Simple (Particle-Excitation) Nuclear Isomers and What They Can Teach Us

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What Are Nuclear Isomers?

In many ways the atomic nucleus is a most antisocial little thing. Atoms and molecules are forever interacting with the outside world, perturbing and being perturbed by their environments. Not so the nucleus. Locked deep within the atom, it is protected from most outside influences except for weak couplings such as the magnetic hyperfine interaction, and these are extremely weak compared with nuclear forces themselves.

The result of this is an almost iron-handed validity of selection rules for nuclear transitions. A "forbidden" (nondipole) transition usually does not "go" in an atomic or molecular system, for such a system most likely can be perturbed enough that an alternate "allowed" transition can proceed much faster than the forbidden one. When a seemingly forbidden transition does occur, it is usually because of perturbations through vibration, and the transition is usually quite slow. Now, forbidden transitions in nuclei have similarities to forbidden transitions in atoms and molecules, but they are much more common and are found with much higher degree of forbiddenness than in atoms and molecules. If the only direct way to get from state A to state B is *via* a many-times forbidden transition, then that many-times forbidden transition will most likely occur, although it may be very slow and state A may have a very long half-life.

When state A is an excited state in a nucleus and state B is a lower-lying state in the same nucleus, state A can deexcite to state B by γ-ray emission, the nuclear equivalent of X-ray emission. There is nothing intrinsically different between X-rays and γ rays except their point of origin and that γ rays are usually of higher energy than X-rays. (However, K X-rays of heavier elements have higher energies than γ-rays from low-energy transitions in nuclei, so there can be a considerable overlap in X-ray and γ-ray energies.)

If state A has a very different spin from state B, the γ transition will have to remove this difference in angular momentum—it is a "forbidden" transition, or, in nuclear parlance, a "high-multipolarity" transition. These high-multipolarity γ-ray transitions can be quite slow, meaning that state A can have quite a long half-life.

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This gives us the basis for defining the term "nuclear isomers." When two nuclear states have sufficiently different spins that each has an appreciable half-life of its own, the two states are said to be isomers, with a state that is not the ground state being called a "metastable" state. The metastable and ground states are symbolized by an m and a g in the mass-number superscript, *e.g.*, ^{53m}Fe (or ^{53}Fe^{m}) and ^{53g}Fe (or ^{53}Fe^{g}).

Deciding just when a half-life is "appreciable" gets to be rather arbitrary. As fast-timing electronics have become capable of probing the sub-nanosecond range, one sees more and more states with half-lives of a few nanoseconds being called metastable. For the purposes of this Account, we shall usually restrict ourselves to states with half-lives of seconds and longer.

Nuclear isomers can result for a number of reasons, including nucleons (protons or neutrons) occupying very different orbitals in states A and B ("particle-excitation" isomers), the nucleus having different shapes in states A and B ("shape" isomers), and selection rules on some of the more exotic quantum numbers in deformed nuclei. For the purposes of this introductory article, we shall restrict ourselves to particle-excitation isomers, which are the most straightforward to describe.

To get a semiquantitative idea of the half-lives involved in γ decay, one has to consider the process in more detail and perhaps invoke a nuclear model. The actual process is analogous to radiation by the motion of macroscopic charges (electric radiation) and currents (magnetic radiation). The electric or magnetic field is expressed in terms of a multipole expansion,[1] the terms in decreasing size then being called dipole (2^1-pole), quadrupole (2^2-pole), octupole (2^3-pole), hexadecapole (2^4-pole), and, in general, 2^l-pole radiation, where l is the (vector) amount of angular momentum that can be carried off by the transition. We call the electric transtions E1, E2, E3, E4, . . . , El and the magnetic ones M1, M2, M3, M4 . . . , Ml.

Detailed calculations of transition rates for individual nuclei quickly become cumbersome. Frequently a simplification called the Weisskopf single-particle estimate[1] is used. This considers that a γ transition results from a single nucleon's (proton or neutron) hopping from one simple harmonic-oscillator-type orbital to another. Even though it is a gross oversimplification, it gives answers that are in the correct ball park, and it is a simplistic but useful

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(1) J. M. Blatt and V. F. Weisskopf, "Theoretical Nuclear Physics," Wiley, New York, N. Y., 1952, Chapter XII.

Table I
γ-Ray Selection Rules and Transition Probabilities

Multipolarity	$\Delta J \leq$	$\Delta\pi$	$t_{1/2}(\gamma)$ eq (sec)	Illustrative $t_{1/2}$, sec, at $E_\gamma =$			
				0.1 MeV[a]	2 MeV[a]	0.1 MeV[b]	2 MeV[b]
E1	1	Yes	$(6.9 \times 10^{-15})A^{-2/3}E_\gamma^{-3}$	5.1×10^{-13}	6.4×10^{-17}	2.0×10^{-13}	2.5×10^{-17}
M1	1	No	$(2.4 \times 10^{-14})A^{0}E_\gamma^{-3}$	2.4×10^{-11}	3.0×10^{-15}	2.4×10^{-11}	3.0×10^{-15}
E2	2	No	$(9.4 \times 10^{-9})A^{-4/3}E_\gamma^{-5}$	5.1×10^{-6}	1.6×10^{-12}	8.0×10^{-7}	2.5×10^{-13}
M2	2	Yes	$(8.3 \times 10^{-9})A^{-2/3}E_\gamma^{-5}$	6.1×10^{-5}	1.9×10^{-11}	2.4×10^{-5}	7.6×10^{-12}
E3	3	Yes	$(2.0 \times 10^{-2})A^{-2}E_\gamma^{-7}$	8.0×10^{1}	6.2×10^{-8}	5.0×10^{0}	3.9×10^{-9}
M3	3	No	$(8.0 \times 10^{-3})A^{-4/3}E_\gamma^{-7}$	4.3×10^{2}	3.4×10^{-7}	6.8×10^{1}	5.3×10^{-8}
E4	4	No	$(6.3 \times 10^{4})A^{-8/3}E_\gamma^{-9}$	1.9×10^{9}	3.6×10^{-3}	4.6×10^{7}	9.0×10^{-5}
M4	4	Yes	$(1.4 \times 10^{4})A^{-2}E_\gamma^{-9}$	5.6×10^{9}	1.1×10^{-2}	3.5×10^{8}	6.8×10^{-4}
E5	5	Yes	$(2.8 \times 10^{11})A^{-10/3}E_\gamma^{-11}$	6.1×10^{16}	3.0×10^{2}	6.0×10^{14}	2.9×10^{0}
M5	5	No	$(4.1 \times 10^{10})A^{-8/3}E_\gamma^{-11}$	1.2×10^{17}	5.9×10^{2}	3.0×10^{15}	1.5×10^{1}
E6	6	Yes	$(1.7 \times 10^{18})A^{-4}E_\gamma^{-13}$	2.7×10^{24}	3.3×10^{7}	1.1×10^{22}	1.3×10^{5}

[a] $A = 50$. [b] $A = 200$.

yardstick against which to compare experimental rates.

