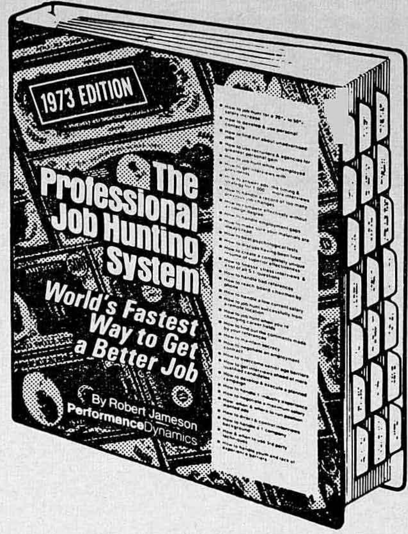

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ments. At the present time no lines have been found in the spectra of the heavy elements.

The intensity of the lines for sigma hyperons is about 2 percent of the intensity of the principal lines for kaons. Several factors contribute to the low intensity. First, only some 8 percent of the kaons react to make negatively charged sigma hyperons. Second, after the hyperons are created, many of them interact with the nuclei in which they are formed. Third, some of the hyperons decay into other particles while they are being slowed down or while they are in higher energy orbits.

Like many other subatomic particles, hyperons have spin and possess a magnetic moment. They are found in three forms: the sigma-plus (positively charged), the sigma-zero (uncharged) and the sigma-minus (negatively charged), and in the antiparticles of these forms. The magnetic moment of the sigma-plus has been crudely measured by observing how the particle precesses in powerful magnetic fields. The orientation of the sigma-plus particles in the field was determined by observing the direction taken by the particles into which the hyperons decay.

When sigma-minus hyperons decay, they do not emit particles that signal their orientation. Hence their magnetic moment cannot be measured by the method that works with sigma-plus hyperons. The measurement of the sigma-minus magnetic moment would be important to particle physics. The study of sigma-minus hyperonic atoms offers this possibility if we can observe the doublet structure of the X-ray lines. The amount by which the lines are split is proportional to the fourth power of the atomic number (the number of protons). Therefore the heavier the element, the easier it should be to resolve the doublet pairs of X-ray lines. The splitting will nonetheless be difficult to observe, particularly if few sigma-minus atoms are made in heavy elements. Even if the lines cannot be completely resolved, it may be possible to set a meaningful upper limit on the magnetic moment of the sigma-minus hyperon. Sigma-hyperonic atoms may also add to the information gained from other exotic atoms in the mapping of nuclear surfaces.

What is the possibility of making other exotic atoms? In the table of subatomic particles there are two more candidates: the xi-minus and the omega-minus. Their lifetime is roughly the same as the lifetime of the sigma hyperons. The xi-minus is 10 percent heavier than the sigma-minus and the omega-minus is 40 percent heavier. The two particles are so scarce and so difficult to produce, however, that the tracks of only some 10,000 xi-minus particles and of a mere 25 omega-minus particles have been identified in bubble chambers at the largest accelerators. Perhaps the more powerful machine now in operation at the National Accelerator Laboratory in Batavia, Ill., and the one under construction at CERN will produce sufficient numbers of xi-minus and omega-minus particles to make it possible to identify atoms of the last two candidates on the present particle list.

In conclusion I should like to relate how the study of one subject can lead to another subject in this fascinating research that involves both high-energy physics and nuclear physics. Let us return briefly to pionic and muonic atoms. In addition to X-ray lines the spectra of these atoms showed gamma-ray lines that had come from excited states of nuclei formed in the targets in which the mesons had stopped. The mesons carried energy to the interior of the nuclei and raised the protons and neutrons to excited levels, in somewhat the same way that the electrons of atoms are raised to excited states. When the nuclei fall back to their ground level, radiation is emitted in the form of gamma rays. Now, when we were getting our kaonic X-ray spectra, we were asked many times: "Why don't you see nuclear gamma rays along with the kaonic X rays?" In some of the spectra there were a few low-intensity lines that we had not been able to attribute to exotic atoms. We finally did identify these lines as nuclear gamma rays.

The relevance of gamma rays induced by kaons has not yet been assessed, but a significant aspect of kaonic reactions is the following. When a kaon encounters a nucleus, it sometimes transforms a neutron into a lambda hyperon, forming what is called a hypernucleus. For example, the hypernucleus lambda-helium 4 consists of two protons, a neutron and a lambda hyperon. Hypernuclei are expected to emit gamma rays that will be of considerable interest because the energy of the radiation will yield information on the force between the lambda hyperon and nucleons. That force is a manifestation of the strong force, the nature of which is one of the fundamental questions facing physics. It is possible that these gamma rays will be made accessible by a refinement of the techniques used to obtain the spectra of kaonic X rays.

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