The implications of these new findings are wide ranging. For example, although *Bd*GPL is globally distributed, other lineages are geographically restricted. This identifies areas that might be susceptible to new invasions by these endemic lineages and may explain variation in species responses to infection (*7*, *8*). Despite decades of research, quantitative studies of the impacts of chytridiomycosis on amphibian populations are lacking from most areas, especially Asia (*8*). Demographic analyses are critical in providing robust estimates of demographic parameters such as species or population-specific survival and mortality rates and population growth rates. In addition, mark-recapture studies that follow the fate of infected individuals are needed to identify mechanisms underlying the causes of population decline, persistence, or recovery and to identify effective conservation measures.

To control emerging infectious diseases (EIDs), we also need a better understanding of the relative contributions of global change (for example, changes in climate, land use, and trade) on the emergence and spread of pathogens. Knowing that all chytrid lineages are circulating in trade routes, but not all are globally distributed (*5*), highlights the need for coinfection experiments to predict responses to future invasions. Knowledge of how the trade ecosystem might amplify disease by promoting hybridization events among lineages or by facilitating the spread of lineages into naïve populations could be useful to mitigate and manage disease within the live-animal trade.

Many areas of the world lack chytrid cultures, disease surveillance programs, or amphibian population studies necessary to study or conserve amphibian biodiversity. Developing collaborative partnerships between investigators from these regions and established research groups could increase the global capacity to understand the emergence of *Bd* and responses of amphibian populations. Even more important is the need to expand veterinary capacity for wildlife diseases. Many national veterinary authorities lack sufficient resources, staff, or bandwidth to respond effectively to the rapidly increasing numbers of wildlife pathogens that threaten global biodiversity.

Proactive measures to address EIDs will be possible when we can predict future outbreaks, species susceptibility, and disease spread, perhaps through analyses to model disease outbreaks from genomics, Google search histories, or social media data (*9*, *10*). Advanced detection technologies would improve the ability to address new introductions. Alternatively, coordination of citizen science programs might serve as an early warning system in some regions.

Successful mitigation of the impacts of chytridiomycosis is also lacking. No effective treatments exist for wild populations, and policies restricting imports are only as strong as enforcement efforts (*7*). One of the most important advances in the global response to *Bsal* was the development of an emergency response plan (*11*, *12*), including the establishment of a *Bsal* task force (*4*); such a coordinated effort is lacking for *Bd* and could speed discovery and identify effective interventions.

Both *Bd* and *Bsal* are notifiable diseases under the World Organisation for Animal Health (OIE) standards, but, despite global support, this agreement has lacked strong, consistent enforcement. Strengthening application of the OIE standards should be a first step. In the United States, new laws are needed to improve the ability of the U.S. Fish and Wildlife Service to monitor and control invasive species and diseases (*13*). New policies developed in collaboration with trade organizations, lobbyists, and national and international organizations to implement quarantine measures, testing procedures, and clean-trade programs could minimize the risk of pathogen introductions. The European Union has recently approved such a law (*14*).

The work of O'Hanlon *et al.* serves as a case study for studying and addressing EIDs. With accelerating global change in a more connected world, we can expect to see more EIDs, so international collaborations such as this one will be increasingly necessary to address global pathogens of wildlife, agriculture, and humans. ■

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NUCLEAR PHYSICS

Resolving the neutron lifetime puzzle

A measurement of trapped neutrons dramatically improves control of systematic uncertainties

By **Pieter Mumm**

Free electrons and protons are stable, but outside atomic nuclei, free neutrons decay into a proton, electron, and antineutrino through the weak interaction, with a lifetime of ~880 s (see the figure). The most precise measurements have stated uncertainties below 1 s (0.1%), but different techniques, although internally consistent, disagree by 4 standard deviations given the quoted uncertainties. Resolving this "neutron lifetime puzzle" has spawned much experimental effort as well as exotic theoretical mechanisms, thus far without a clear explanation. On page 627 of this issue, Pattie *et al.* (*1*) present the most precise measurement of the neutron lifetime to date. A new method of measuring trapped neutrons in situ allows a more detailed exploration of one of the more pernicious systematic effects in neutron traps, neutron phase-space evolution (the changing orbits of neutrons in the trap), than do previous methods. The precision achieved, combined with a very different set of systematic uncertainties, gives hope that experiments such as this one can help resolve the current situation with the neutron lifetime.

> ***"Researchers have primarily used two techniques to measure the neutron lifetime, typically referred to as 'beam' and 'bottle' measurements."***

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The semileptonic decay of neutrons is the simplest example of nuclear β-decay and plays a key role in validating our understanding of weak processes. In the early universe, the neutron lifetime ultimately determined the ratio of neutrons to protons during primordial light-element nucleosynthesis. The neutron decay is also closely connected to processes relevant in solar physics and in the detection of reactor antineutrinos (*2*, *3*). In combination with other neutron decay parameters, it affords the potential of a sensitive test of the unitarity of the quark-mixing matrix competitive with, and independent of, other methods (*4*). For these reasons, determining the free neutron lifetime has been the focus of extensive experimental effort (*5*) since the first measurement in 1948 (*6*).