Equations[2] for calculating half-lives from the single-particle estimate are given in Table I. The odd electric multipoles change the parity of the states, whereas the even ones do not; for magnetic transitions the reverse is true. All else being equal, each unit of increase in multipolarity retards the transition by a factor crudely in the vicinity of a million, and the magnetic transitions are roughly slower than their electric counterparts by a factor of 10 to 100.

In most cases the transition that takes place will be the lowest multipolarity allowed by the selection rules. Thus, a $J^\pi = 3^+ \rightarrow J^\pi = 2^-$ transition could be E1, M2, E3, etc., but the E1 is so much faster than the others that, for all practical purposes, it is the only one to occur. There is also a dependence on the mass number A and a very strong energy dependence, especially for the higher multipoles. An E4 or M4 transition, for example, has a ninth-power energy dependence. Thus, changing the energy from 100 keV to 2 MeV, a factor of 20, changes the rate by a factor of 5×10^{11}!

As can be seen from Table I, it does not take a terribly large change in J to obtain a metastable state with an easily measurable half-life, and, if ΔJ is large enough, the metastable state may very well decay by β emission in addition to γ emission. [When a nucleus has too many neutrons to be stable, it can convert a neutron into a proton plus an electron (a β^- particle) and an antineutrino ($n \rightarrow p^+ + \beta^- + \bar{\nu}$). The β^- and $\bar{\nu}$ are not bound in the nucleus and are shot out. This is known as β^- decay. When a nucleus has too many protons, it can convert a proton into a neutron plus a positron (antielectron or β^+ particle) and a neutrino ($p^+ \rightarrow n + \beta^+ + \nu$). Again the two light particles are shot out. This is β^+ decay.] In fact, there are numerous metastable states known that decay only by β emission, completely independently of the ground state.

The transition probabilities and half-lives given in Table I are only for γ-ray or photon emission. Besides this, an electromagnetic transition can occur in which the nucleus interacts with one of the atomic orbital electrons and ejects it. This process is known as "internal conversion," from the original (mistaken) idea that a γ ray first came out and then struck an orbital electron. (That this is not true can be seen from the existence of $J^\pi = 0^\pm \rightarrow 0^\pm$ transitions, for which photon emission is forbidden—a photon, having one unit of angular momentum, must carry off at least that much. These occur by so-called E0 transitions, in which an electron is the sole radiation.) It is the nuclear equivalent of Auger electron emission. The energy of the ejected electron is just E_γ minus the binding energy of the electron. The ratio of electrons given off to photons given off is called the internal conversion coefficient, α, and becomes larger for higher multipoles and lower E_γ. Thus, the rates for such transitions are somewhat faster than implied in Table I because of the additional competing process. The corrections for this competition are straightforward but tedious to calculate, and tables of reliable internal conversion coefficients are readily available.[3] The conclusions stated in this Account will not be affected by these corrections, so they will not be considered further here.

An example of a long series of nuclear isomers, in the neutron-deficient Pb isotopes, is shown in Figure 1. For most of these the isomeric or rate-determining transition is of M4 multipolarity. It can be seen that the half-lives of the metastable states are indeed strongly energy dependent. With decreasing A the γ-transition energy decreases and the β-decay energy increases; therefore the lighter isotopes start to decay independently by electron capture (ϵ) as well as γ decay. (Electron capture is a form of β decay in which a proton absorbs an orbital (usually K) electron to become a neutron, the energy being carried away by a neutrino.)

Occurrence of Nuclear Isomers

Below Nuclear Closed Shells. The choice of the neutron-deficient Pb isotopes in Figure 1 as a representative series was no accident. They occur just below the major neutron closed shell at $N = 126$. Isomerism has long been known to occur in abundance in regions just below closed shells.

Our understanding of this is incorporated in the nuclear shell model,[4] which in many ways is analo-

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(2) S. A. Moszkowski in "Alpha-, Beta- and Gamma-Ray Spectroscopy," K. Siegbahn, Ed., North-Holland Publishing Co., Amsterdam, 1966, Chapter XV.

(3) R. S. Hager and E. C. Seltzer, *Nucl. Data Sect. A*, 4, 1 (1968).

