Chapter 14 WRU Experiment, Round 2

B. Robinson, Casper, McGervey, Jha, Reichert, Huang
1960-70 1960-67 1960-99 1966-69 1966-70 1966-74

Western Reserve chairman John Major took charge of the rapid expansion of the WRU department. In the decade following 1955 he brought in several theorists, including Stefan Machlup, Joseph Weinberg and Paul Zilsel. Their work was described in Chapter 11. During the same period, he added experimentalists Berol Robinson, Karl Casper, John McGervey, Ben Green and B.S. Chandrasekhar. The work in experimental low temperature physics done by Green and Chandra will be described in Chapter 15. In the current chapter, we shall look at the research of Robinson, Casper, and McGervey, as well as that of three other experimenters who joined WRU shortly before the 1967 federation.

Nuclei

Robinson and Casper studied nuclear excited states. Their experiments made use of radioactive materials produced at nuclear reactor facilities or at particle accelerators. Typically, if the sources had lifetimes long enough, the experiments could be performed in a modestly equipped laboratory, such as those found in many universities. Particle detectors including scintillation counters and the newer solid-state devices, along with associated electronic pulse height and timing circuits, were adequate to elucidate many details of nuclear structure. Thousands of measurements made at laboratories around the world contributed to the compilation of extensive tables of nuclear properties, listing the energies, spins and parities of each ground state and excited level. Each entry in this data bank required the measurements of lifetimes, decay branching ratios, and angular distributions of the γ's, electrons and positrons emitted by the unstable nuclei. Some of this information has been applied to nuclear technology, for example in nuclear reactor or weapons design, but most of it has been used to develop, test and substantiate theoretical nuclear models. This was "the hot topic" in experimental and theoretical research in the first few decades of the "nuclear age".

Fig. 14-1. Berol Robinson

Robinson: nuclear spectroscopy

Berol Robinson was born in Detroit in 1924. His photo is shown in **Fig. 14-1**. He served as a radar officer in the Air Force during World War II, completed his A.B. at Harvard, and went on to receive a PhD at Johns Hopkins in 1953. At Hopkins, Robinson was one of Leon Madansky's first students, working on angular and polarization correlations of gamma rays emitted sequentially from radioactive cesium. He spent three years on the faculty of the University of Arkansas where, with radio-chemist Richard W. Fink, he published a review of experiments on electron capture. "Recent experimen-

tal results on orbital electron capture" *Rev. Mod. Phys*. **32** 117 1960. *(Electron capture is the process whereby an orbiting electron is captured by the atom's nucleus, transforming a proton into a neutron. The resulting new nucleus is most often in an excited state and subsequently emits one or more photons.)*

Robinson joined the WRU department in 1956 at age 32. He brought with him the unfinished vacuum-tube multichannel-analyzer he had begun to construct at Arkansas. He continued his work in experimental nuclear physics, eventually joining Mike Kalvius and S. Jha in the application of the Mössbauer effect to the determination of very short lifetimes of nuclear states.

Aside on nuclear lifetimes. The promptness with which an excited nucleus emits a γ depends on the quantum numbers of the initial and final nuclear states. Consequently, the measurement of the transition probabilities (or equivalently the lifetimes) of the excited states provides information on the spin and parity of each level. Lifetimes of long-lived nuclear states can be measured by measuring the radioactivity as a function of time. For sequential decays in which a second emission takes place very quickly after the first, the time interval between them can be measured electronically by "delayed coincidence" circuitry. For states which decay extremely quickly, one can estimate the lifetime by measuring the "width" of the state. The outgoing particle has a spread in energies, partly due to the finite resolution of the equipment, partly due to a Doppler-shift caused by thermal motion of the emitting nucleus, and partly due to the Heisenberg uncertainty principle. This last contribution to the spread in energy (i.e., the width of the bump in the energy plot) is correlated with the lifetime by the uncertainty relation: $\Delta E\ \Delta t = h/2\pi$. A width of one eV implies a lifetime of about 10^{-15} sec; one milli-eV implies 10^{-12} sec, i.e. one picosecond.

Lifetimes by Mössbauer

Robinson and his colleagues specialized in the measurement of extremely short lifetimes by exploiting the Mössbauer effect. Mössbauer's 1958 discovery (1961 Nobel prize) was all the rage in the 1960's. In Chapter 12 we described how Dick Hoffman used this effect to measure tiny shifts in the energy of gammas emitted by ^{57}Fe nuclei in order to determine the magnetism in thin iron films. Later in this chapter, **Jonathan Reichert** will be another member of the Mössbauer club.

*A further aside on **Mössbauer spectroscopy**. In Chapter 12 we described how Hoffman used a moving absorber to measure precisely the energy levels in iron atoms in thin films. A related technique for minimizing the energy stolen by the recoiling nucleus is called "recoilless emission". In this case, the emitting nucleus sits in a crystal lattice at low temperature so that when the γ is emitted the recoil momentum is taken up by the whole crystal. As a result, the γ gets almost all the energy from the transition. If the emission is nearly recoilless, then one can measure the energy spectrum with enough precision to determine the natural width and lifetime of the state.*

An important aspect of Robinson's work was the preparation of the radioactive nuclear sources. As an example, to study two excited states in osmium-189, he and his colleague **S. Jha** (to be introduced shortly), bombarded an iridium-191 target with 26 MeV protons at the University of Colorado cyclotron. This sometimes produced platinum-189 which decayed into iridium-189 which decayed into excited osmium-189 which decayed to the osmium ground state:

$$_{77}Ir^{191}\ (p,3n)\ _{78}Pt^{189}$$
$$_{78}Pt^{189}\ (10\ \text{hours by e-capture}) \rightarrow\ _{77}Ir^{189}$$
$$_{77}Ir^{189}\ (13\ \text{days by e-capture}) \rightarrow\ _{76}Os^{189*} \rightarrow\ _{76}Os^{189}\ \gamma$$

