Nuclear isomer

A **nuclear isomer** is a metastable state of an atomic nucleus caused by the excitation of one or more of its nucleons (protons or neutrons). "Metastable" refers to the fact that these excited states have half-lives more than 100 to 1000 times the half-lives of the excited nuclear states that decay with a "prompt" half life (ordinarily on the order of 10^{-12} seconds). As a result, the term "metastable" is usually restricted to refer to isomers with half-lives of 10^{-9} seconds or longer. Some sources recommend 5×10^{-9} s to distinguish the metastable half life from the normal "prompt" gamma emission half life.[1]

Occasionally the half-lives are far longer than this, and can last minutes, hours, years, or in one notable case $^{180m}_{73}Ta$, so long that it has never been observed to decay (at least 10^{15} years). Sometimes, the gamma decay from a metastable state is given the special name of an isomeric transition, but save for the long-lived nature of the meta-stable parent nuclear isomer, this process resembles shorter-lived gamma decays in all external aspects. The longer lives of nuclear isomers (metastable states) are often due to the larger degree of nuclear spin change which must be involved in their gamma emission to reach the ground state. This high spin change causes these decays to be relatively forbidden, and thus delayed. However, other reasons for delay in emission, such as low or high available decay energy, also have effects on decay half life.

The first nuclear isomer and decay-daughter system (uranium X_2/uranium Z, now known as $^{234m}_{91}Pa$/$^{234}_{91}Pa$) was discovered by Otto Hahn in 1921.

Nucleus

The nucleus of a nuclear isomer occupies a higher energy state than the corresponding non-excited nucleus, which exists in the lowest energy state, called the ground state. In an excited state, one or more of the protons or neutrons in a nucleus occupy a nuclear orbital of higher energy than an available nuclear orbital of lower energy. These states are analogous to excited states of electrons in atoms.

Excited atomic states decay by fluorescence which usually involves emission of light near the visible range. However, because of the much higher binding energies involved in nuclear processes, most nuclear excited states decay instead by gamma ray emission. For example, a well-known nuclear isomer used in medical procedure is $^{99m}_{43}Tc$, which decays with a half-life of about 6 hours, by emitting a gamma ray of 140 kiloelectron-volts of energy (this is close to the energy of medical diagnostic X-rays).

Nuclear isomers owe their long half lives to the fact that their gamma decay is (relatively, not absolutely) forbidden due to a large change in nuclear spin needed to emit a gamma. For example, $^{180m}_{73}Ta$ has a spin of −9 and must gamma decay to $^{180}_{73}Ta$ with a spin of +1. Similarly, $^{99m}_{43}Tc$ has a spin of +1/2 and must gamma decay to $^{99}_{43}Tc$ with a spin of +9/2.

Internal conversion

Metastable isomers may also decay by internal conversion — a process in which the energy of nuclear de-excitation is not emitted as a gamma ray, but instead used to accelerate one of the inner electrons of the atom, so that it leaves at high speed and energy. This process is only possible because inner atomic electrons penetrate the nucleus, where they are subject to the intense electric fields which result when the protons of the nucleus re-arrange in a different way. In nuclei which are far from stability in energy, still other decay modes are known.

Metastable isomers

Metastable isomers can be produced through nuclear fusion or other nuclear reactions. A nucleus thus produced generally starts its existence in an excited state that relaxes through the emission of one or more gamma rays or conversion electrons. However, sometimes it happens that the de-excitation does not proceed rapidly all the way to the nuclear ground state. This usually occurs because of the formation of an intermediate excited state with a spin far different from that of the ground state. Gamma-ray emission is far slower (is "hindered") if the spin of the post-emission state is very different from that of the emitting state, particularly if the excitation energy is low. The excited state in this situation is therefore a good candidate to be metastable if there are no other states of intermediate spin with excitation energies less than that of the metastable state.

Metastable isomers of a particular isotope are usually designated with an "m" (or, in the case of isotopes with more than one isomer, m1, m2, m3, and so on). This designation is placed after the mass number of the atom; for example, Cobalt-58m (abbreviated $^{58m}_{27}Co$, where 27 is the atomic number of cobalt). Increasing indices, m1, m2, etc., correlate with increasing levels of excitation energy stored in each of the isomeric states (e.g., hafnium-177m2 or $^{177m2}_{72}Hf$).

A different kind of metastable nuclear state (isomer) is the **fission isomer** or **shape isomer**. Most actinide nuclei, in their ground states, are not spherical, but rather spheroidal—specifically, prolate, with an axis of symmetry longer than the other axes (similar to an American football or rugby ball, although with a less pronounced departure from spherical symmetry).[*citation needed*] In some of these, quantum-mechanical states can exist in which the distribution of protons and neutrons is farther yet from spherical (in fact, about as non-spherical as an American football), so much so that de-excitation to the nuclear ground state is strongly hindered. In general, these states either de-excite to the ground state (albeit far more slowly than a "usual" excited state) or undergo spontaneous fission with half-lives of the order of nanoseconds or microseconds—a very short time, but many orders of magnitude longer than the half-life of a more usual nuclear excited state. Fission isomers are usually denoted with a postscript or superscript "f" rather than "m", so that a fission isomer in, e.g., plutonium 240 is denoted plutonium-240f or $^{240f}_{94}Pu$.