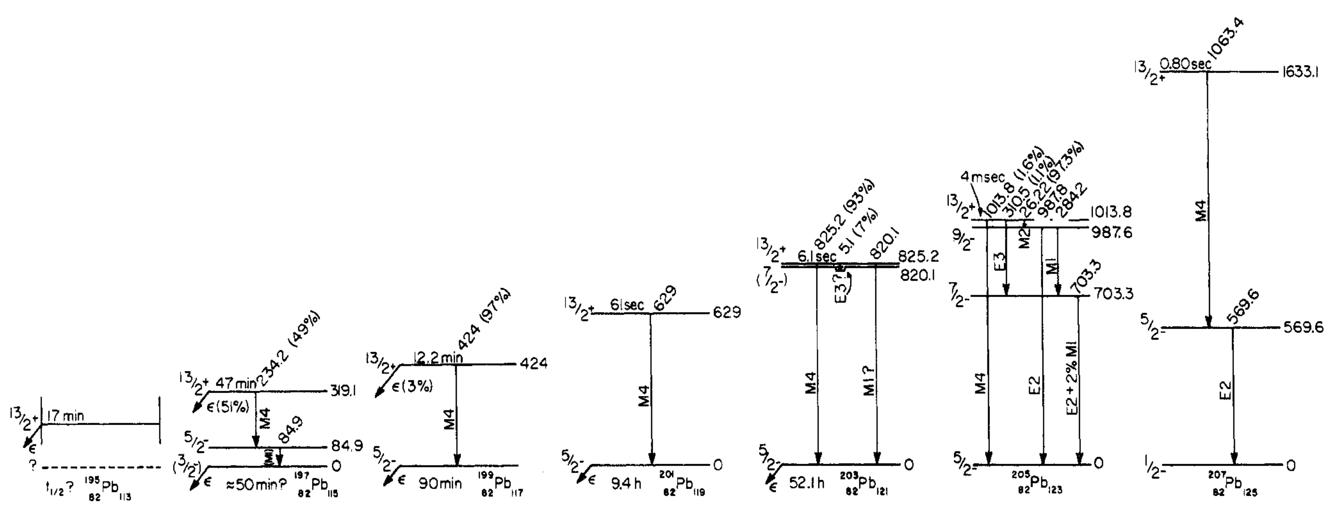

Figure 1. Decay schemes of the odd-mass neutron-deficient Pb isotopes, showing the wealth of nuclear isomers below a major closed shell (here at $N = 126$). The state energies are given in keV, and where more than one mode deexcites a metastable state, intensities are given for each.

gous to the atomic shell model, except that the nucleons have to supply their own potential. (Also, we deal with nuclear forces, which are not so well understood as the electromagnetic forces that dominate the atomic shell model.) Nucleons in nuclei are highly relativistic, and consequently one has to deal with a large spin–orbit coupling, which, in contrast to atomic systems, is *negative* (attractive). Thus, the $j = l + \frac{1}{2}$ member of each spin–orbit pair is depressed, while the $j = l - \frac{1}{2}$ member is raised in energy; also, this effect becomes more important for higher l values. In fact, the splitting becomes so great that high-spin, $l + \frac{1}{2}$ states from one n lie down among the lower-spin states of the previous n. Thus, the observed "magic numbers" in nuclei correspond to shell closures that involve groupings of "subshells" sometimes from different n's.

This can be seen in Figure 2, where the states surrounding the closed shells at 50 and 82 are shown. The $g_{9/2}$ ($l = 4$) orbital is split from the $g_{7/2}$ orbital and depressed to close the nuclear shell at 50 nucleons. (Protons and neutrons fill separate shells, and one finds closed shells when *either* the protons or neutrons reach a gap, in this case at Z or $N = 50$.) The $g_{9/2}$ orbital is thus the only even-parity, high-spin orbital lying among a cluster of odd-parity, lower-spin orbitals. Similarly, the $h_{11/2}$ ($l = 5$) orbital is depressed from its "normal" position and lies among lower-spin, even-parity orbitals, and the shell at 82 is closed. Quite often these high-spin orbitals form excited states of nuclei which can deexcite only by a highly forbidden transition.

Consider, for example, the $i_{13/2}$ orbital for the Pb isotopes of Figure 1; the next highest spin orbital of lower energy is 5/2⁻ or $\Delta J^\pi = 4^{\text{yes}}$, making M4 transitions the fastest ones available for deexcitation.

Similarly, there are large "islands" of isomerism, most often M4 isomerism, just below major closed shells. Some of these can be seen in Figure 3, where all known isomer pairs with both states having half-lives of a second or longer are plotted. Here it can be seen that there are more isomers, say, below $Z = 82$ and $N = 126$ than there are just above $N = 82$. But it can also be seen that isomers are scattered throughout the middle to heavy region of the nuclidic chart, so we should also look for other means of accounting for them.

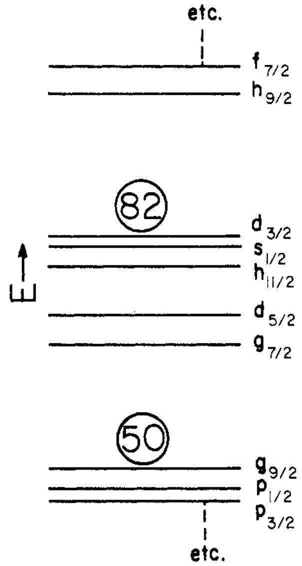

Figure 2. Nuclear shell model orbitals near the closed shells having 50 and 82 nucleons.

Odd–Odd Nuclei. Among the nuclear isomers scattered about the nuclidic chart, a surprisingly large number are for odd-Z, odd-N or "odd–odd" nuclei. Because of the tendency of nucleons to pair up, protons with protons and neutrons with neutrons, by far the most stable nuclei are those with an even number of protons and of neutrons, the "even–even" nuclei. The ground states of all even–even nuclei have $J^\pi = 0^+$, and there are no excited states until quite high excitation energies have been reached, usually in the vicinity of 1 MeV or even more. Thus, there are very few even–even isomer pairs.

The odd-mass nuclei (even–odd or odd–even) have an intermediate stability between the even–even and odd–odd nuclei. The properties of their lower-lying states can be attributed fairly well to the single last nucleon orbiting around the more or less inert even–even 0⁺ core. Thus, in the Pb isomeric series shown in Figure 1, the spins, parities, magnetic moments, wave function details, etc., of almost all the states shown (the only exceptions are the 820.1-keV state in

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(4) M. G. Mayer and J. H. D. Jensen, "Elementary Theory of Nuclear Shell Structure," Wiley, New York, N. Y., 1955.

