Spintronic Materials and Devices *Research Summary*

Spintronics Enter the Iron Age

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In this paper, a set of spintronic circuit elements are introduced which can be used to build complete analog circuits. This allows circuit development using stable quantum states in the bulk of iron based alloys. As an example application a simple circuit is used to learn about hydrogen in iron whose minor concentration plays a large role in altering the activity of the Bose–Einstein-like condensations under measurement.

INTRODUCTION

Spintronics is an adaptation of using spins to carry information replacing charge in a circuit. Circuits are composed of active elements: gain stages, mixers, detectors, storage elements either active or passive, and attenuators, transformers, and wiring. Multiple superimposed states of differing energy and total angular momentum can be created, manipulated, and coupled for entirely new types of circuits. This year it became apparent that a collection of components necessary to build these analog circuits existed. By accident and design these components have been examined while trying to figure out the complexities of time-dependent ferromagnetism in iron and steel.[1] The question of limiting the work to iron-based alloys is not just a cost issue. In magnetically soft iron and steels it is possible to form at low applied field levels (10^{-7} to 10^{-5} tesla) Bose–Einstein-like condensations (BELC), which can be made to interact easily with each other, creating new states. This is due to the feature of the iron band structure that has populations of conduction electrons at the Fermi surface with both spin types represented. This feature is not shared in the band structure of cobalt and nickel.[2] This allows for rapid transitions of charge carriers interacting with spin waves and applied fields that conserve total angular momentum by changing their spin state when emitting or absorbing a boson. The coupling of an induced current or injected current directly to the spin wave population is an essential feature required to couple the two different circuit types, the charge and coherent spin-based circuits.

The circuit development in spintronics deals with many and variable quantities of spin excitations and charge carriers and their interactions. These are quantum objects with properties that can be surprising and unfamiliar. They are also very interesting objects that are at the center of a great deal of current research in spin waves (magnon) and Bose–Einstein condensations (BEC)[3] properties. A history is a good place to start both for the magnetic properties of iron[4] and for how ferromagnetism's study was split off from the early development of quantum electrodynamics.[5] Ferromagnetism, unlike electrostatics, where the contributions of the polarization of the vacuum is a small effect on the electronic mass, the interactions of the spins dominate both the static and dynamic responses in iron to the extreme and cannot be treated as small perturbations.

How would you…

…describe the overall significance of this paper?

This paper introduces a simple description of weak field time-dependent electromagnetism in iron and steel. From this a set of novel mechanisms based on spin wave excitations can be used to create circuit structures and explore material properties.

…describe this work to a materials science and engineering professional with no experience in your technical specialty?

This paper describes a bit of missed physics that was overlooked in the 1930s because of experimental difficulties and narrow assumptions on ferromagnetic material properties. Being a quantum mechanical phenomenon on a large scale made it invisible when one thinks quantum phenomena are all scaled to the size of atoms.

…describe this work to a layperson?

Iron has always been a material for making tools. Now it can be used as a tool to understand quantum mechanics of collective behavior on a physically large scale. From this understanding new types of circuits can be constructed with simple materials by almost anyone willing to learn some new things about iron, physics, and a little electronics.

Since the circuits are macroscopic, just using the tools of electrodynamics (i.e., Maxwell's equations), it is possible to measure the collective contributions of unsaturated soft iron or steel providing sufficient data to show collective behavior in the spin wave population to produce a BELC far from absolute zero. We call these states BELC because they occur by pumping at a finite frequency ω rather than zero frequency, which would be a BEC. The BELC give rise to a measurable magnetization, $M_{BELC}(k,\omega,\mathbf{J})$, that has a time-dependent propagation vector, angular momentum, and a measurable phase. The $\omega = 0$ state would be equivalent to the magnetostatic case and also the most evident property of a ferromagnetic material. It is important for the purpose of generating BELC that the $\omega = 0$ state provides a transition mechanism $<\mathbf{k},\omega,\mathbf{J} = 1|H_{int}(\omega)|0,0,0>$, to allow the state at ω to be pumped directly with the ap-