The star in the last line indicates that the osmium nucleus is in an excited state. An important number is the "13 days", long enough to get home from Colorado with a radioactive sample. An alternative procedure, which replaces the first two steps above, was used at the cyclotron of the nearby NASA-Lewis Research Center. It involved bombardment of a rhenium target by alpha particles:

$$_{75}Re^{187}\ (\alpha,2n)\ _{77}Ir^{189}$$

The Mössbauer velocity spectrum for the 69.6 keV γ's coming from the excited osmium is shown in **Fig. 14-2**. The transmission is plotted against the speed of the absorber, from -2 to +2 cm/sec. The source was the bombarded rhenium foil and the absorber was osmium metal (enriched in the A=189 isotope). Both source and absorber were at liquid helium temperature to reduce thermal motions. Because the emission is recoilless, the shape of this curve reflects the true energy spread of the nuclear state. The width of the observed dip was (5.34 ± 0.08) mm/s, which corresponds to a lifetime of (2.35 ± 0.06) nanoseconds. Note how *slowly* the absorber must be moved (half a centimeter per second) to map out the width of the state. "Studies of Osmium-189: Gamma Rays, Lifetimes, and Mössbauer Effect" *Phys. Rev*. **180** 1158 1969.

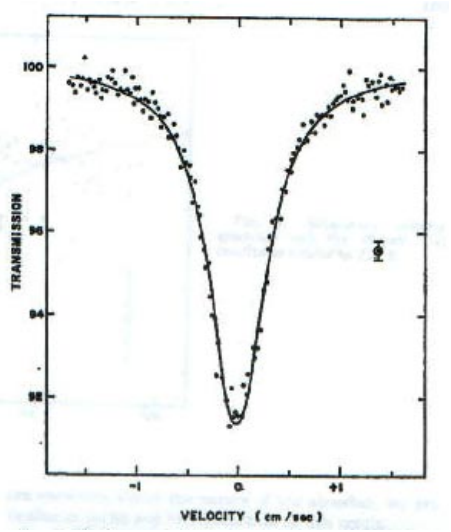

Fig. 14-2. Mössbauer spectrum.

Robinson initiated a small program of research on positron annihilation physics which was taken over and expanded brilliantly by John McGervey and his students. This work will be described later in this chapter. Robinson took a year's leave in 1961-62 on a fellowship from the Israel Atomic Energy Commission. He worked at the "Atoms for Peace" swimming-pool reactor at the Soreq Research Laboratory. He kept in constant contact with WRU chair, John Major, as they planned the coming year when the department would move into the brand new Science Center (now named in honor of WRU president John S. Millis).

Robinson and Jha and their several graduate students published a series of papers on the properties of nuclear states, for example "Gamma Rays in the Decay of Barium-131" *Phys. Rev*. **101** 149 1956. "Precision Determination of the Energy of the Gamma Ray of Potassium-40" *Phys. Rev*. **B134** 506 1964. "Intensity of the E3 Transition in Argon-38" *Phys. Rev*. **B140** 1529 1965.

Their Mössbauer work resulted in papers such as "The Mössbauer effect in ^{191}Ir and ^{189}Os" *Phys. Lett*. **25B** 115 1967. "Gyromagnetic Ratio of the 129-keV State in Iridium-191" *Phys. Rev*. **185** 1555 1969. "Mössbauer-Effect Studies in Hafnium-Metal Single Crystals" *Phys. Rev*. **187** 475 1969.

In 1967, Robinson was appointed vice-chair of the WRU department, thus allowing then-chairman Chandrasekhar to concentrate on the preparations for the merger with Case. Robinson was an extremely popular teacher and was successful in devising ways to make undergraduate laboratories more effective. In fact, Robinson and Weinberg were awarded first prize in the 1966 AAPT teaching apparatus competition for two “up-to-date” demonstration experiments: one on the Mössbauer effect, the other on positron annihilation.

His promotion to full professor was strongly supported by his chairman and department in 1967. But, in view of the merger and related uncertainties, it was not approved by the acting-president. Two years later, after Harvey Willard had taken over as chairman of the combined department, Robinson took a year’s leave of absence. He accepted a position at the Education Research Center of MIT, where he joined an experimental program in undergraduate education, including research in alternative learning methods and undergrad research participation. The time spent at MIT would be a turning point in Robinson’s career. He was asked to prepare the “educational component” of the “U. S. Metric Study”. This assignment would pique his interest in science in the public arena. The report, mandated by Congress, concluded that the US should “go metric” by 1980. (A similar recommendation was made before World War II – and it too was ignored.)

Robinson resigned from the CWRU department in 1970, joining a dozen other members of the WRU department, tenured and non-tenured, who left for one reason or another between 1965 and 1970. He joined the Paris headquarters of the United Nations Educational, Scientific, and Cultural Organization (UNESCO). His responsibilities in the Division of Science Teaching led him to work on educational programs in Brazil, Africa, and all over the Middle East. He retired from UNESCO in 1985. Still based in France, Robinson is (2004) a very active spokesman for the Association of Environmentalists for Nuclear Energy, as an advocate for the use of nuclear power for energy production. He is the founder and president of the American affiliate.