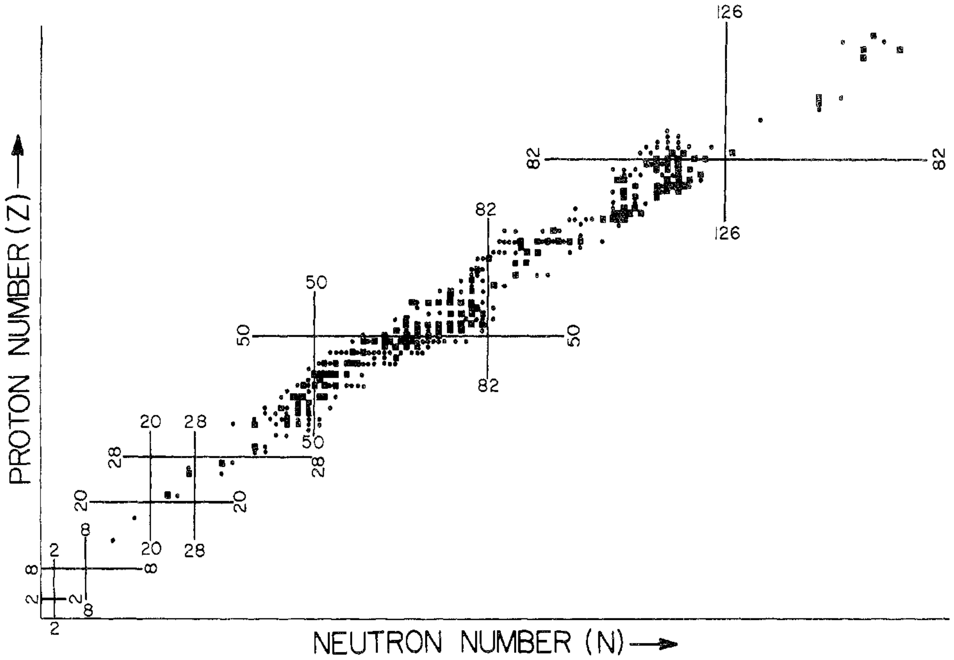

Figure 3. Plot of the known longer lived isomer pairs. The circles indicate nuclei where both the ground and the metastable state have half-lives of at least 1 sec; the squares, both have half-lives of at least 10 min. The lines indicate the major proton and neutron closed shells.

^{203}Pb and the 987.6-keV state in ^{205}Pb) can be explained in such a fashion. Incidentally, this means that the γ transition probabilities between these states follow the single-particle estimates remarkably well. Also, in odd-mass nuclei these simple particle-excited states lie at reasonably low energies, usually two or more below 1 MeV. Thus, isomers in odd-mass nuclei are much more common than in even–even ones.

In odd–odd nuclei, the least stable (in fact, only four are stable: ^{2}H, ^{6}Li, ^{10}B, and ^{14}N), both the odd proton and neutron contribute angular momentum to low-lying states. In most regions of the nuclidic chart their angular momenta can couple vectorially to provide a wealth of possible low-lying states. Thus, a "typical" odd–odd nucleus can easily have 10 or 20 excited states below 1 MeV, and at least one of these is usually a good candidate for a metastable state. In fact, oftentimes the spins of the metastable state and the ground state are so different that each decays independently, and it is difficult to determine which is actually the ground state.

An example of this is the isomer pair in $^{140}_{61}$Pm$_{79}$.[5] One state has $J^{\pi} = 1^+$, the other $J^{\pi} = 8^-$; an E7 isomeric transition between the two would lead to a half-life in the millions of years for the metastable state. This nucleus is far enough from β stability, however, that its ϵ-decay energy is about 6 MeV. Thus, the 1^+ state decays by ϵ/β^+ with a half-life of 9.2 sec, the 8^- state with a half-life of 5.8 min, and as far as their nuclear properties are concerned they might as well be two separate isotopes.

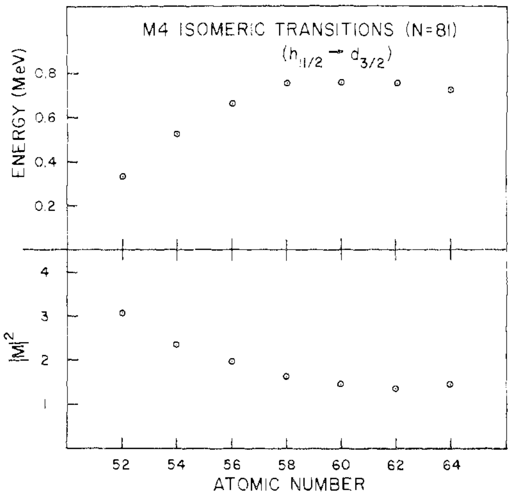

Figure 4. Energies and radial matrix elements ($|M|^2$) for the seven M4 isomeric transitions in the odd-mass N = 81 isotones.

Looking at the available single-particle states in Figure 2, we can make fairly definite assignments. $^{140}_{61}$Pm has 11 protons outside the closed shell at Z = 50. The $g_{7/2}$ orbital can hold eight of these and the $d_{5/2}$ orbital three. Thus, the last (unpaired) proton is probably a $d_{5/2}$ proton. ^{140}Pm$_{79}$ also has three neutron holes in the N = 82 closed shell. Counting down, we see that the $d_{3/2}$ orbital can accommodate all three. Thus, the unpaired neutron (or equivalently, neutron hole) is most likely $d_{3/2}$. The $d_{5/2}$ proton and $d_{3/2}$ neutron can couple to $J^{\pi} = 1^+, 2^+, 3^+$, and 4^+, and if one calculates which of these should lie lowest (a straightforward calculation but beyond the scope of this paper), he finds it is the 1^+ state.

Similarly, the 8^- state can be constructed by coupling a $d_{5/2}$ proton with an $h_{11/2}$ neutron. From the systematics of measured J^{π}'s in this region (and Figure 2), one would predict that the 1^+ state is the ground state and the 8^- state is the metastable state. For example, in the neighboring even–odd nuclei, the $h_{11/2}$ neutron state lies several hundred keV above the $d_{3/2}$ state. However, the independent-particle shell model is not perfect, and residual interactions coupling the proton and neutron states can cause significant energy shifts that must be determined experimentally. In this case we have no direct evidence as

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(5) R. B. Firestone, Ph.D. Thesis, Michigan State University, 1974, COO-1779-112; R. B. Firestone, R. A. Warner, W. C. McHarris, and W. H. Kelly, to be published.

to which lies lower, the 1^+ or the 8^- state. Many such examples of odd–odd isomer pairs are known, and many more will undoubtedly be found.

Isomers in Other Types of Nuclei. Although the two classes discussed above account for the majority of isomers, a quick glance at Figure 3 shows that there are a myriad of others scattered about. Many of these arise from complex, multinucleon couplings that lead to very high spins at high excitation energies, and such configurations have even led to the few even–even isomer pairs known. Other isomer pairs come about in the deformed nuclear regions far from closed shells, when the nuclei have rotational bands similar to those of diatomic molecules and the density of states is quite high. Some of these other types of nuclear isomers will be touched on in the following sections, but a thorough review of each is beyond the scope of this paper.

