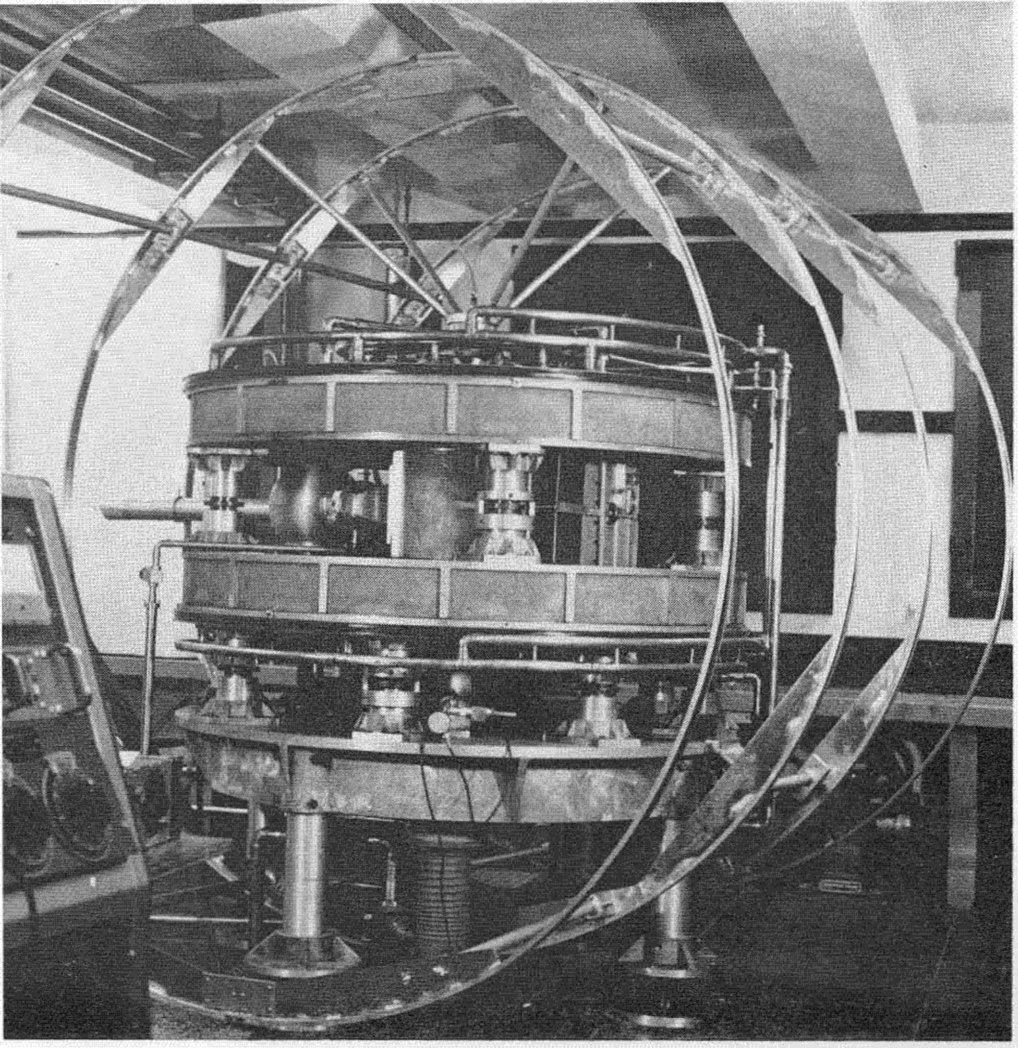

by Jesse W. M. DuMond and Edwin C. Seltzer

THE IRON-FREE, MAGNETIC, BETA-RAY SPECTROMETER

Designed and built at Caltech, it is one of the newest instruments for studying atomic nuclei.

The Caltech physics research group known as Physics 34, under the leadership of Felix Boehm, has been engaged for a number of years in nuclear spectroscopic studies in an effort to learn more about what goes on inside the nuclei of atoms, how they are constructed, and what laws they obey.