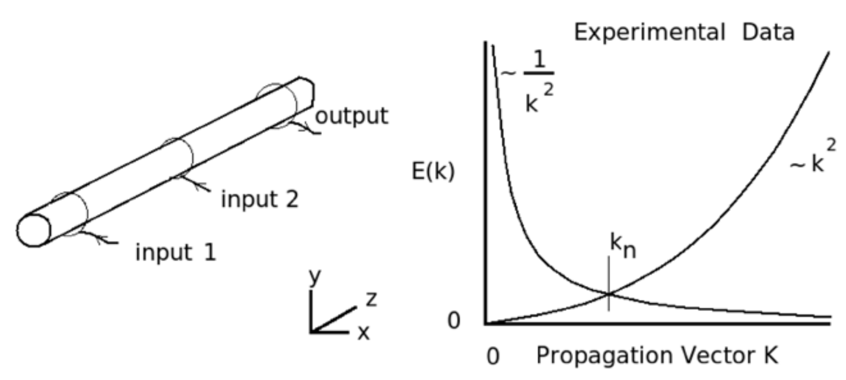

Figure 1. Two responses are driven by a single indicator 1 at low field levels resulting in a propagating spin wave band and a state bound to the source that decays exponentially. The strongest responses are for propagation vectors values less than k_n. This plot is a schematic made by extending the experimental data, κ_n = 1.2 1/meter from Figure 11 in Reference 1.

Table I. Observed Transitions Common in Iron-like Band Structures, where V_i Represents the Interaction Hamiltonian

Transition	Comment
$< \omega_1, J = 1 \vert V_o \vert 0,0>$	Source
$<\omega_1 \pm 2\omega_2, J = 1 \vert V_1 \vert \omega_1, J = 1>$	BELC ⊗ BELC
$<\omega_1 \pm \omega_2, J = 2 \vert V_2 \vert \omega_1, J = 0>$	BELC ⊗ BELC

plied field to produce a sufficient number of spin waves, **n**. Mobile magnetic domain boundaries are key to allowing the system to be pumped. Work hardened or magnetically saturated metals show only a weak response. In order to form a BELC the number of spin waves required to form the coherent state at a temperature, T_{BEC}, is defined in the relation below,[6]

$$T_{BEC} = \frac{\mathbf{n}^{2/3}}{m}\frac{2\pi\hbar^2}{k_b\zeta^{\frac{2}{3}}\left(\frac{3}{2}\right)} \tag{1}$$

where ħ is Planck's constant divided by 2π, k_b is Boltzman constant, and ζ is the zeta function. The mass of the spin wave in our case is represented by *m*. The experimentally measured mass[1] is interesting because the spin wave in the BELC has a mass many orders of magnitude less than the electron mass. This reduction in effective mass to a range of $10^{-9}m_e$ electronic mass permits a T_{BEC} to form far from absolute zero. One can explore the static case by measuring the effective mass of the spin waves as a function of frequency and temperature to determine if the Curie point temperature can be extracted from the limiting point of the BELC formation. For the dynamic case as long as one can drive more than approximately 10^{12} spin waves into the same state, forming a BELC should be possible at room temperature.

In 2006 it was shown that laser-pumped spin wave population in yttrium iron garnet had the characteristics of a BEC at room temperature[7] and this year it was shown that a cooled ^{87}Rb ferromagnetic BEC had magnetic domains.[8]

BAND STRUCTURE OF BELC SPIN WAVES

Some of the more useful properties of the BELC magnetization can be found in the band structure of the BELC spin waves which are very dependent both on the three-dimensional geometry into which the spin wave propagations are launched and the intensity with which the fields are driven. Two features that disguised the behavior of the spin wave activity are the over lapping propagating distributions and the amplitude dependent behavior. By using a long thin geometry to launch the set of BELCs and displacing the receiver allows the separation of the different components. In addition a simple schematic is presented to show the multiple bands that form and their dependence on the geometry of the ferromagnetic material. When magnetization measurements are made close to the source of the injected field, contributions from all fields will be measured simultaneously.