Pure States and Unusual γ Rays

Like most quantum mechanical systems, nuclei are quite complex, and most of our attempts to describe them are only first approximations, *e.g.*, the nuclear shell model. Most nuclear states have complex wave functions that consist of many components, and, consequently, transition probabilities can vary greatly from the norms that we set up—it is usually difficult to calculate these decay probabilities in detail because of the constructive and destructive interferences between the various "minor" components of the wave functions.

Some exceptions to this generally complicated picture are the nuclei just below closed shells. The high-spin states that were lowered by spin–orbit coupling to lie among lower-spin states of opposite parity cannot mix with most of the nearby states. Thus, one has a fighting chance to describe these states *correctly* in very simple terms, and in the M4 isomeric γ-ray transitions nature has supplied a natural probe.

In Figure 4 the results of such a study[6] are shown. The odd-mass $N = 81$ isotones form one of the longer series of isomer pairs known, consisting of the nuclei $^{133}_{52}\mathrm{Te}_{81}$, $^{135}_{54}\mathrm{Xe}_{81}$, $^{137}_{56}\mathrm{Ba}_{81}$, $^{139}_{58}\mathrm{Ce}_{81}$, $^{141}_{60}\mathrm{Nd}_{81}$, $^{143}_{62}\mathrm{Sm}_{81}$, and $^{145}_{64}\mathrm{Gd}_{81}$. In the first six the ground state consists essentially of a single $d_{3/2}$ neutron hole in the $N = 82$ closed shell; in ^{145}Gd the $d_{3/2}$ hole has been displaced by an $s_{1/2}$ hole, but the $d_{3/2}$ hole forms the first excited state, which is so close to the ground state that its energy has not been measured yet. The $h_{11/2}$ neutron hole forms the metastable state whose energy varies from 334.0 keV in ^{133}Te to a maximum of 756.7 keV in ^{141}Nd, where it then starts to drop off slightly, reaching the vicinity of 725 keV in ^{145}Gd. The half-lives of the metastable states vary from 50 min for $^{133\mathrm{m}}$Te to 60 sec for $^{141\mathrm{m}}$Nd.

In Figure 4 the energies of the M4 transitions ($^{11}\!/\!_2{}^- \rightarrow {}^3\!/\!_2{}^+$) are plotted along with the radial matrix elements $|M|^2$, which were obtained by a somewhat more sophisticated calculation than the Weisskopf single-particle estimate. These radial matrix elements are all much smaller than what would be predicted by straightforward single-particle wave functions, but, more interesting than that, they are not constant over the series. It is not uncommon for M4 transitions to be retarded, but it is unusual for the matrix elements for a series of similar M4 isomeric transitions not to be constant.[7]

Detailed examinations of this variation give us the possibility of determining better wave functions for these states: first, the degree to which the $d_{3/2}$ state gets configuration admixtures from nearby states; second, the actual density of occupation in the $h_{11/2}$ state—one of the first corrections to the simple shell model is a "pairing force," which fuzzes out the nuclear surface and, as a result, the actual probability of finding a pair of particles in a particular orbital.

It is interesting to compare the isomers for $N = 81$ to a similar series for the $N = 79$ odd-mass isotones.[8] For $N = 79$, the $^{11}\!/\!_2{}^-$ metastable states (one $h_{11/2}$ and two $d_{3/2}$ neutron holes) all lie about 200 keV above the $^3\!/\!_2{}^+$ states (three $d_{3/2}$ neutron holes). Thus, the M4 transition rates are much slower; for example, $^{139\mathrm{m}}_{60}\mathrm{Nd}_{79}$ has a half-life of 5.5 hr and only 12.7% of its decay proceeds through the 231.2-keV M4 transition to 30-min $^{139\mathrm{g}}$Nd, the remainder going *via* ϵ/β^+ decay to states in $^{139}_{59}\mathrm{Pr}_{80}$.[9] One would expect the states in $N = 79$ nuclei (three neutron holes) to be much less pure than those in $N = 81$ (only one neutron hole), and this is borne out by the M4 transition rates. After correction for the energy dependence, the M4 rates are greater than those in Figure 4 by a factor of about three, indicating that other components of the wave functions contribute significantly.

The most exotic (highest multipolarity) electromagnetic transitions known occur in nuclear decays. For many years the record was held by the E5 isomeric transitions in the even–even isomers, $^{202\mathrm{m}}$Pb and $^{204\mathrm{m}}$Pb, shown in Figure 5.[10] The highly excited 9^- metastable states consist of an $i_{13/2}$ neutron hole coupled to various lower-spin, odd-parity neutron holes; for example, the $i_{13/2}{}^{-1}f_{5/2}{}^{-1}p_{1/2}{}^{-2}$ combination is the most important contribution to the wave function of $^{204\mathrm{m}}$Pb. Compared with atomic and molecular transitions, the E5 transitions deexciting the 9^- states are strikingly forbidden; yet they are the prime means by which these metastable states can deexcite.

These transitions also carry information about the pairs of 4^+ states to which they lead. Both of the higher-energy E5's, *i.e.*, to the lower 4^+ states, have transition probabilities that are remarkably close to the single-particle estimates, while the lower-energy ones are retarded by a factor of 9.5. This indicates that the two lower 4^+ states are similar, probably consisting of a mixture of two-phonon quadrupole vibrational states along with a large component also of $f_{5/2}{}^{-2}p_{1/2}{}^{-2}$ particle states. The "excited-particle" component allows the E5 to be a "real" single-particle transition. The matrix element is actually larger than expected for an E5 because $i_{13/2}{}^{-1} \rightarrow f_{5/2}{}^{-1}$ is intrinsically "M4". On the other hand, the upper 4^+

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[6] R. E. Eppley, W. C. McHarris, and W. H. Kelly, *Phys. Rev. C*, **2**, 1929 (1970).

[7] R. E. Doebler, W. C. McHarris, and C. R. Gruhn, *Nucl. Phys. A*, **120**, 489 (1968).