Karl Casper: nuclear beta decay

Karl J. Casper was a member of the WRU department from 1960 to 1967. He had completed his PhD at Ohio State in 1960, having worked in experimental nuclear

physics with P. S. Jastram. His work at WRU was mainly concerned with the development and use of solid state detectors to make precision measurements of the energy spectra of beta rays (i.e. electrons and positrons) emitted by radioactive nuclei.

An aside on "beta decay". If the energy of a nucleus would be reduced by the transformation of a proton to a neutron with the emission of a positron or by the transformation of a neutron to a proton with the emission of an electron, the transformation will take place eventually, along with the emission of a neutrino: *that is* $p \rightarrow n\ e^{+}\ \nu$ *or* $n \rightarrow p\ e^{-}\ \bar{\nu}$ *The probability for this happening depends on the available energy and on the spin and parity of the initial and final states. The energy of the electron or positron can have any value from zero up to a specific maximum available kinetic energy. This maximum energy gives information about the mass-energy of the initial and final nuclide (*nuclide *is shorthand for any nuclear state). The shape of the electron's energy spectrum gives information about the quantum numbers of the initial and final nuclides. Energy spectra for beta decay are usually displayed in a special way, in a graph called a Kurie plot. The variables plotted are chosen so that a Kurie plot takes the form of a straight line for the least complicated transitions. The place where the Kurie plot goes to zero gives the "end point" energy, i.e. the maximum energy which the electron can have for the given transition.*

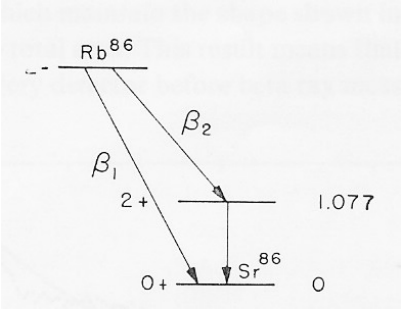

Fig. 14-3. Beta decay of rubidium.

As an example of Casper's work, **Fig. 14-3** shows the energy level diagram for the beta decay of rubidium to strontium, where transitions take place to two levels in the strontium nucleus. **Fig. 14-4** is a Kurie plot for the betas from the β_2 branch. Its shape indicates that the transition is "allowed", i.e. having no change in angular momentum. Casper and grad student Richard Thompson, had developed particularly sensitive "lithium drifted silicon detectors" which had the required resolution. This experiment's contributions to the nuclear tables were the energies of the two transitions and the spin and parity of the excited state in strontium. The data were analyzed on the Case Univac 1107 computer. "Beta Decay of ^{86}Rb" *Nucl. Phys*. **72** 106 1965. "Energy of the First Excited State of Sr^{86}" *Nucl. Phys*. **47** 443 1963.

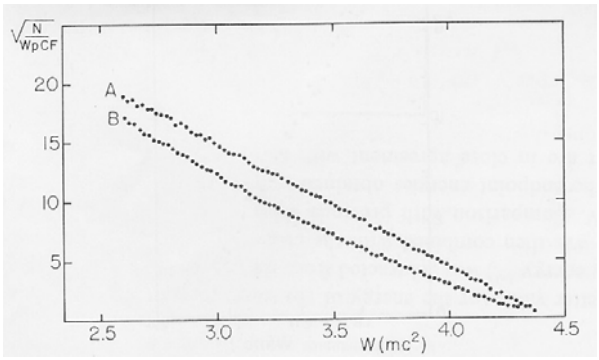

Fig. 14-4. Kurie plots. (curve A has been corrected for detector response.

In a somewhat different type of measurement, Casper determined the spin and parity of several nuclides by observing the angular correlation between pairs of sequentially emitted gammas. For example, **Fig. 14-5** shows the decay scheme for rubidium Rb^{84}. This nucleus changes a neutron into a proton and can arrive at any of three levels in the resulting Kr^{84} nucleus. The ten-microcurie Rb^{84} source (half life 33 days) was created at the 86-in cyclotron at Oak Ridge National Laboratory. Lithium-drifted germanium detectors were used to catch the gammas coming from the excited states at 1901 and 883 keV. The main result of the "table-top" measurement was the determination of the spin and parity of the 1901 keV level (2^+). "Angular Correlation of Gamma Rays in the Decay of Rb^{84}" *Phys. Rev*. **138** B1378 1965.

Casper and Robinson collaborated on a study of the effects of random background and finite efficiencies on coincidence logic. "Analysis of Chance Coincidences in Fast-Slow Coincidence Systems" *Nucl. Instr. & Meth.* **24** 482 1963. The development of the high resolution detectors warranted a technological paper: "Fabrication Methods for Lithium Drifted Surface Barrier Silicon Detectors" *Nucl. Inst. & Meth.* **40** 330 1966.

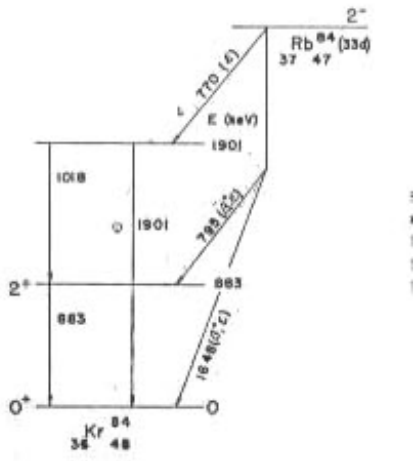

Fig. 14-5. Decay scheme for rubidium-84.