One of the newest tools used in this work is an instrument known as the high-resolution, iron-free, magnetic, beta-ray spectrometer, designed and built entirely at Caltech. In one of its important applications, the instrument is used to study the spectral distribution of the energies of "internal conversion electrons" by deflecting the electrons in a magnetic field as they escape from radioactive sources prepared in a nuclear reactor.

The spectrometer has been designed, as its name implies, to be free of iron or other ferromagnetic materials, the magnetic field being entirely generated by direct electrical currents flowing in coils of copper ribbon of very accurately constructed geometrical configuration. The magnetic field in the vicinity of such coils can be calculated very accurately from the geometrical dimensions of the coils and from the current. If iron were present, the phenomenon known as hysteresis would interfere seriously with this accuracy and reproducibility.

The instrument is used to obtain information as to the energy levels, spins, parities, and other properties of nuclear "excited states" in the complicated heavy nuclei of such atomic species as hafnium 175 and 177, lutecium 175, tantalum 181, ytterbium 175, tungsten 182 and 183, and thulium 169. These eight nuclidic species have recently been studied by two Caltech graduate students, now postdoctoral fellows—Ralph Hager and Edwin Seltzer.

The number attached to each of these eight nuclear species is known as the mass number of that nuclide. It corresponds to the total number of nucleons (protons and neutrons) of which that nucleus is believed to be composed. Since neutrons are electrically neutral (i.e., they have no electrical charge), the number of protons alone determines the atomic number. The atomic number corresponds to the number of electrons which the nuclear charge requires to form an electrically neutral atom. Most of the chemical and physical properties of each atomic species, including the size of the atom, depend on the outer electronic structure.

The nuclei of atoms, when excited, can assume only well-defined *discrete* energy states, called *energy levels*. The nucleus is said to be quantized, just as are the various modes of excitation of the electrons. The intervals between energy values of these levels may differ markedly from each other, forming a pattern characteristic of each nuclear species. For each nuclear species the lowest rung of the energy stepladder formed by these levels is called the ground state, and the levels above it are called excited states. The pattern of unequally spaced energy levels is called the "level diagram" for that nuclear species.

NUCLEAR ENERGY PHENOMENA

When, as may often happen spontaneously, an excited nucleus goes from a higher to a lower energy level, the difference in nuclear energy thus lost may result in several observable phenomena such as:

(a) the emission of a photon of gamma radiation, or

(b) the ejection, from the atom to which the nucleus belongs, of one of that atom's electrons—a process called internal conversion.

When this process occurs, the ejected electron possesses a very sharply defined kinetic energy—the characteristic energy it received from the nuclear transition, minus the energy required to free the electron from its attachment in the atom. A study of the kinetic energies of such ejected converted electrons, therefore, yields highly accurate information as to the energy level diagram of the nucleus of the atom under study.

ENERGY DISPOSAL METHODS

These two processes are not the only ones through which excited nuclei dispose of their energies. For example, they may also:

(c) capture electrons from the atom in which they are situated, or

(d) give birth to electrons where none existed before (beta decay).

The magnetic spectrometer detects the internally converted electrons ejected by process (b), and it measures the different characteristic *speeds* of these electrons by deflecting them with a magnetic field of precisely designed spatial distribution whose intensity can be progressively varied at will over a wide range. The spatial distribution of this field is purposely designed with great care so that electrons of one, and only one, well-defined kinetic energy issuing from one fixed point in the field where the radioactive source is placed will be refocused. This is done sharply and selectively by the magnetic field at another fixed point, the secondary focus, where a fine slit is placed to receive them. The electrons that find their way through the slit are counted by means of a Geiger-Muller counter placed with its thin window immediately behind the slit.