[8] R. E. Eppley, R. R. Todd, R. A. Warner, W. C. McHarris, and W. H. Kelly, *Phys. Rev. C*, **5**, 1084 (1972).

[9] D. B. Beery, W. H. Kelly, and W. C. McHarris, *Phys. Rev.* **188**, 1851 (1969).

[10] Jean Guile, R. E. Doebler, W. C. McHarris, and W. H. Kelly, *Phys. Rev. C*, **5**, 2107 (1972).

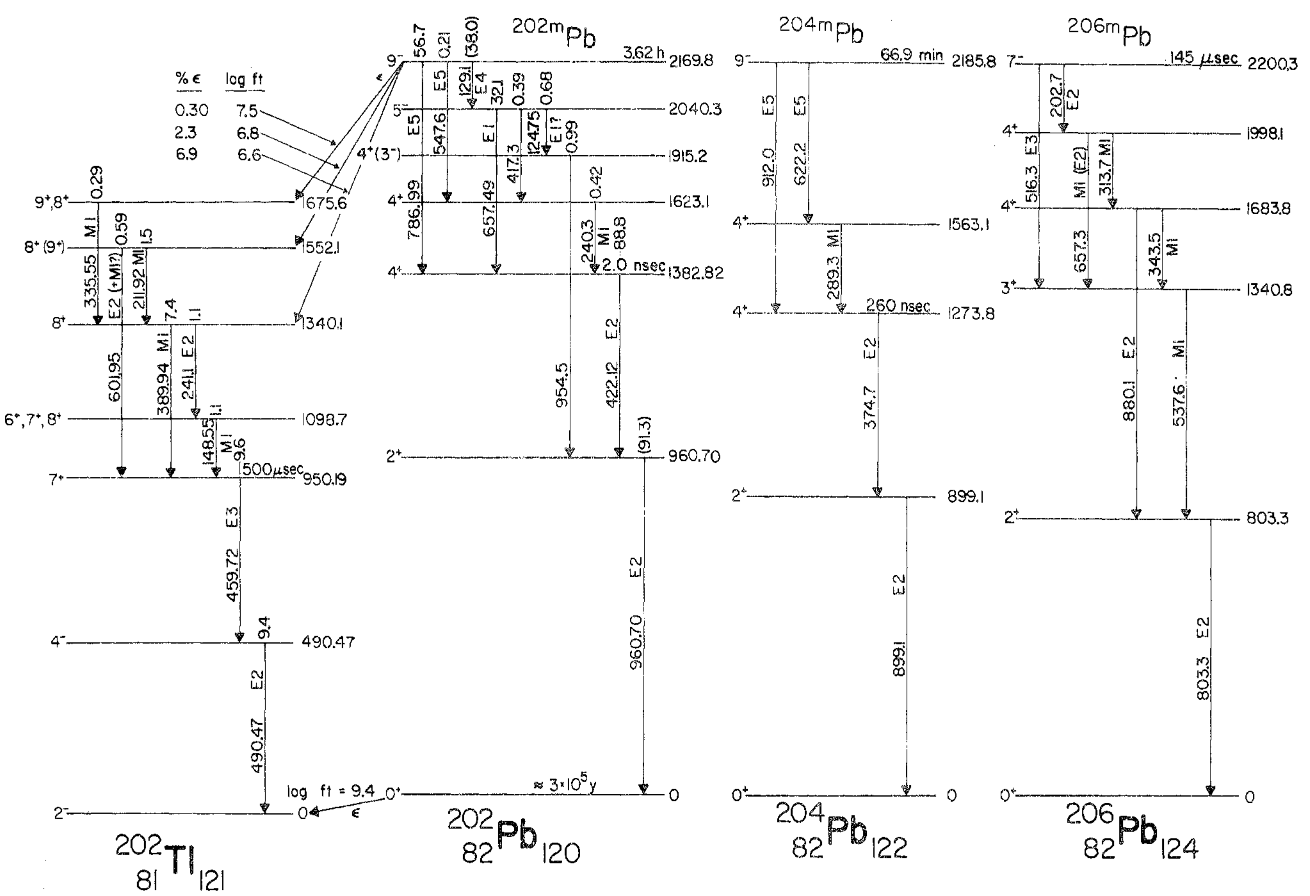

Figure 5. Decay schemes of the three known even–even Pb metastable states. Note the E5 transitions that deexcite the 9⁻ ^{202m}Pb and ^{204m}Pb states.

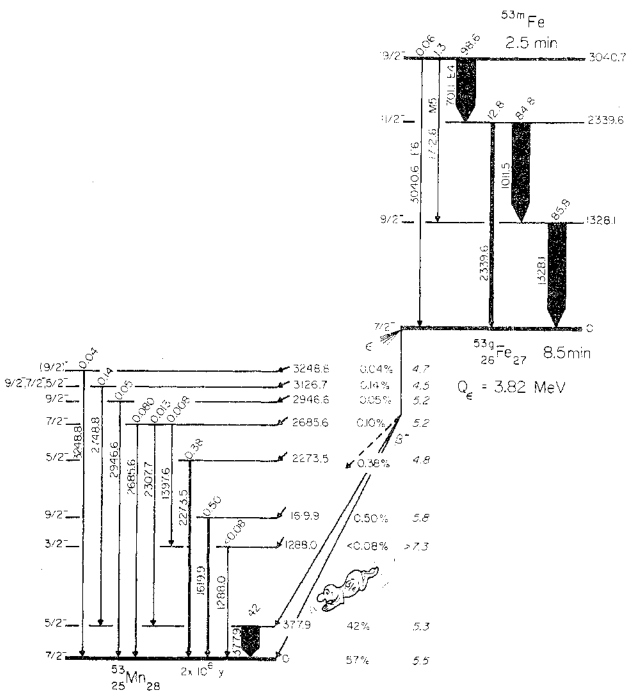

Figure 6. Decay schemes of ^{53m}Fe and ^{53g}Fe. The E6 and M5 transitions are the highest multipolarities yet known.

states are mostly $f_{5/2}^{-1}p_{3/2}^{-1}p_{1/2}^{-2}$, which means that formally the $i_{13/2}$ neutron hole has to change into a $p_{3/2}$ neutron hole, a much more difficult process.