One limitation on the detection of the beta rays in a nuclear decay is the finite solid angle presented by the detectors. The solid-state detectors of the time were quite small. The effective solid angle can be increased by placing the radioactive source and detectors in a strong magnetic field. Casper built a magnetic spectrometer to achieve this. He used a geometry in which two 2-inch-diameter detectors were placed at the ends of a six-inch-long cylinder with the source at the middle, all lying in a superconducting, "commercially available", 30 kiloGauss solenoid. The betas leaving the source in nearly all directions get caught-up by the magnetic field and spiral down the cylinder to the detectors, sort of like incoming cosmic rays which wind around the earth's magnetic field lines. "Superconducting Magnet Beta-Ray Spectrometer" *Rev. Sci. Inst*. **38** 1110 1967.

Karl Casper left WRU in 1967, the year of the merger with Case Tech. In a letter from chairman Chandrasekhar, Casper was informed that support for the program in low energy experimental nuclear physics could not be guaranteed. Casper accepted a position at Cleveland State University where he is now professor emeritus.

S. Jha: γ's from nuclei

Shacheenatha Jha was born in Bihar, India in 1918 and was 48 years old when he joined the WRU department in 1966. He had done his BS and MS (1941) at Patna University where he remained as part of the staff for an additional five years. He completed his PhD under N. Feather at the University of Edinburgh in 1950, and returned to

Fig. 14-6. S. Jha

India to do experimental nuclear physics research at Patna and the Tata Institute in Mumbai for eleven years. In 1961 he came to America to become assistant professor at the Carnegie Institute of Technology. He joined the WRU department in 1966 as associate professor. His photo is in **Fig. 14-6**.

At WRU, Jha worked with Berol Robinson. Several of their joint papers on Mössbauer studies of nuclear levels were described earlier in this chapter. In a paper with two colleagues at NASA Lewis, Jha reported a study of the isomers of xenon-130. They detected γ's emitted by xenon nuclei which had been produced in the beta decay of two neighboring nuclides: ${}_{53}I^{130} \rightarrow \beta^{-}\ {}_{54}Xe^{130}$ and ${}_{55}Cs^{130} \rightarrow \beta^{+}\ {}_{54}Xe^{130}$ (each with neutrinos, of course). This was an interesting way to get at some of the xenon levels because the iodine-130 has spin 5 and the cesium-130 has spin 1. As a result, they decay into different selections of xenon levels. The iodine source was prepared by neutron capture and the cesium source by alpha bombardment at the NASA cyclotron. Forty different transitions were observed and eighteen levels identified. "Levels of ^{130}Xe Populated in β Decay of ^{130}I and ^{130}Cs" *Phys. Rev*. **174** 1472 1968.

In a paper with his graduate student, Peter Bond, Jha tackled another nucleus: molybdenum-95. The sample was prepared at NASA by alpha bombardment of niobium which produced technecium-95 which decays to the isomers of Mo^{95}. *(Isomers are excited states which take a fairly long time to decay.)*

$$_{41}Nb^{93}\ (\alpha,2n)\ _{43}Tc^{95} \rightarrow (20\text{ hour e capture})\ _{42}Mo^{95}*$$

A similar, but alternate route from Nb to Tc to Mo passes through a metastable state in Tc, one with a 61 day mean-life. The Tc ground state and this metastable state have different quantum numbers, (9/2+ vs 1/2-), so different levels in the molybdenum are fed from each. One set of transitions decays away in the first few days. The experimenters also looked at the angular correlations between γ's coming from sequential decays, another tool in tying down the parameters of the molybdenum levels. The resulting level-scheme was compared with several theoretical models for this almost spherical Mo nucleus, including a model proposed by Jha's colleague, **Leonard Kisslinger**. "Nuclear-Structure and Hyperfine-Field Studies with Mo^{95}" *Phys. Rev*. **C2** 1887 1970.

Jha teamed up with colleague **John McGervey** and Peter Bond to devise an experimental setup which allowed the accurate measurement of the time interval between two γ-rays. This was used to determine the lifetimes of excited states in ten different radioactive nuclei. The measured lifetimes were in the 1 to 10 nanosecond range, and the experimental uncertainty about 3%. An example of a measured state is the 127 keV level in ^{101}Ru. A sample of radioactive ^{101}Rh (prepared at NASA), decays spontaneously to a state of ^{101}Ru which is (198+127) keV above the ground state. This emits a 198 keV γ

when it drops to the 127 keV level. It then subsequently emits a 127 keV γ as the nucleus returns to its ground state. The time difference between the detection of the 198 and the 127 keV γ's gives the lifetime of the 127 keV level. The ten different nuclei studied came from the decays of ten different radioactive sources, prepared by commercial suppliers or at NASA or at Oak Ridge National Laboratory. "Measurements of Some Nuclear Lifetimes in the Nanosecond Region" *Nucl. Phys.* **A163** 571 1971. Jha took a faculty position at the University of Cincinnati in 1969, not long after the merger of the WRU and CIT departments.

McGervey: positrons

John D. McGervey received his PhD in 1961 from Carnegie Institute of Technology. He was a student of Sergio DeBenedetti; his dissertation was titled "Mean Lives of Positrons in Oxidizing Solutions" (according to the abstract: "an attempt to detect oxidation of positronium (Ps) by positive ions"). McGervey was hired that same year by John Major as an assistant professor in the Western Reserve department. His picture is in **Fig. 14-7**.

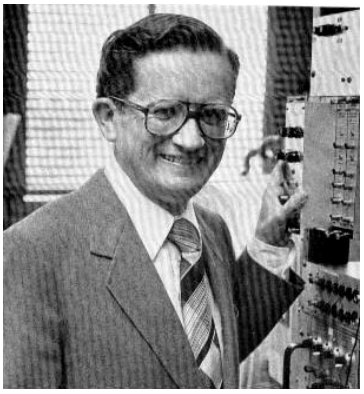

Fig. 14-7. John McGervey.