Nearly-stable isomers

Most nuclear excited states are very unstable, and radiate away the extra energy immediately (on the order of 10^{-12} seconds). As a result, the term is usually restricted to refer to isomers with half-lives of 10^{-9} seconds or longer. Quantum mechanics predicts that certain atomic species will possess isomers with unusually long lifetimes even by this stricter standard, and so have interesting properties. By definition, there is no such thing as a "stable" isomer; however, some are so long-lived as to be *nearly* stable, and can be produced and observed in quantity.

The most stable nuclear isomer occurring in nature is $^{180m}_{73}Ta$, which is present in all tantalum samples at about 1 part in 8,300. Its half-life is at least 10^{15} years, markedly longer than the age of the universe. This remarkable persistence results from the fact that the excitation energy of the isomeric state is low, and both gamma de-excitation to the ^{180}Ta ground state (which itself is radioactive by beta decay, with a half-life of only 8 hours), and direct beta decay to hafnium or tungsten are all suppressed, owing to spin mismatches. The origin of this isomer is mysterious, though it is believed to have been formed in supernovae (as are most other heavy elements). When it relaxes to its ground state, it releases a photon with an energy of 75 keV.

It was first reported in 1988 by Collins that ^{180m}Ta can be forced to release its energy by weaker x-rays. After 11 years of controversy those claims were confirmed in 1999 by Belic and co-workers in the Stuttgart nuclear physics group.

Another reasonably stable nuclear isomer (with a half-life of 31 years) is $^{178m2}_{72}Hf$, which has the highest excitation energy of any comparably long-lived isomer. One gram of pure $^{178m2}Hf$

contains approximately 1.33 gigajoules of energy, the equivalent of exploding about 315 kg (694 lb) of TNT. Further, in the natural decay of ^{178m2}Hf, the energy is released as gamma rays with a total energy of 2.45 MeV. As with ^{180m}Ta, there are disputed reports that ^{178m2}Hf can be stimulated into releasing its energy, and as a result the substance is being studied as a possible source for gamma ray lasers. These reports also indicate that the energy is released very quickly, so that ^{178m2}Hf can produce extremely high powers (on the order of exawatts). Other isomers have also been investigated as possible media for gamma-ray stimulated emission.

Holmium has an interesting nuclear isomer, $^{166m1}_{67}$Ho with a half-life of 1,200 years, which is nearly the longest half-life of any holmium radionuclide (only ^{163}Ho, with a half-life of 4,570 years is longer).

$^{229}_{90}$Th has a remarkably low-lying metastable isomer, only 7.6 ± 0.5 electron volts above the ground state, as calculated from spectroscopic measurements. This direct decay has not been observed, however. If this isomer were to decay it would produce a gamma ray (defined by its origin, not its wavelength) in the ultraviolet range. These "ultraviolet gamma rays" were thought to have been detected at one time, but this observation has since been found to be from nitrogen gas excited by higher energy emissions.

High spin suppression of decay

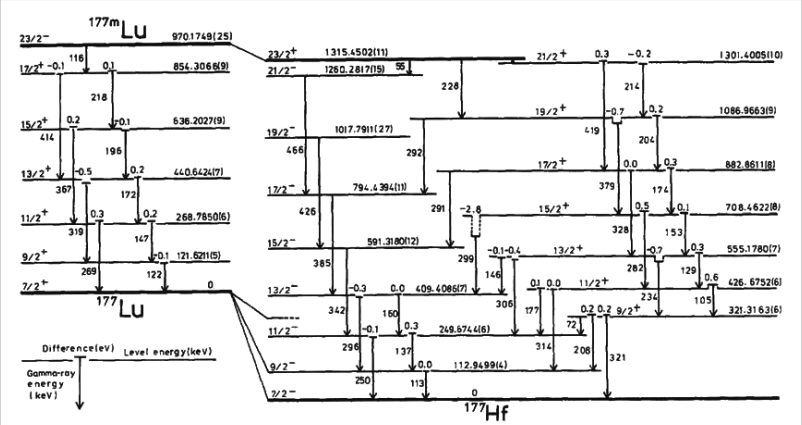
The most common mechanism for suppression of gamma decay of excited nuclei, and thus the existence of a metastable isomer for the nucleus, is lack of a decay route for the excited state that will change nuclear angular momentum (along any given direction) by the most common amount of 1 quantum unit $\hbar$ of spin angular momentum. Such a change is necessary to emit a gamma photon, which has a spin of 1 unit in this system. Integral changes of 2,3,4, and more units in angular momentum are possible (the emitted photons carry off the additional angular momentum), but changes of more than 1 unit are inhibited by about 5 orders of magnitude in rate for every additional unit of spin change larger than 1, that the emitted gamma ray must carry.[2] The highest known spin change of 8 units occurs in the decay of Ta-180m, which suppresses its decay by a factor of 10^{35} from that associated with 1 unit, so that instead of a natural gamma decay half life of 10^{-12} seconds, it has a half life of more than 10^{23} seconds, or at least 3 x 10^{15} years, and thus has yet to be observed to decay.