SOLUTIONS TO THE WAVE EQUATION

The basic form of wave function for a BEC is for the ensemble as a whole for a constant number of bosons is:

$$i\hbar\frac{\partial\psi(\bar{r})}{\partial t} = \left(-\frac{\hbar^2\nabla^2}{2m} + V(\bar{r}) + U_o\,|\,\psi(\bar{r})\,|^2)\psi(\bar{r})\right) \tag{2}$$

The sign of the potential U_o along with scattering determines the lifetime of the condensate. In the circuit when operation is continuous, the solution required is for a steady-state system where a continuous stream of particles is being supplied. The solution of the equation with no external potential in the limit of small U_o is that of a free particle with an effective mass. If there is no binding potential then the cyclical boundary value conditions are dropped and we are not restricted to Block functions. The solutions can have wavelengths greater than the sample size approaching infinity. By examining deviations in the band structure from free particle motion, the $U_o(k)$ sign and magnitude

Table II. Circuit Elements

Function	Element	Comment
Source/detector	Inductively coupled volume	Coil around ferromagnet
Filter	Length of ferromagnet	Dispersion to separate fields
Linear Mixer *z*	Two connected driven volumes	$\omega_1 \otimes \omega_2 \rightarrow \omega_1 \pm 2\omega_2 z$ and $\omega_1 \pm \omega_2 z$
Quadrature Mixture *xy*	Perpendicular driven volume	$\omega_1 \otimes \omega_2 \rightarrow \omega_1 \pm 2\omega_2 x$ and $\omega_1 \pm \omega_2 y$
Field Splitter	Planar grain boundary array at 45°	$\omega_1 x \rightarrow a\omega_1 x + b\omega_1 y$
Reflector	Planar grain boundary array at 90°	$\omega_1 x \rightarrow a\omega_1 x + b\bar{\omega}_1 x$
Wiring	1-, 2-, or 3-dimensional ferromagnetic volume	$\omega_1 x \rightarrow \omega_1 x$
Gain Stage	Thermal, electrical noise injected volume	$\omega_1 \rightarrow g\omega_1$
Phase Shifter	Gain control on ω_2 in linear mixer	$\omega_1 \otimes g\omega_2 \rightarrow e^{i\phi}(\omega_1 \pm 2\omega_2)$
Pump Control	Surface control of oxidation/hydrogen	

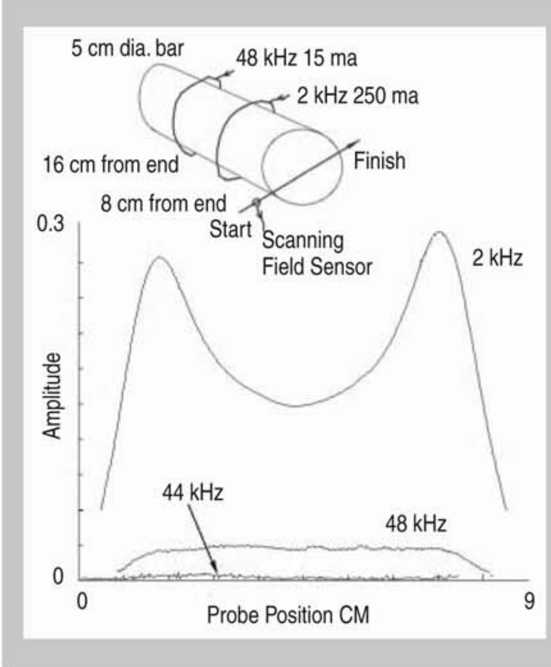

Figure 2. Amplitude transmission level from two displaced sources. 5 cm diameter hot-rolled bar of 1018 steel sampled with a 0.5 cm diameter coil scanned across the bar end.

could be extracted which contain the interaction controlled by the magnetization of the BELC. In the limit of a low-density population of BELC spin waves 10^{12} the term can be dropped for the first solution. The term V(r) is the external potential and in our measurements only has a value in the region of the source coil. The internal ferromagnetic magnetization **M**(x,y,z) is a rapidly varying function because of the domain structure and its integral over the volume of the sample will vanish. Thus, the Gross–Pitaevskii equation is reduced to a free particle Schrödinger equation away from the sources, with linear one-dimensional geometry as shown in Figure 1, considering the solutions along the z-axis where z > 0.

$$i\hbar\frac{\partial\psi(z)}{\partial t} = -\frac{\hbar^2\nabla^2}{2m}\psi(z) \qquad (3)$$