We have seen in Chapter 11 how the Case researchers, Gordon, Eck, and Schuele, were investigating the behavior of electrons in crystals and their interaction with the lattice. They did so by looking at such things as the effect of external fields, temperature, and pressure on electrical and magnetic properties. McGervey had worked with positrons at Carnegie Tech and he would use them as a complementary probe of solids.

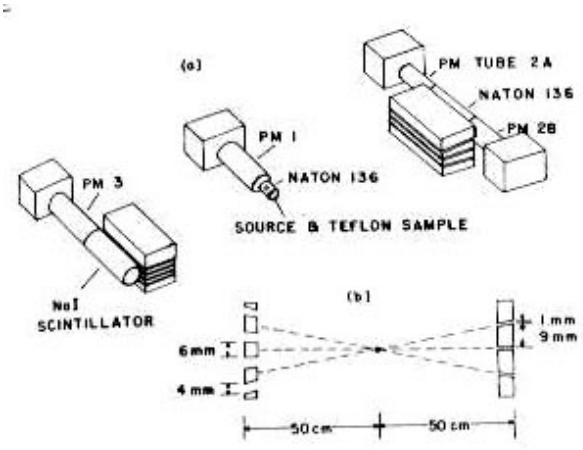

Fig. 14-8. Positron annihilation telescope.

When a positron from a radioactive source finds itself inside a crystal or other material, it most often finds an electron with which it forms a mini-hydrogenlike-atom, called positronium (Ps). If the electron and positron have opposite spins, the atom (called parapositroniuim or p-Ps) has zero angular momentum and decays in about 10^{-10} s into two γ's. If the spins are parallel, the "orthopositronium or o-Ps has total angular momentum unity and must decay into three γ's. This is more complicated and it takes a thousand times longer: about 10^{-7} s. For the 2γ decay, the angle between the outgoing γ's gives

a measure of the momentum of the positronium (it'd be 180 degrees if the Ps were at rest), and provides therefore a probe of the momentum distribution of the electrons in the material.

With graduate student Virginia Walters (the first woman physics PhD student at Western Reserve), McGervey did a series of experiments in which positrons were introduced into a Teflon sample, and their survival time was measured as a function of the angle between the two outgoing γ's. **Fig. 14-8** shows a schematic of the experiment, with the Na^{22} positron source and Teflon sitting inside a hole in the scintillator which is looked at by photomultiplier #1. When a positron is emitted, it is quickly followed by a 1.3 MeV γ. The detection of this gamma marks the time at which the positron enters the Teflon. Two sets of lead collimators were placed 50 cm from and on opposite sides of the Teflon. Narrow slits in the lead allowed the selection of well-defined ranges of the angle between the two γ's. Three ranges of angles (i.e. away from 180 degrees) were studied, 0 to 2 mrad, 4 to 12 mrad, and 8 to 12 mrad. Scintillators and photomultipliers #2 and #3 were placed beyond the slits. The lifetime of the positron in the material, as determined by the delay between counter #1 and #2, was recorded in a multichannel analyzer. A chi-square fit to the lifetime distribution, shown in **Fig. 14-9**, indicated that it was a superposition of three different mean lifetimes: 0.33, 1.05, and 4.06 ns. (Note that this is a logarithmic plot, covering three orders of magnitude.) That means that the positron found at least three different things to do in the Teflon. It could form spin zero para-Ps, or spin one ortho-Ps, or perhaps form some sort of bound-state with the Teflon. The fractions of the annihilations associated with each lifetime could also be determined: roughly 67, 17, and 16%. The long-life time components were found to be associated with the larger angle annihilations, as is evident in **Fig. 14-10** where the small and large angle data are plotted separately. Fits to the combined angle-and-lifetime data "support the hypothesis of a bound-state between the Teflon molecule and the positron". "Correlation of Positron Lifetime with the Angle between the Annihilation Gamma Rays" *Phys. Rev. Lett.* **13** 408 1964; also *Nucl. Instr. and Methods* **25** 219

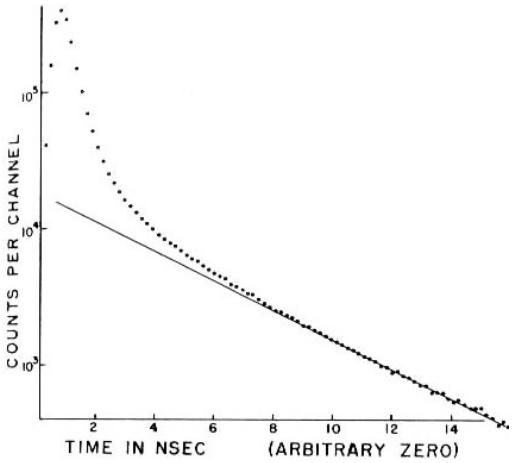

Fig. 14-9. e^+ annihilations in Teflon: 3 different lifetimes.