The magnetic field is produced by a system of six coaxial oil-cooled coils of copper ribbon. The intensity of this entire magnetic field distribution can be controlled and varied over a wide range by controlling the electrical current flowing in the copper coils. The spectrum of conversion-electron energies is explored as the magnetic field intensity is automatically varied in successive small steps, stopping at each step and recording the rate at which the electrons are counted at the secondary focal slit. Whenever a magnetic field intensity is reached of a precisely correct amount to focus electrons having one of the energies characteristic of the nuclear source under examination, the counting rate recorded by the detector rises abruptly. This, together with the field intensity, is automatically recorded, thus giving evidence that there is a characteristic line (energy step in the nuclear energy level ladder) at a sharply determined energy corresponding to the existing magnetic field intensity. The energy is automatically recorded.

The energies thus determined yield important information as to the magnitudes of the energy intervals between pairs of levels on the diagram of the nuclear species under study.

The relative *intensities* of these conversion lines also furnish equally important information of another kind. Not all transitions between pairs of levels in the diagram are expected to be equally likely to result in the ejection of conversion electrons. Some of them, on the contrary, may be more likely to emit gamma rays instead. Thus the relative intensities of the conversion electron lines give a valuable clue regarding the nuclear level diagram structure and, when combined with other information, help to identify the nuclear spins and parities associated with the various energy states. For any nuclear transition between a specified pair of levels, the ratio of conversion electrons knocked out to gamma rays emitted is called the conversion coefficient for that transition. This is a very important quantity, of great interest for the interpretation of nuclear spectra, and the iron-free, magnetic, beta-ray spectrometer can play an important role in its experimental determination.

TWO KINDS OF NUCLEONS

Nuclei are believed to be clusters of particles called nucleons. These are of two kinds—protons, each of which carries one unit of positive electrical charge; and neutrons, which are electrically neutral. These two varieties are of nearly equal mass, the neutron being just a little more massive. The nucleons are conceived to be in rapid movement in the nuclear cluster, and the entire cluster is presumed to be held together by extremely strong internucleonic forces, of quite different character from either electrical or gravitational forces, whose range of action is very short—the size of the entire nuclear cluster being only of the general order of one ten-thousandth the linear dimensions of the atom in which it resides. Nevertheless, the mass of the nucleus may be from 2,000 to 4,000 times that of the remainder of the atom (i.e., the atomic electron cloud surrounding the nucleus). It is this electron cloud, however, which determines the size of the atom—the volume it occupies in solid matter.

A reasonably successful nuclear model proposed circa 1950 by Mayer and Jensen, called the "Shell Model," pictures the two kinds of nucleons as executing orbits inside the nucleus, a little like planets. They are conceived as belonging to "shells" in close analogy to the shell structure of the *electron* orbitals *outside* the nucleus which also cluster in so-called shells having different energies of attachment to the parent atom, the innermost shells being those most strongly bound.

CLOSED NUCLEAR SHELLS

Quantum theory tells us that, just as in the case of atomic electrons, a given nuclear shell can contain only a limited number of nucleons. A proton or neutron shell with such a limiting number of nucleons is said to be closed and, if one tries to add further nucleons to reach a larger nuclear mass number, a new shell must be started. Many nuclei may thus consist of closed shells forming a stable core plus a *residue* of additional nucleons external to the core and insufficient in number to form another complete closed shell.

In 1953 A. Bohr and B. R. Mottelson, in Copenhagen, devised a theory of "collective motion" of nucleons, which describes certain states of nuclei behaving as if all the nucleons moved together, rotating and executing surface vibrations—a kind of liquid drop motion.

The shell model of Mayer and Jensen and the collective-motion model of the Copenhagen school seem at first to be incompatible and to confront us with a dilemma. In the first model the nucleons seem to execute more or less independent orbital motions; in the second they seem tied together so as to behave like a fluid. This is indeed exciting, for a dilemma of this sort is likely to conceal a gold mine of new information and new viewpoints.