Applications

Hafnium and tantalum[*citation needed*] isomers have been considered in some quarters as weapons that could be used to circumvent the Nuclear Non-Proliferation Treaty, since they can be induced to emit very strong gamma radiation. DARPA has (or had) a program to investigate this use of both nuclear isomers. The potential to trigger an abrupt release of energy from nuclear isotopes, a prerequisite to their use in such weapons, is disputed. Nonetheless a 12-member Hafnium Isomer Production Panel (HIPP) was created to assess means of mass producing the isotope.

Technetium isomers $^{99m}_{43}$Tc (with a half-life of 6.01 hours) and $^{95m}_{43}$Tc (with a half-life of 61 days) are used in medical and industrial applications.

Nuclear batteries



Lutetium nuclear isomer energy levels

Nuclear batteries in development use small amounts (milligrams and microcuries) of radioisotopes with high energy densities. In one design, radioactive material sits atop a device with adjacent layers of P-type and N-type silicon, so that ionizing radiation directly penetrates the junction and creates electron-hole pairs. Nuclear isomers could replace other isotopes, and with further development it may be possible to turn them on and off as needed. Current candidates for such use include ^{108}Ag, ^{166}Ho, ^{177}Lu, and ^{241}Am. As of 2004 the only isomer which had been successfully triggered was ^{180m}Ta, which required more photon energy to trigger than was released.

Fission of an isotope such as ^{177}Lu releases gamma rays by decay through a series of internal energy levels within the nucleus, and it is thought that by learning the triggering cross sections with sufficient accuracy, it may be possible to create energy stores that are 10^6 times more concentrated than high explosive or other traditional chemical energy storage.

Decay processes

Isomers decay to lower energy states of the nuclide through two isomeric transitions:

1. γ (gamma) emission (emission of a high-energy photon)
2. internal conversion (the energy is used to ionize the atom)

Isomers may also decay into other elements, though the rate of decay may differ between isomers. For example, ^{177m}Lu beta decays to ^{177}Hf with half-life 160.4 d, or can undergo internal transition to ^{177}Lu with half-life 160.4 d, then beta decays to ^{177}Hf with half-life 6.68 d.

An **isomeric transition** is a radioactive decay process that involves emission of a gamma ray from an atom where the nucleus is in an excited metastable state, referred to in its excited state, as a nuclear isomer.

The emission of a gamma ray from an excited nuclear state allows the nucleus to lose energy and reach a lower energy state, sometimes its ground state. In certain cases, the excited nuclear state following a nuclear reaction or other type of radioactive decay, has a half life that is more than 100 to 1000 times longer than the average 10^{-12} seconds, and this excited state is referred to as a metastable nuclear excited state. Some nuclei are able to stay in this metastable excited state for minutes, hours, days, or occasionally far longer, before undergoing *gamma decay*, in which they emit a gamma ray.

The process of isomeric transition (that is, the gamma decay of nuclear isomers), is therefore similar to any gamma emission from any excited nuclear state, but differs in that it involves excited metastable states of nuclei with longer half lives. These states are created, as in all nuclei that undergo gamma radioactive decay, following the emission of an alpha, beta particle, or occasionally other types of particles that leave the nucleus in an excited state.

The gamma ray may transfer its energy directly to one of the most tightly bound electrons causing that electron to be ejected from the atom, a process termed the photoelectric effect. This should not be confused with the internal conversion process, in which no gamma ray photon is produced as an intermediate particle.

References

[1] Nuclear isomers (http://epubs.surrey.ac.uk/137/1/fulltext.pdf)
[2] Discussion of spin suppression of decay (http://www.eng.fsu.edu/~dommelen/quantum/style_a/ntgd.html)

External links

- Research group which presented initial claims of hafnium nuclear isomer de-excitation control. (http://www.utdallas.edu/research/quantum/) – The Center for Quantum Electronics, The University of Texas at Dallas.
- JASON Defense Advisory Group report on high energy nuclear materials (http://www.fas.org/irp/agency/dod/jason/he.pdf) mentioned in the *Washington Post* story above
- Bertram Schwarzschild (May 2004). "Conflicting Results on a Long-Lived Nuclear Isomer of Hafnium Have Wider Implications" (http://scitation.aip.org/journals/doc/PHTOAD-ft/vol_57/iss_5/21_1.shtml). *Physics Today*: 21. login required?
- Confidence for Hafnium Isomer Triggering in 2006. (http://www.hafniumisomer.org/Hafnium_isomer_triggering.htm) – The Center for Quantum Electronics, The University of Texas at Dallas.
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