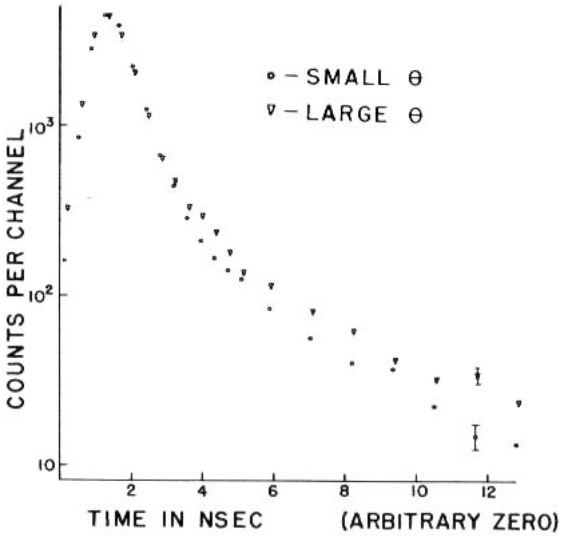

Fig. 14-10. e^+ survival times for two γ separation angle selections.

1964; and later "Correlation between Lifetime and Momentum for Positron Annihilations in Teflon" *Phys. Rev.* **B2** 2421 1970.

Positrons as probes of crystal structure

McGervey next used positron annihilations in silicon and germanium to look at electron momentum distributions along three different orientations of the crystals. The data were compared with theoretical predictions for each orientation, and found to be in good agreement for only one of the three orientations. "Electron Momentum Distribution in Silicon and Germanium by Positron Annihilation", *Phys. Rev.* **151** 615 1966.

In McGervey's later experiments, various alloys of copper and aluminum or copper and nickel were tested. A bit of radioactive ^{64}Cu was introduced into the mix to provide an *in situ* source of positrons, and the emerging γ's were detected after passing through 3 mm wide slits 4 meters from the crystal. The crystal was aligned so that the measured electron momentum could be related to the lattice orientation. (Recall that the angle between the two annihilation γ's gives the momentum of the electron before it got involved with the positron.) This in turn gives information about the Fermi surface for the crystal (we described Fermi surfaces in Chapter 12). McGervey was able to identify "necks" in the Fermi surface (i.e. preferential directions in which the electron momenta are large) and to determine the effects of the alloy composition. "Positron Annihilation in Copper Alloys" *Phys. Rev. Lett.* **24** 9 1970.

While on sabbatical in Jülich in Germany, McGervey worked with W. Trifthäuser on another experiment which used positron annihilation to probe the properties of metal crystals. The object was to determine the vacancy formation energies (how much energy does it take to kick an electron out of its place in the crystal?). The experimental technique involved measuring the rate of positron annihilation as a function of the temperature of the crystal. For "zero angle" events, where the two annihilation photons emerge back to back, the rate is expected to be proportional to $\exp(-E_V/kT)$, where E_V is the desired vacancy formation energy. Measurements were made from near 0 to 1000 K, and the data indicated the expected exponential form between 400 and 800 K. A value, $E_V = 0.98 \pm 0.07$ eV, was determined for both silver and copper. "Vacancy-formation Energies in Copper and Silver from Positron Annihilation" *Phys. Lett.* **44A** 53 1973.

Positrons to detect voids

A second paper written with his German collaborators concerned the detection of voids in aluminum caused by neutron irradiation. The authors explain: "The creation of voids in neutron-irradiated materials, and their deleterious effects on mechanical properties, pose serious problems in reactor technology. In the case of irradiated aluminum it is puzzling that, even during annealing studies, no voids smaller than about 100 Å diameter are seen in the electron microscope. Hence, additional experimental techniques known to be sensitive to very small voids have been sought." Here, then, was a challenge for the positron-annihilation approach. Single crystals of pure aluminum were exposed to high neutron fluxes at Oak Ridge National Laboratory. These were then exposed, in the Jülich

laboratory, to a source of positrons, and the two 0.51 MeV photons resulting from each annihilation in the aluminum were measured using a two-narrow-slit arrangement as described above. The photons travel approximately in opposite directions, and, as mentioned above, the deviation from co-linearity is a measure of the momentum of the positronium, and indirectly of the "target" electron. McGervey and his colleagues found that photons coming from the irradiated sample (i.e. the one with tiny voids) were significantly more co-linear than those emitted from the non-irradiated sample. This means that the electrons' higher momentum component is suppressed. The author's suggest, in explanation, that the positrons are trapped at the boundary of the voids, and encounter mostly low-momentum valence electrons. "Positron-annihilation studies of voids in neutron-irradiated aluminum single crystals." *Phys. Rev.* **B9** 3321 1974. *Phys. Rev.* **B9** 2402 1974. **Fig. 14-11** is a plot of positron meanlives in irradiated aluminum versus the annealing temperature shows how abruptly the voids are cooked out of the crystal. *Phil. Mag*. **36** 117 1977.

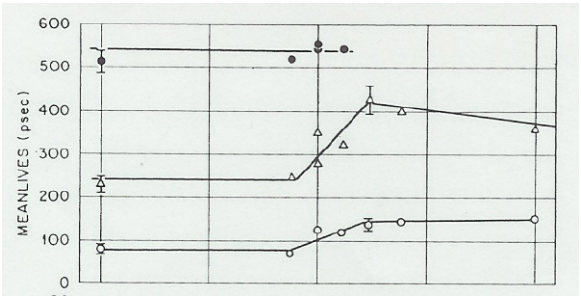

Fig. 14-11. Positron survival times vs. annealing temperature in irradiated aluminum.