Recently, transitions of even higher multipolarity, E6 and M5, have been observed[11] in the decay of 2.5-min ^{53m}Fe. This decay scheme is depicted in Figure 6. Again, this nucleus lies just below closed shells, here the doubly closed shell at $Z = N = 28$. The ground state of ^{53}Fe is basically an $f_{7/2}$ single-neutron hole, while the other three states include the $f_{7/2}$ proton pair, which have been recoupled to higher angular momentum. The E4 transition to the 2339.6-keV state is the rate-determining transition, and the only reason the M5 and especially the E6 could be detected was because of their very high energies. Even so, the E6 is only 0.06% as intense as the much lower energy E4. (In order to observe these interesting E6 and M5 transitions, hundreds of bombardments were required to make enough of the short-lived ^{53m}Fe.) All three of these high-multipolarity transitions follow the predicted single-particle estimates quite well, not too surprising when one remembers that they represent recoupling of the protons rather than actual orbital changes.

β Decay and Isomers Far from β Stability

Close to the valley of stability β decay provides a relatively meager amount of information about nuclear structure. Nuclei near stability have but little energy for β decay, and this coupled with stringent selection rules means that only few states are populated in the daughter nuclei. However, the β-decay energy increases roughly quadratically with the distance from β stability, so the decay of a nucleus only two or three nucleons removed from stability can populate many states and furnish much important

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(11) J. N. Black, W. C. McHarris, and W. H. Kelly, *Phys. Rev. Lett.* 26, 451 (1971); J. N. Black, W. C. McHarris, W. H. Kelly, and B. H. Wildenthal, to be published.

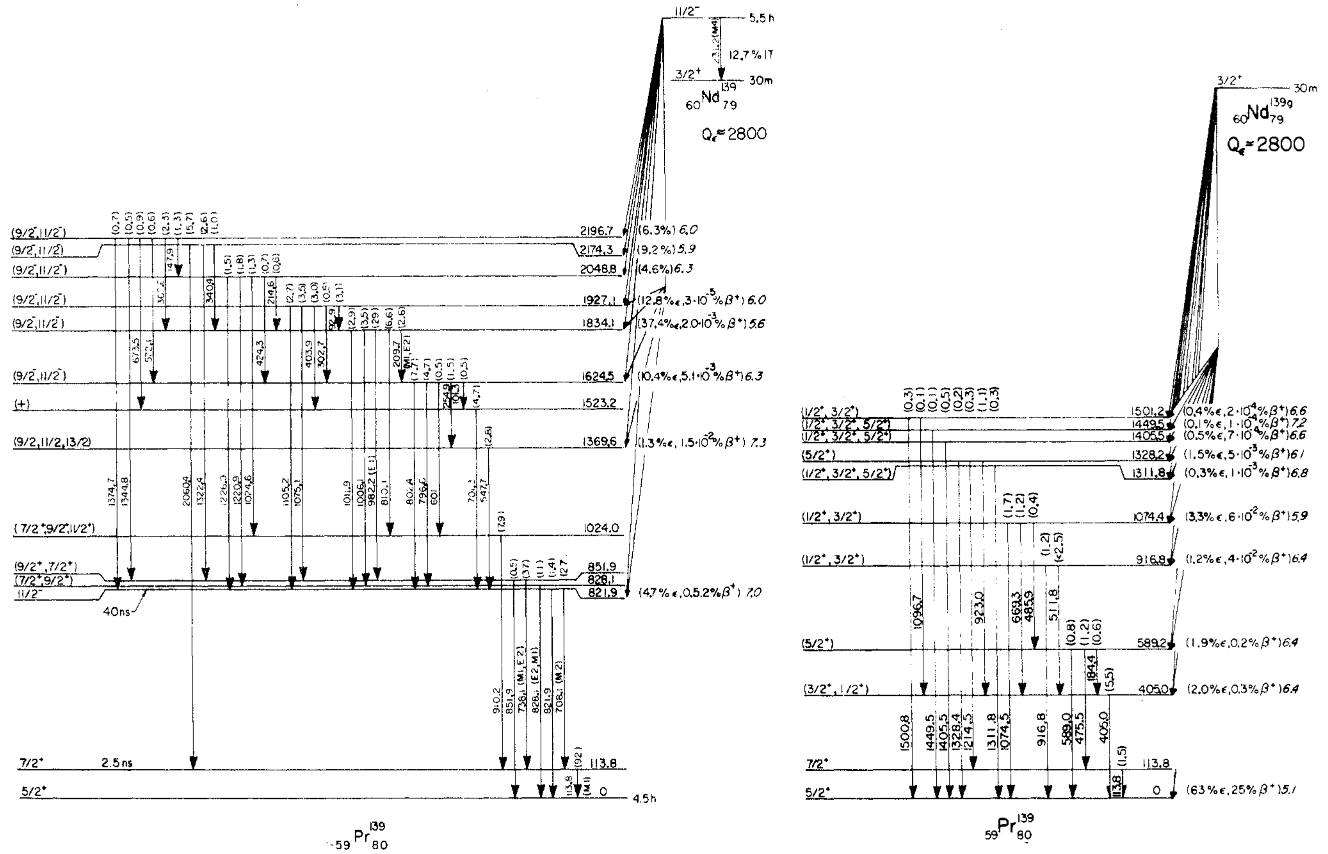

Figure 7. Decay schemes of ^{139m}Nd and ^{139g}Nd. Note that they populate almost completely different states in the same daughter nucleus. ^{139m}Nd also populates a multiplet of high-lying, three-particle states (see text).

information. Odd–odd nuclei, having the extra decay energy that results from their added instability, are particularly informative. Nuclei far from β stability also furnish information in unexpected ways, by decay to states in the daughter that have unusual and intriguing structures. The separate β decay of isomer pairs provides a particularly powerful probe of the states in the daughter, for the two members of a pair will populate very different kinds of states. The resulting information about both high-spin and low-spin states in the daughter will give us a rather complete picture of the structure of that nucleus. Here the whole picture is equal to more than the sum of its component parts.

