Cold Energy *

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Abstract. Deviations in Q for resonant superconducting radio frequency niobium accelerator cavities are generally correlated with resistivity loss mechanisms. Field dependent Qs are not well modeled by these classical loss mechanisms, but rather can represent a form of precision cavity surface thermometry. When the field dependent Q variation shows improvement with increasing **B** field level the classical treatment of this problem is inadequate. To justify this behavior hydrogen as a ubiquitous impurity in niobium, which creates measurable property changes, even at very low concentrations is typically considered the cause of such anomalous behavior. This maybe the case in some instances, but more importantly any system operating with a highly coherent field with a significant time dependent magnetic component at near $2^o K$ will have the ability to organize the remaining free spins within the London penetration depth to form a coupled energy reservoir in the form of low mass spin waves. The niobium resonant cavities are composed of a single isotope with a large nuclear spin. When the other loss mechanisms are stripped away this may be the gain medium activated by the low level residual magnetic fields. It was found that one resonant cavity heat treatment produced optimum surface properties and then functioned as a MASER extracting energy from the $2^o K$ thermal bath while cooling the cavity walls. The cavity operating in this mode is a simulator of what can take place in the wider but not colder universe using the cosmic microwave background (CMB) as a thermal source. The low mass, long lifetimes, and the scale of the magnetic spin waves on the weakly magnetized interstellar medium allows energy to be stored that is many orders of magnitude colder than the cosmic microwave background. A linear accelerator cavity becomes a tool to explore the properties of the long wave length magnetic spin waves that populate this cold low energy regime.

Introduction

The major goals for a metallurgist working on a superconducting accelerator cavity is to improve the Q of the cavities in operation while maintaining the stability of the cavity performance over time. The metallurgical involvement in this effort was principally in the design of a non-contaminating high temperature vacuum furnace that could heat treat an entire test cavity to beyond 1800C [1]. The high operating temperatures were necessary to allow metallurgical recovery to take place and possibly recrystallization in niobium. The furnace was designed to remove hydrogen that easily enters niobium in the EDM cutting process, during chemical polishing and even directly from a moist environment. Other purity issues of the common metallic impurities in ingot niobium have been shown to be a manageable condition with respect to superconducting properties [2]. This in itself was a major finding because it immediately brought into question the difference between dynamic high field loss mechanisms that cannot be explained from conduction scattering. Other loss contributing factor have been removed by the use of large grain size material. With grain dimension many times the cavity wall thickness removes a major sink for impurity trapping where large quantities of hydrogen can be stored while reducing phonon scattering sites, which improves low temperature heat transfer. As improvements are made in cavity processing by reducing the dominant loss mechanisms the weaker processes that were once suppressed will be observed and these can either contribute to the losses or add to the gain of the cavity.

The cavity in operation sees an increasing RF **B** field level, which is modest even at quench at less than 100 milli Tesla. These field levels will not alter the superconducting properties of niobium by affecting the band structure as the elastic stresses are low and the internal fields are very low. The RF field levels can only affect the heating of the surface of the cavity or its cooling. The measurement of Q as a function of the RF field levels becomes a very sensitive form

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TABLE 1. Some useful data from the CRC Handbook of Chemistry and Physics

isotope	nuclear spin	nuclear magnetic moment	T_c
^{93}Cb or ^{93}Nb	$\frac{9}{2}$	6.1705	9.3
^{181}Ta	$\frac{7}{2}$	2.371	4.47
^{1}H	$\frac{1}{2}$	2.79	-

of thermometry of the cavity surface. Using Q measurements as a form of thermometry will allow an exploration of the case when the cavity surface is cooled by increasing the RF field level. There is a great deal of cavity data available but here the focus will concern one particular cavity and its processing because it shows the largest measured cooling effect we have come across after a major baseline increase in Q.