McGervey joined collaborators at the University of Guelph and Queen's University in Ontario to look at positron survival times in cadmium as a function of temperature and pressure. One would expect that lowering the temperature or raising the pressure would increase the density of the host material, and thus decrease the lifetime of the positron. The experimenters measured the positron lifetime at atmospheric pressure both at 77 K and at 296 K, finding 170 ± 2 and 190 ± 2 picoseconds respectively, as expected. They then increased the pressure at 296 K until the cadmium was squeezed down to the density it had at 77 K and one atmosphere, i.e. 9.8 kilobar (98 thousand atmospheres). The positron lifetime dropped to 178 ps, but not all the way down to 170 ps. The conclusion was that the fate of the positron depends not only on how close it gets to the atomic electrons, but perhaps also on how vigorously the atoms are jiggling around. "Temperature and pressure dependence of positron mean lives in cadmium" *J. Phys. F: Metal Phys.* **7** L255 1977.

McGervey had become an expert in the technique of using positron annihilations to probe electrons in matter. He joined his colleague, **Arnold Dahm**, in an experiment to chase down the electrons in gaseous, liquid and solid helium. Dahm had been studying electrons in helium, and the positron annihilation technique provided yet another tool. Because the physics of this work is more "helium" than it is "positronium", I shall describe it in the section on Dahm's work in Chapter 15, rather than here.

McGervey experimented with a superconducting material, V_3Si, to examine the connection between defects and positron lifetimes. His colleagues Farrell and Chandrasekhar had been studying a certain class of materials in which it was believed that the presence of defects radically changed the temperature at which the materials be-

came superconducting. (Their work is described along with Dahm's in chapter 15.) McGervey measured the lifetime of positrons in V_3Si as a function of pressure up to 20 thousand atmospheres, with the expectation that the voids associated with the defects might be squeezed out by high pressure. They found no change in the positron survival time over this wide range of pressure. "It is tempting to conclude that the postulated vacancies in V_3Si do not exist. However, it is also possible that vacancies are present, but that they do not produce a sufficiently deep potential well to trap a positron." "Pressure dependence of positron lifetimes in V_3Si" *Phys. Lett.* **63A** 393 1977.

John McGervey authored a very popular paperback called *Probabilities in Everyday Life* (Ballantine Books 1986) in which he analyzed, for example, the odds in card-playing, in horseracing, in the stock market, in surviving tobacco smoking, in life insurance, in driving without seatbelts, and a number of other fascinating areas in which people try to beat the odds. On the internet, he is most often cited as being the debunker who compiled the astrological signs of some 17,000 scientists and found them evenly distributed. He was a born-campaigner: for railroad travel, for arms control, for any number of (in my opinion) enlightened causes. He published two undergraduate texts: *Introduction to Modern Physics* (Academic Press 1983) and *Quantum Mechanics* (Academic Press 1995). For many years John directed a program to assist primary and secondary school teachers of science. He died only two years after his retirement in 1999.

Reichert: hyperfine structure in solids

Jonathan F. Reichert earned his BS in physics at Case in 1953. He completed his PhD at Washington University St. Louis in 1962, where he worked with Jonathan Townsend on the magnetic interaction between electrons and the lattice nuclei in solid metals. "Dynamic Nuclear Enhancement in Metallic Sodium" *Phys. Rev.* **137** A476 1965. He continued in this area of experimental condensed matter physics for two years as a post-doc at Harvard. "Electron-nucleus Double-Resonance Studies of F Centers in KCl: Electric Field Effects" *Phys. Rev. Lett*. **15** 780 1965. In 1965, the 34 year old Reichert accepted an offer of an assistant professorship from John Major's successor as chairman, Gerald Tauber. Reichert's photo is in **Fig. 14-12**.

Fig. 14-12.
Jonathan Reichert.

Electron spin resonance in crystals

Reichert measured hyperfine interactions in atoms. These result from the interplay between the magnetic moment associated with the electron's spin and orbital motion with the magnetic moment of the nucleus. The atomic energy levels are consequently split into two or more closely spaced levels. But Reichert and his collaborators were not studying atomic physics. They were using hyperfine structure to study the interaction between electrons and nuclei in a crystalline structure. By subjecting a sample to high frequency electromagnetic radiation, they could simultaneously induce transitions associ-

ated with the nuclei and with single electrons trapped in vacancies in the crystal. **Fig. 14-13** shows such a trapped electron in a sodium chloride crystal. Their technique was called ENDOR (electron-nucleus-double-resonance) spectroscopy. (It was thus a combination of electron-spin-resonance, ESR, and nuclear-magnetic-resonance, NMR.) In these experiments, the samples were further subjected to extremely strong steady electric fields, up to 50 kV/cm. The idea was to pull the electron around in its trap so it could cozy up to one neighboring nucleus or another. "Electric Field Effects in Electron-Nuclear Double-Resonance Spectroscopy of F Centers" *Phys. Rev.* **180** 482 1969.

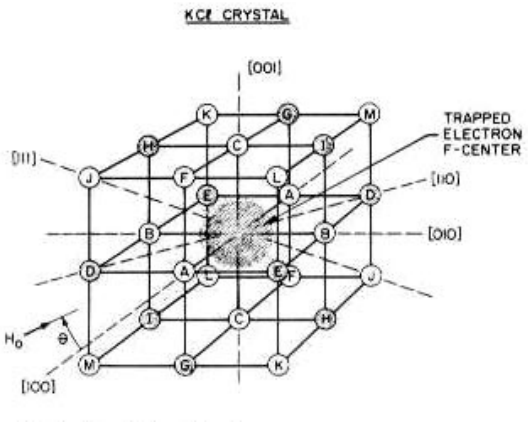

Fig. 14-13. An electron in a NaCl cage.