It seems probable that the shell model describes the behavior of the nucleons in the closed shells which together form the core of the nucleus. This core is probably normally of spherical symmetry, relatively inert, and playing a fairly passive role in the nuclear dynamics. The leftover nucleons, those outside the core, if few in number, can be described as moving independently. The low-lying energy levels of many nuclei can be fairly well described in this way. If there is a sufficient number of these extra nucleons, it may be energetically favorable for the nucleus to exist in configurations where these nucleons move in a correlated manner. In fact, the core is disrupted, and nucleons normally associated with the core now have their motion strongly correlated with the extra nucleons. In this manner we understand the stably deformd nuclei, exhibiting rotational states, and vibrational states of many kinds in all nuclei. Even though the collective states are very complicated in that they involve the interplay of many nucleons, the predictions of the "collective model" have been verified in exceptional detail by precision experimental measurements. Considerable success has been obtained in the last decade in efforts to develop these simple models quantitatively. Many of the techniques developed in the study of electron gases and liquid helium have been extensively utilized.

ELECTROSTATIC REPULSION

Astronomers are greatly interested in a better knowledge of the properties of nuclear matter in a hypothetical state in which an unlimited number of nucleons can cluster together. While this state cannot be realized under terrestrial conditions, it might conceivably exist in postulated astronomical objects such as neutron stars. It is thought that unlimited numbers of nucleons cannot cluster together to form stable nuclidic species, because in ordinary nuclei the electrostatic repulsion between the protons renders nuclei with a large excess of protons unstable. If we try to dilute this repulsion by adding to such nuclei a comparably large increment of neutrons, a different sort of instability results. Such heavy neutron-rich nuclei disintegrate radioactively by alpha and beta decay and by spontaneous fission into lighter and more stable nuclei. However, in neutron stars (the dead corpses of once-ordinary stars) the total mass and density of the star may, through gravitational force alone, be sufficiently large to hold it together as a single huge mass of nuclear matter.

These considerations make it plain why there is great fundamental interest in trying to gain a more satisfactory understanding of the precise nature and properties of the forces which bind nuclei together.

SOME ACKNOWLEDGMENTS

Science, and especially physics, becomes ever more and more a cooperative enterprise to which scientists of all nations and races freely contribute. The present instrument furnishes an excellent example.

The first iron-free beta-ray spectrometer utilizing the principle of two-dimensional (so-called double) focusing was designed and built by N. Svartholm and Kai Siegbahm in 1946 in Uppsala, Sweden. They in turn acknowledged their indebtedness to two Americans, D. Kerst, the inventor of the betatron, and theoretician R. Serber, who were the first to derive the conditions for radial and vertical focusing. These concepts were developed from their observation of the electron orbits in the betatron, a device with a quite different purpose than electron spectroscopy.

The principal difference between the Caltech instrument and its Swedish predecessor is in the design of the d.c. current-carrying coils which generate the magnetic field. The design calculations for the geometrical parameters of our present six-coil design were first worked out for a much larger instrument (about three times the linear dimensions of the present Caltech instrument) designed by G. E. Lee-Whiting and E. A. Taylor, at Canada's Chalk River Atomic Energy Establishment. However, for the smaller, less expensive, and more compact Caltech design the Chalk River results had to be considerably modified through an electronic computer program by Thomas Taylor, then at UC, Riverside.

Acknowledgments are also due to Herbert Henrikson, project engineer of Caltech's Physics 34 group, for his design of the heat exchanger for cooling the circulating supply of transformer oil which removes the Joule heat generated in the coils and for many other design contributions. The winding of the six coils to meet the required dimensional accuracy was an extremely demanding job, performed in the Caltech Central Machine Shop with great care by Mr. Henrikson. The excellent resolving power of the instrument is largely due to his effort.

The designs of the d.c. power source and of the automated data-handling system were the responsibility of Peter Alexander, formerly of Physics 34. He also first brought the instrument into successful operation in 1964.

The skill and interest displayed by Norman Huehl, D. Meyers, V. Thune Stephensen, and Ellsworth Kiersey of the Caltech Central Machine Shop contributed greatly to the success of this instrument.

—Jesse W. M. DuMond