Researchers have primarily used two techniques to measure the neutron lifetime, typically referred to as "beam" and "bottle" measurements. In the beam measurement, a very well-characterized beam of cold neutrons (neutrons with energies of a few milli–electron volts) passes through an arrangement of magnetic and electric fields that forms a pseudo-Penning proton trap. Every so often, the trap is emptied, and the decay protons are counted. By comparing the proton detection rate with the number of neutrons traveling through the trap, the neutron lifetime can be readily extracted. Although conceptually simple, this approach depends on accurate proton counting and the absolute determination of the neutron flux at or below the 0.1% level, both of which are extremely challenging. With the lifetime puzzle in mind, an updated measurement based on this technique, with an expected uncertainty of below 1 s, is currently under way (*7*).

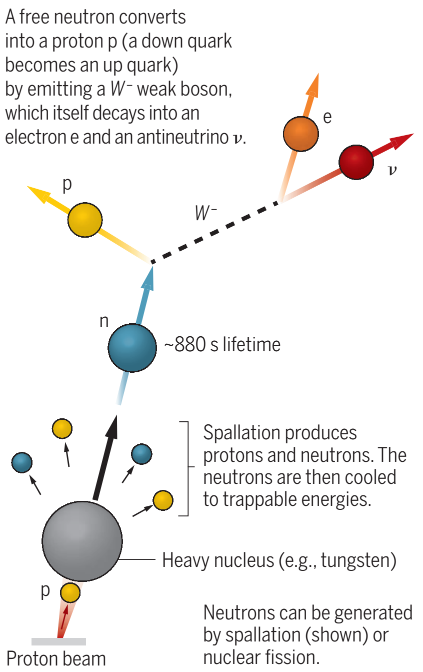
An alternative approach that avoids some of the difficulties of the beam method is to trap neutrons for times that are large compared with the lifetime. Neutrons can be cooled from milli- to nano–electron volt energies through nonequilibrium inelastic scattering processes (*8*). These "ultracold" neutrons (UCNs) are of such low energies that they travel only a few meters per second. A useful accident of nature is that for UCNs, gravitational, magnetic, and nuclear interaction energies are roughly similar, so UCNs are easily manipulated (for example, spin-polarized to very high levels). In particular, UCNs below a few hundred nano–electron volts can be trapped in vessels made of appropriately chosen material.

Neutron traps have become the most common method used in neutron lifetime measurements (*9*–*12*). In these experiments, neutrons are loaded into a trap, stored for a variable length of time, and then drained into a detector, where they are counted. By comparing surviving neutrons over multiple storage times, the neutron lifetime can be extracted independently of the absolute number of neutrons loaded into the trap. For this approach to work, neutron losses from the trap during storage must be both minimized and well understood, but neutrons interact strongly with matter. For example, neutrons can be absorbed or scattered by imperfections in the trap. Because UCNs are not in thermal equilibrium with their surroundings, any scattering process will tend to increase their energy and eject them from the trap.

As a result, all material bottle experiments must make corrections for these effects. Such effects can be reduced by using magnetic traps, and there are several examples of this approach (*13*, *14*). More difficult, however, are effects caused by UCN phase-space evolution either during storage or during the unloading of the trap. It is generally the case that some fraction of UCNs in a trap have total energies above the trap depth because some of the energy is in orbital motion. Orbits can evolve slowly, on time scales of hundreds of seconds, and eventually, the UCNs are lost. Similarly, some orbits may take long times to drain and be detected, requiring additional corrections.

Neutron decay

Free neutrons (n) undergo β-decay through the weak interaction after ~880 s. A new trapping measurement by Pattie *et al.* provides a way to better determine this value.



A free neutron converts into a proton p (a down quark becomes an up quark) by emitting a W^- weak boson, which itself decays into an electron e and an antineutrino ν.

Spallation produces protons and neutrons. The neutrons are then cooled to trappable energies.

Neutrons can be generated by spallation (shown) or nuclear fission.

The work of Pattie *et al.* combines several clever advances to address these systematic difficulties. Like most other modern experiments, their study uses a magnetic trap. However, in their case, the trap is a semitoroidal magneto-gravitational trap formed from a magnetic Halbach array and gravity. The trap is asymmetric, leading to quasi-chaotic orbits, which creates an efficient and rapid mixing of phase space. This process allows the use of a "cleaner," a neutron absorber placed just below the maximum trap depth. All neutrons that could eventually escape from the trap are quickly removed before the storage period begins. Most importantly, however, Pattie *et al.* developed an in situ detector, consisting of a neutron-absorbing layer deposited on a scintillating material coupled to optical detectors (*14*). Neutron absorption produces light that is detected with high efficiency. This detector can be lowered in stages so that a neutron energy spectrum can be mapped at various storage times and prove that any phase-space evolution is minimized.

The results are remarkable. Once cleaned, the storage time in their trap is >3 weeks, and perhaps most importantly, the unloading sequence is identical at long and short holding times. Thus, not only do Pattie *et al.* report the most precise measurement of the neutron lifetime but also the first modern measurement in which the systematic corrections are below the stated uncertainty. Assuming that the discrepancy with the beam measurements will be understood, a precision of 0.2 s appears quite plausible in the near future. In addition to the impacts discussed above, at this level of precision, comparison with other techniques will allow new precision tests of the Standard Model (*15*). ■

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