This was followed by a second paper, with his student Zahiruddin Usmani, which elaborated on the associated theory: *Phys. Rev.* **B1** 2078 1970. A variation on this experiment was performed using lithium fluoride as the medium. The twist here was the use of a 50-50 mixture of the two lithium isotopes: Li^6 and Li^7. The object was to find out what happens when the electron lies between two nuclei with differing quantum numbers. ("Isotopic Substitution for Observing Linear Electric Field Effects" . II. Theoretical Considerations", *Phys. Rev. Lett.* **24** 709 1970.

Reichert also worked on a related experiment with his colleague Chao-Yuan Huang whose work will be described later in this chapter. They measured the hyperfine structure associated with manganese ions in fluoride crystals, studying how the coupling with the lattice changes with increasing temperature. "Temperature-dependent Hyperfine Coupling Constants of Mn^{2+} in Fluorides" *Phys. Lett.* **26A** 219 1968.

In another application of electron-spin-resonance, Reichert got together with Arnold Dahm to look at spin-flip transitions of electrons injected into liquid helium. This work will be described in Dahm's section of Chapter 15.

Finally, we mention an experiment in which the ESR spectroscopy was combined with Mössbauer spectroscopy. Reichert would thus follow Hoffman and Robinson in using this powerful tool for the precise measurement of energy values. He and grad-student James Lock were looking at magnetic transitions in ^{57}Fe when the iron nucleus resides in a nonmetallic host lattice. (As in experiments described earlier, a cobalt-57 source provided the γ-rays to be absorbed by the iron nucleus.) The Mössbauer spectrum of the γ-rays shifted when the sample was subjected to external radio-frequency radiation. "This article reports what we believe is the first observation of an electron spin-Mössbauer double resonance effect of dilute paramagnetic ions in a nonmetallic host lattice." What they were seeing was a change in the energy at which the γ-rays are absorbed by an iron nucleus when a microwave magnetic field is simultaneously producing transitions in the

electronic levels in the iron atom. "Mossbauer-Electronic Double Resonance in $NH_4(^{57}Fe,Al)(SO_4)_2 \bullet 12\ H_2O$" *J. Magnetic Resonance* **7** 74 1972.

Jonathan Reichert came up for promotion in 1969; unfortunately it was a time when the newly combined department was clearly too large. The department was moving toward more particle physics and the vote was not in his favor. Reichert was an extremely popular teacher and the students reacted strongly to the department's action. The headline of the newly established Observer, CWRU's student newspaper, was "Dr. Reichert canned". The Cleveland Plain Dealer picked up on the story with front-page coverage. The following month the students organized a Teach-In on the issue, but to no avail. Reichert moved on to SUNY at Buffalo where he continued his research and teaching.

Chao-Yuan Huang: foreign atoms in solids

Chao-Yuan Huang joined the Western Reserve physics department in 1966 during the period of the negotiations which led to federation with Case. Huang was born in Taiwan in 1935; he completed his doctorate in applied physics at Harvard in 1964. At WRU, Huang joined the Condensed State Center which had been set up by Chandrasekhar and colleagues.

Fig. 14-14. C-Y Huang.

Huang's principal interest was the study of what happens to a foreign atom when it is placed within a crystal lattice. This was quite similar to what Reichert was doing. In the simplest terms, the atom's electrons feel the presence of its neighboring lattice atoms and its energy levels are slightly shifted and their widths changed. Huang observed these changes experimentally by "electron paramagnetic resonance" (EPR) spectroscopy. The sample, held at very low temperatures (4 K), is placed in a strong magnetic field (3 to 10 Tesla) which can be varied. The field splits the energy levels in two, one with electron spin up, the other with spin down. The amount of this "Zeeman" splitting is proportional to the strength of the applied field.

One can flip the spin of the electron by applying microwave radiation to the crystal (in the 10 GHz or 3 cm wavelength range). When the microwave energy matches the difference in the energies of the two levels, the electrons flip over and the radiation is strongly absorbed. The location and shape of the bump in the plot of the absorption vs. magnetic field gives an accurate measure of the electronic energy levels. Huang made EPR studies of a large number of rare-earth ions which have unpaired electrons and permanent magnetic moments. The ions were placed in a variety of crystal structures and the temperature dependence of the electronic levels was measured. From this, the coupling between the phonons of the crystal lattice and the ion's electrons can be determined. "Temperature-dependent hyperfine interactions of Mn^{2+} in alkali halides *Phys. Rev*. **158** 280 1967. "Phonon-induced spectral linewidths in crystals" *Phys. Lett*. **24A** 740 1967. The role of the magnetic moment of the ion's nucleus was studied by using different isotopes. "Temperature-dependent isotope shifts and phonon-induced zero-field splitting" *Phys. Lett*. **27A** 437 1968.

In the early 1970's, Huang supervised the research of two graduate students: Kazushi Sugawara and Frederic Rachford. While at CWRU, Huang published over three dozen experimental and theoretical papers, many with Sugawara, on the interactions between selected foreign ions and the host crystal. In 1974, he became interested in a very different line of research: superconducting materials. In a series of papers with Rachford, Huang reported measurements, for example, of current flow through small "microbridges" in superconducting tin. This work was related to the new "superconducting quantum interference devices" (SQUID's). "Limiting flux passage time in narrow superconductors" *Phys. Rev. Lett*. **35** 305 1975.

Huang moved to the Los Alamos National Lab in 1974 while maintaining his connection with CWRU as adjunct associate professor. He continued collaborative studies with his CWRU colleagues for several years. He would remain at LANL for eleven years, working on superconductivity and on the use of μ-mesons, essentially heavy electrons, as probes of materials. After a four-year stint as senior scientist at the Lockheed Research Laboratory, he returned, after more than thirty years in the US, to Taiwan to assume a professorship at National Taiwan University.