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# Perspective: Magnetic traps for nearly untrappable particles: "Invited Article: Development of high field superconducting Ioffe magnetic traps" [Rev. Sci. Instrum. 79, 031301 (2008)]

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Precision studies of subatomic particles, atoms, and molecules benefit tremendously from electromagnetic traps. These traps confine particles away from material walls, thereby removing the dephasing, sample loss, and systematic backgrounds which result from collisions with these walls. The same confinement also allows for greatly increased measurement times, thereby reducing the measurement's statistical uncertainty.

The most elementary requirement for a successful trap is that it produce a potential well deeper than the particles' kinetic energy. The difficulty in achieving this scales inversely with the strength of the particles' electromagnetic interactions. For example, particles with an electric charge (e.g., ions, molecular ions, and electrons) are routinely trapped at room temperature using electric fields produced in centimeter- and millimeter-scale traps.[1] On the other hand, neutral atoms with a magnetic moment of roughly $1\mu^B$ can only be trapped in the magnetic fields produced by resistive coils (typically a few hundred Gauss) if the atoms are cooled below 1 mK (e.g., by laser cooling).[2] If one replaces the normal-metal coils with superconducting coils, trapping fields of a few Tesla can be realized,[3] and magnetic atoms can be trapped at temperatures close to 1 K. This temperature can be achieved using helium buffer gas and standard cryogenic techniques.

This last approach has been pioneered over the past 15 years by Doyle and co-workers at Harvard University,[4] building on earlier work at MIT and elsewhere.[5] It can be applied to virtually any atomic or molecular species with a magnetic moment (unlike laser cooling, which requires atoms with specific optical properties). However, deep superconducting traps present a number of significant technical challenges.

One such challenge is simply keeping the coils in place. Magnetic trapping requires a magnetic field minimum,[6] typically achieved using a split-coil solenoid with opposite currents in the two coils. At the center point of the trap, the magnetic fields from the two coils exactly cancel, providing the necessary field minimum (which also happens to be a field zero). Thus, this geometry produces a magnetic field profile suitable for trapping; however a quick inspection will also reveal that the two coils repel each other magnetically.

For the atom traps developed in the Doyle group (which achieve trap depths of ~4 T and trap volumes of several cubic centimeters), this force is roughly 30 metric tons.[3] To safely contain this force, the magnet support structure must be carefully designed, with special attention paid to the cryogenic mechanical properties of the materials used in its construction. The design of these magnets has been described previously.[3]

In addition to these large forces, superconducting magnets also differ from their resistive counterparts in that they carry current in a metastable dissipationless state. If a small section of superconducting wire in a magnet is heated above its critical temperature (e.g., if an inadequately secured piece of wire moves suddenly as a result of the Lorentz force produced by the magnet's own field), this portion of the wire will become resistive, and the current flowing through the magnet will heat it still further. A larger section of the wire will then be driven normal, leading to still more heating, and so on. This runaway process is known as a "quench" and typically leads to the dissipation of the magnet's stored energy in a small portion of the magnet coil. A sufficiently violent quench can melt sections of the coil and ruin the magnet.

To mitigate these issues, the atom-trapping magnets developed by Doyle *et al.* make use of relatively simple coil geometries (i.e., the split-coil geometry, also known as the spherical quadrupole or "anti-Helmholtz pair"). The magnets are wound on cylindrical bobbins and closely resemble standard solenoids except that opposite currents flow in the two-halves of the "solenoid." This approach simplifies the magnets' construction, the analysis of mechanical strain in the magnets' support structure, and the design of quench protection circuits.