The decays of such a pair of isomers, ^{139g}Nd and ^{139m}Nd, are shown in Figure 7. The ground-state ($J^\pi = 3/2^+$) decay populates low-spin states in the daughter ^{139}Pr. In fact, 88% of its decay goes directly to the ^{139}Pr ground state, with the remainder "spraying" to at least nine excited states. The very strong β branch to the ^{139}Pr gound state is easily understood in shell-model terms. Looking again at the states depicted in Figure 2, we see that $^{139}_{60}Nd_{79}$ is three neutron holes removed from $N = 82$, and these are $d_{3/2}$ neutron holes. Moreover, it has ten protons above $Z = 50$; eight of these fill the $g_{7/2}$ orbital, leaving two in the $d_{5/2}$ orbital. Now, ϵ and β^+ decay change a proton into a neutron, so a $d_{5/2}$ proton can become a $d_{3/2}$ neutron, thus filling one of the neutron holes. This is a highly favored, fast transition, which is borne out by the low value for the log ft. (A log ft is a "corrected" half-life that puts all β transitions on equal footing, *i.e.*, the energy and atomic number dependence have been taken out so that the "intrinsic" parts of the transition probabilities can be compared.)

Next, look at the very different decay pattern of ^{139m}Nd. Not only does it populate high-spin states in ^{139}Pr, as expected, but also it populates a multiplet of high-energy, high-spin states. One can ask why only 5.2% of its decay goes to the $11/2^-$ state at 821.9 keV, whereas 80.7% is split among the six states between 1624.5 and 2196.7 keV. (β decay, like other decays, is highly energy dependent, so, all else being equal, the transition to the 821.9-keV state should be favored.) As discussed in the previous section, the M4 isomeric transition rate indicates that ^{139m}Nd is constructed of two $d_{3/2}$ and one $h_{11/2}$ neutron-hole states, while ^{139g}Nd has three $d_{3/2}$ neutron holes.

On closer examination of the shell-model possibilities, one finds that its decay behavior is not at all unexpected: there are no protons in states that can easily be converted to fill the $h_{11/2}$ neutron hole, so the fastest β decay is identical in essence to the ^{139g}Nd decay—a $d_{5/2}$ proton is converted into a $d_{3/2}$ neutron, filling one of the $d_{3/2}$ holes. This leaves the ^{139}Pr daughter in a configuration with three excited particles. The $h_{11/2}$ neutron hole remains unfilled, one $d_{3/2}$ neutron hole remains, and the $d_{5/2}$ proton is left over from the pair broken by the β decay. The γ transitions out of the multiplet of six three-particle states are all highly retarded because they also involve multiple rearrangements in the nucleus.

Also, the hindered decay to the 821.9-keV state is explained: it involves converting a $d_{5/2}$ proton into an $h_{11/2}$ neutron, a difficult procedure because of the large spin difference, and simultaneously promoting the remaining $d_{5/2}$ proton into the $h_{11/2}$ proton orbital. Thus, the two decays, ^{139g}Nd and ^{139m}Nd, give us a wealth of information about high-spin, low-spin, single-particle, and three-particle states in ^{139}Pr, far more than one could ever get from a single decay or, for that matter, from nuclear reaction experiments.

It would be possible to go on at length about the intriguing facts that have been found or will be found from the decay of nuclei far from stability: strange and unusual nuclear configurations, odd transition rates, shape isomers (in which the metastable state actually has a different degree of deformation than the ground state), fundamental changes required in weak interaction theory from what had been expected, etc. The important thing, however, is that from isomer pairs one gets at least twice as much information as from a single decay. Another aspect that will probably be of more and more importance in the future is the added stability that the high-spin isomers give nuclei far from stability. Mostly because of their more complex configurations and the relative dearth of high-spin states to decay to, the high-spin states far from stability become longer lived than the low-spin states, even when the low-spin state is the ground state. Thus, it may well be high-spin isomers that will allow us to study the more exotic nuclei.

Isomers and the Future

Figure 3 shows almost 350 isomer pairs; yet hundreds more will likely be found. Many of these will lie far from stability, but many others, both very long- and very short-lived, will probably be found among known nuclei. A rather unnerving fact is that, whenever one irradiates a target in a particular beam to produce a particular nuclide, he almost invariably observes "unidentified" short-lived activities that have not yet been tracked down. In brief, there are isomers waiting to be identified almost everywhere.

Even aside from their value in probing nuclear structure, the uses of isomers will continue to be legion. There will be many applications in biology and medicine, where the search for shorter-lived tracers continues. They will find uses in metallurgy for quality control or for gauge monitors. They will furnish added tracers for chemistry, and a few may even be used as probes for atomic and molecular structure—for example, 26.1-min ^{235m}U lies only 73 eV above the ground state,[12] and chemical effects can significantly affect its decay rate because its decay is by conversion in the P electron shell.

Finally, nuclear isomers should make possible the eventual production of a γ-ray laser, with all its awsome implications. In fact, a γ-ray laser appears to be more feasible than an X-ray laser because it is easy to obtain population inversions with nuclear metastable states. The main difficulty will be how to stimulate emission, for nuclear states are far narrower than atomic states. It will be necessary to compensate for recoil, quadrupole shifts, and a host of other small, but important perturbations.

In this Account I have tried to give a short overview of what nuclear isomers are and how they can be of use to us. In this, I hope that I have conveyed some of the excitement engendered by the elusive, antisocial nucleus. In its isolation, providing us with the strange high-multipolarity forbidden transitions and metastable states of wildly differing half-lives, it has provided science with powerful tools found nowhere else.

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Cobalt-59 Nuclear Quadrupole Resonance Spectroscopy

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Since the original observation in 1950 of a pure nuclear quadrupole resonance (nqr) transition in a solid,[1] a substantial literature dealing with nqr spectroscopy has developed.[2-4] Nevertheless, it is fair to say that it remains a rather specialized tool. In part this derives from the inherent limitations of the technique. Pure nuclear quadrupole resonance spectroscopy must be carried out on crystalline solids. The nqr spectrum is simpler, and therefore less liable to provide interesting and instructive detail than is often seen in nuclear magnetic resonance spectra of solutions. In addition, the instrumental requirements are considerably more varied than is the case for nmr. Finally, the acquisition of nqr data has proven quite difficult for several nuclear quadrupole systems which would be of great chemical interest, *e.g.*, ^{14}N, ^{2}H.

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