This simple equation has eight solutions made up from the products $e^{\pm kz}$, $e^{\pm ax}$ multiplied by $e^{\pm i\omega t}$ where *a* is a real number. Four of the eight solutions are called negative energy solutions because they produce dispersion curves that take on negative values. In our choice we have some help from the experimental dispersion curves of Figure 1. The parabolic curve looks very much like a simple free particle:

$$\psi_+(z,t) = \frac{1}{\sqrt{L}}e^{ikz-i\omega t}, z>0 \qquad (4)$$

The hyperbolic curve in Figure 1 is even more interesting with its dispersion curve E(k) ~ $1/k^2$. This allows us to set $a = \alpha/k$ and then the solution is a decaying exponential. This function describes a linear magnetic polarizaiton of the medium coupled to the source which is not propagating. These are steady-state responses and this looks like an oscillating linearly polarized S state bound to the source. To get linear polarization one needs at a minimum a pair of spin waves with right- and left-hand circular polarization at the driven frequency.

$$\psi_-(z,t) = \sqrt{\frac{k}{2a}}e^{-\frac{\alpha z}{k}+i\omega t}, z>0 \qquad (5)$$

As the frequency is increased the size of the state is increased. The angular momentum of this linear polarization response is assumed without proof to be J = 0. This is a feature that dominates at higher frequencies. The two dispersion curves are

$$E_+(k) = \frac{\hbar^2k^2}{2m} \qquad (6)$$

$$E_-(k) = \frac{\hbar^2\alpha^2}{2mk^2} \qquad (7)$$

Where the mass for both branches is assumed to be equal, but can be measured individually as a function of the propagation vector **k**. These two solutions are driven by the applied field and are easily resolved. The second solution has some interesting characteristics—at high frequency the field decays very slowly, spanning large distances relative to the source. The intersection point between the two dispersion curves only depends on the corrections to the effective mass as a function of their propagation vectors. When measuring these curves it is found that the ability to pump a particular branch is favored by being below the point where the curves cross $k < k_n$, as shown in Figure 1. The parameter α can be found from the crossing $\alpha = k_n^2$.

With the descriptions of the wave functions for the two fields in an unperturbed region of the sample the effect of applying a time-dependent magnetic field, B_z, results in an interaction Hamiltonian, H_{int}. Where the interaction is with the time-dependent moment μ(t) of the spin wave.

$$H_{int}(w) = -B_z e^{i\omega t}\cdot\mu(t) \qquad (8)$$

Along with this term there will be a contribution from induced currents that will drive transition that also must be

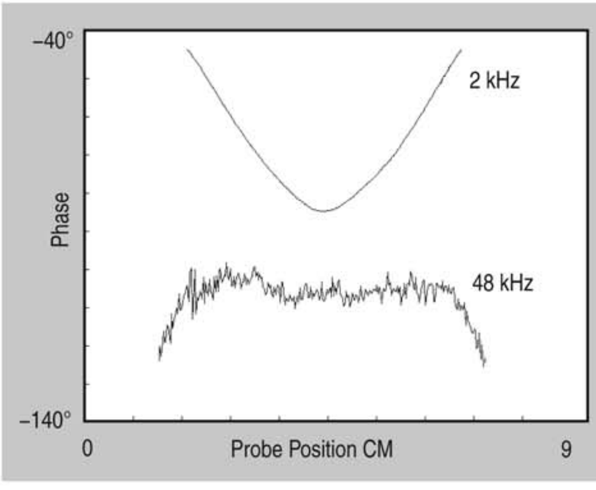

Figure 3. Phase shift transmission delays from two displaced sources. A 5 cm diameter hot rolled bar of 1018 steel sampled with a 0.5 cm diameter coil scanned across the bar end.

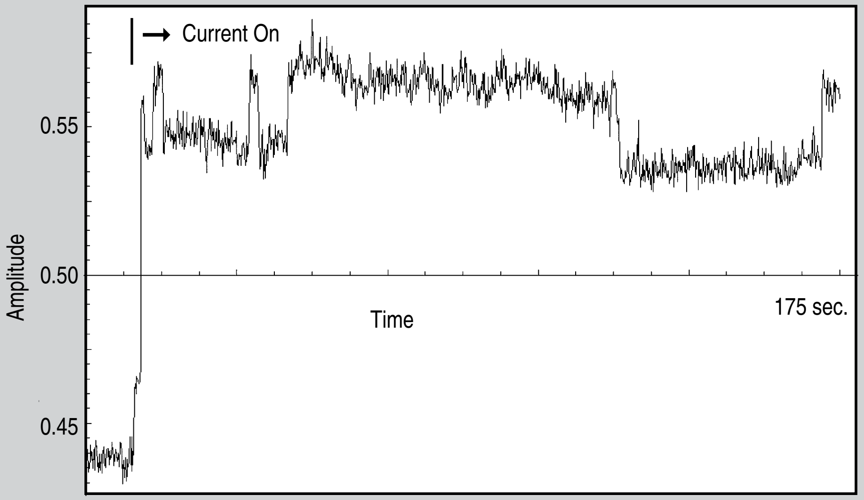

Figure 4. Hydrogen charging initiated and the transmission amplitude at 15 kH.