If instead of atoms, one is interested in trapping neutrons, the situation appears much more daunting. The neutron's magnetic moment is roughly 1000 times smaller than typical atomic magnetic moments, meaning that a given magnetic trap is 1000 times shallower for a neutron than for a magnetic atom. However, precision measurements of the lifetime of isolated neutrons may shed light on difficult-to-measure parameters in the standard model of particle physics.[7] As a result, a collaboration lead by Huffman *et al.* has developed magnetic traps which are specifically tailored to the needs of neutron lifetime measurements.[8]

Although neutrons are stable in a wide variety of nuclei, an isolated neutron has a lifetime of roughly 800 s. To date, the most precise measurements of this lifetime[9] have been made by trapping ultracold neutrons in a "bottle"—a solid container whose walls are coated with a neutron-reflecting material. In such a bottle, the observed neutron loss is a combination of the intrinsic decay of neutrons and the loss of neutrons due to imperfections in the neutron-reflecting material. In practice, the intrinsic neutron lifetime is determined by measuring the trap loss as a function of the bottle size and extrapolating the result to an infinite bottle. Despite this extrapolation, wall-induced loss remains one of the main sources of uncertainty in the neutron lifetime.

Magnetic traps can, in principle, remove this uncertainty, but only offer trapping potentials which are about 1 mK deep. This apparent problem is overcome by filling the trapping region with superfluid $^4$He and loading the trap via the "superthermal process"[10] as follows. A beam of low-energy neutrons passes through a monochromator chosen to select neutrons with a kinetic energy corresponding to 11 K. After the monochromator, the nearly monoenergetic neutrons are injected into the trapping region. Because the dispersion curve of superfluid excitations intersects the dispersion curve of neutrons at an energy of 11 K, it is possible for a neutron to generate an excitation in the superfluid and in doing so give up nearly all its kinetic energy. Neutrons which undergo this process will not be reexcited by the superfluid because the superfluid's temperature is far too low to produce the necessary 11 K excitation. As a result, the downscattered neutron is at close to zero energy and sees the superfluid as a vacuum.[8]

This resolves the question of how to ensure that the neutrons' kinetic energy is less than the trap depth, but there are two other important trap-related issues which complicate matters further. The first is that the size of the signal in these experiments is proportional to the number of trapped neutrons, and so the statistical uncertainty in the measured neutron lifetime decreases as more neutrons are trapped. The number of trapped neutrons scales as the trapping volume (assuming all other parameters are held constant),[11] meaning that it is desirable to have a physically large trap.

The second issue is that the simplest trap geometry, the spherical quadrupole described above, is not well suited to neutron lifetime measurements. This is because the magnetic field minimum in the spherical quadrupole trap is actually a magnetic field zero, and particles which pass close to this point can transition to an untrapped spin state (through a type of Landau–Zener tunneling known as a Majorana transition[12]). Thus, the spherical quadrupole trap has a "hole" at its center, which leads to neutron loss and, hence, a systematic error in estimates of the neutron lifetime.

This hole can be "plugged" using a coil geometry in which the magnetic field minimum is not also a magnetic field zero. The Ioffe trap is an example of such a geometry, and resistive Ioffe traps are widely used in atom-trapping experiments. However, it is much more challenging to realize a deep, large-volume superconducting trap in the Ioffe configuration than the spherical quadrupole configuration. In the Ioffe configuration, various coils are not coaxial, leading to considerably more complicated forces and a correspondingly complex design for the coils' support structure. Furthermore, many of the individual coils are not cylindrical but rather have a "racetrack" shape: each turn of wire has two long, straight segments, and two curved segments. When the wire is wound on the racetrack form, it is difficult to maintain tension in the straight segments. This may lead to an inadequately secured stretch of wire and an increased risk of a quench, as described above.

Yang *et al.* have made tremendous progress in the design, construction, testing, and use of these magnets for neutron lifetime measurements. Their progress is all the more remarkable given that it has been achieved by a small group of academic researchers. Powerful superconducting quadrupole magnets are also being developed by large particle accelerator laboratories, and it seems likely that they can be used in future generations of neutron-trapping experiments. One of the most exciting advances made by Yang *et al.* is the integration of a powerful set of racetrack coils (developed for the KEK accelerator in Japan) into a full Ioffe trap, leading to greatly increased trap depth and trap volume. Yang *et al.* present a detailed description of these advances, which constitute the state of the art for magnetic trapping of neutrons.

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