described. The kinetics of pumping the formation of a BELC are controlled by the density of mobile magnetic domain boundaries, which allow bulk spin flip transformations that can couple into the BELCs. At the magnetic domain boundaries the magnetization transitions through zero aiding the applied source fields to drive transitions. The principal transition will be to drive the ground state, $\omega = 0$, into a time-dependent state. In effect, H_{int} is acting over a short distance and can be described by a delta function for the long wave lengths being considered. It will couple the ground state into ψ_+ and ψ_- conserving angular momentum by altering a spin of a charge carrier.

Transitions to states with frequencies $\omega_1 \pm \omega_2$ are the weakest detected (Table I). For a strong field at port 2 then the pair production states of $\omega_1 \pm 2\omega_2$ which preserve the momentum vector direction of ω_1 are found to be strong transitions. There are also strong transitions driven from the thermal spin waves and phonon that can produce some gain. The transition activity found experimentally has yet to be worked out in detail.

A good example is the propagation of a field in a large diameter bar of annealed hot-rolled low-carbon steel and with a small search probe scan the end of the bar to monitor the injected signal's amplitude and phase. A classical analysis of the field penetration shows they would not be measurable as the fields are many electromagnetic skin depths ($\delta < 1$ mm) from the source. The strong dispersion in phase of the low-frequency component which is nearest the sensor indicates that the scanning is sensing overlapping components of the three axial fields that can be created. The fact that there is so large a measurable component at the center of the bar indicates the strength of the pumped signal. As long as the curl of these slowly varying fields are small eddy current losses are minimal.

CIRCUIT ELEMENTS

The main component for a source and medium is a soft ferromagnetic material with mobile magnetic domain boundaries to facilitate the pumping of the states (Table II). This can be further enhanced by increasing temperature to the Curie point. Crossing the Curie temperature halts pumping of a state but not the transmission of a component of the BELC through the material above the Curie point. The mixers have been found to work in some iron-based metallic glasses as well as carbon steels. The quadrature mixer produces two polarizations of the mixed state. This mixer is realized by using a plate and embedding two perpendicular drive coils in the plate along with a set of displaced detectors with are perpendicular and similarly embedded. A planar array of grain boundaries on a diffusion-bonded interface that were not recrystallized when driven by a magnetization at 45° to the interface normal produces a beam at 90° from the source. It is supposed if this interface were rotated normal to the beam then it would behave as a semitransparent reflector.

There are a number of ways to achieve gain. Using the schematic in Figure 1 of a source at port 1 we can increase the temperature at position 2 or inject a coherent signal or incoherent white noise to generate gain. Phase shift can be done with a delay line segment or actively by using the band structure feature that there is a phase difference on the two different branches of the band which can be accessed by controlling the level of the injected signal. Pump control appears to be a surface effect to control the pinning strength of magnetic domain boundaries that intersect the surface. Controlling oxide, mechanical damage and coating properties will have strong effects on the ability to efficiently pump the BELC states.

In all cases measurements were

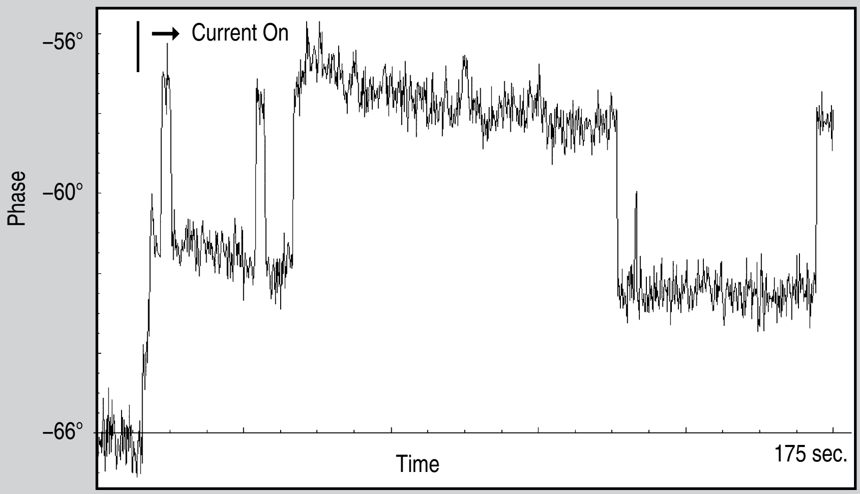

Figure 5. Hydrogen charging initiated and the transmission phase at 15 kH.

coupled through a three channel phase coherent signal source and couple quadrature detectors in an instrument called the Process Monitor IV by Casting Analysis Corp.

PUMPING A BELC AND SURFACE HYDROGEN

The activity of BELC is rather immune to small perturbation, defects, and holes within the ferromagnetic material. Their sensitivity to other BELCs and applied fields is of greater significance. Alloying iron with Cr, Ni, Mo, and Si shows well behaved small changes in the coupling strength between the four principal measured transitions and probably reflects continuous changes in the alloy's band structure. Hydrogen produces a dramatically different response. In a geometry much like that shown at the top of Figure 2, with a 0.0127 meter diameter by 0.22 meters in length, a 1018 hot rolled and polished bar had a plating current of 2.5 mA/cm^2 (Figure 3) Two fields were induced into the bar at the same levels for monitoring transitions as used in Reference 1 with the additional condition that an electrolytic charging cell encircled the central portion of the bar where ω_2 was injected. The injected field ω_1 was 20 kH, ω_2 was 2.5 kH and the observed mixed state was 15 kH. The interesting features occurred in the mixed state depending in part on whether the charging current plating hydrogen on the bar was turned on. In Figure 4 there is a prompt response with the application of the current that cannot be confused with bulk diffusion on the time scale with which the measurements were made.

The sets of data covering the probe field, ω_1, and injected field, ω_2, phase and amplitude have not been included. The three features due to hydrogen in the data are best illustrated by these two data sets. First is the abrupt increase in response with the application of the charging current. Second is the two-state charging condition which the system transitions between randomly. Third is the longer-term slow decay of the response that looks as if it is bulk diffusion controlled.

The magnitude of the increased response with charging is 20% which is an enormous change in a process that is relatively insensitive to bulk changes. The abruptness of the response and the transition while being charged also indicate a surface phenomenon is controlling the response. This initial response can probably be associated with the reduction and removal of the surface oxide. It is the secondary, almost random, responses that are characteristic of hydrogen-charged iron. The fact that there are only single secondary levels indicated the controlling response is widespread and covers the area of the sample where ω_2 is applied. From the phase reduction of the second shift in Figure 5 it indicates that the normal field penetration to activate boundary motion has been moved toward the surface for both processes. An analogous feature with respect to the magnetic response occurs when iron or steel is coated with a sub-micrometer layer of chromium. Chromium is an anti-ferromagnetic metal that increases the inductive magnetic response of coated iron. This is a well-known phenomenon in eddy current testing for determining the coverage of chromium electroplated parts. The reason for this behavior is probably the reduction pinning strength at the free surface of the magnetic domain boundaries. A question then could be raised of whether hydrogen can form an anti-ferromagnetic surface phase on iron. The significant signal phase reduction associated with this secondary transition also indicates the source is surface related. By doing measurements on samples during backside charging, for example from within a tube, the bulk and surface effects can be separated.

The slower fall in amplitude as a function of time indicates the BELC responses are attenuated as hydrogen concentration builds within the bulk. This is a large response as a function of concentration when compared to other alloying elements. Another feature that is different is the relative short time period noise levels which are an order of magnitude greater than those found for a sample not in a charging cell.

CONCLUSION

From the list of circuit components there is a sufficient selection for the construction of an interferometer, a tunable magnetic receiver, and more complex circuits allowing multiple states to interact over a significant period of time. In short, these tools allow one to explore with macroscopic components, quantum phenomenon normally only accessible when one approaches absolute zero for groups of atoms which are often numbered only in the tens of thousands.

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