Magnetic alloying components of interest in niobium are restricted to surface process changes in structure or dissolved hydrogen, which can either be an interstitial proton or one trapped at a defect site. There is one particular test cavity heat treated condition that was generated after a 3 hour 1400^oC vacuum purge whose Q measurement show a sharp improvement of a few hundred percent over lower temperature heat treatments. In this cavity not only did the low field Q level improve significantly, the Q also rose as the resonant field level was increased until there was a quench of the superconductivity by flux penetration. It is the increasing Q as function of the applied field that is really unusual as the x-rays diffraction search found a thin epitaxial alpha *NbN* nitride on the surface [3] [4]. Titanium would act as a nucleating agent to drive alpha nitride to form as the titanium nitride is more stable than the niobium nitride. Growth to a measurable thickness is probably dominated by parabolic niobium diffusion from the substrate once the epitaxial nitride is formed. The titanium addition was an accident that contaminated the furnace as the end coupling rings of the test cavity were fabricated with a *NbTi* alloy and the *Ti* sublimated from the rings and coated the cavity walls and the furnace chamber. Nitrogen is the principal residual gas in the vacuum and the cavity surface oxides were reduced by hydrogen evolving from the cavity. Normally *NbN* does not form a single stable epitaxial film when grown but forms a set of mixed compounds. However, in the presence of *Ti*, which is a stronger nitride former by comparison of their respective free energies allows a stable alpha nitride to grow. The *Ti* acted as a nucleation agent for forming a stable epitaxial film. The nitride layer has a significantly higher T_c for the *NbN* over *TiN* thus producing a large improvement in the baseline Q. T_c is the superconducting transition temperature and for the coating is $\sim 14^oK$ and for the base niobium the value is $\sim 9^oK$. The temperature, pressure conditions, internal hydrogen concentration, the sublimation rate of Ti and the geometry of the structure and vacuum path all dictate the quality of the film that is produced. The deposition resulting from a particular 3 Hr heat treatment at 1400C for this high Q film was a total accident. It was a fortunate accident for two reasons because it generated a cavity that had a large positive improvement in its baseline Q plus a strong positive dependence of Q on the magnitude of the **B** field level. If losses were dominating the value of Q would have rolled off to lower values as a function of the increasing field. This non-ohmic behavior requires that the entire internal cavity system when operating at 2^oK has to be treated as one large quantum system if the gains are to be understood. That is not currently the practice in the analysis of field dependent cavity properties [12].

Hydrogen in Niobium

Niobium is a body centered cubic transition metal along with tantalum. Tantalum is the major metallic impurity in niobium and is difficult to separate because similar chemistry and nearly the same lattice parameter. Both niobium and tantalum only have a single stable isotope and those particular isotopes have a large nuclear spin angular momentum of 9/2 and 7/2 respectively. Being transition metals, neither of these metals are BCS superconductors [13]. This means that the mechanism that supports superconductivity may not be a phonon coupling to produce a Cooper pair of the electron charge carriers. The strong nuclear moments do provide alternate mechanisms which may be active. A lattice of niobium and tantalum is a magnetic substrate that can interact with magnetic impurities such a hydrogen.

Hydrogen in niobium is a problem on many different levels. In searching for cases where interstitial hydrogen maybe beneficial two instances might be thought to be useful. One involves the out gassing of hydrogen at elevated temperatures at low pressures where the leaving hydrogen reduces the surface oxide and is taken away as water. The second case is where trapped hydrogen and possibly interstitial hydrogen act as a refrigerant medium extracting thermal energy from the cavity walls and pumping it back into the cavity mode. This is a slim possibility because niobium has a large nuclear magnetic moment that should become active as interfering processes are removed. In terms of superconductivity there is anecdotal evidence that in free standing thin niobium foils with absorbed hydrogen can precipitously improve conductivity at temperatures greater than $77^{o}K$ [11]. But free standing foils will not build a good vacuum tube. The major problem with hydrogen is structural, it wants to form molecular compounds with niobium and does this very efficiently where the concentration of hydrogen is increased by destroying the surface. The beginning stages of this destruction reveals a nearly amorphous x-ray diffraction pattern [14].

The interstitial potential well of proton in niobium will vary from .106 eV to .068 eV below -50^{o} C. [15]. That well depth limits the electron population that can strongly scatter with the proton to those within that energy band of the fermi surface. This is an inefficient energy transfer mechanism compared to lattice vibration energy transfers to the proton. The reason for this is the mass difference between the electron and the proton. The shallow quantum well depth limits the effectiveness of these scattered conduction electron in screening the proton and allows it to remain a quantum interstitial within quantum potential well. The reason the proton cannot take a single electron as screening electron is that the volume of the interstitial sites are too compact to allow a hydrogen *1S* state to be embedded. Something that has not been studied in detail has been the ability of the interstitial proton to be stable in the angular momentum state $l = 1$ [11]. This should be a magnetically active state. At temperatures near room temperature niobium with dissolved trace hydrogen is a very active magnetic material. This behavior is also found with trace hydrogen in iron [6]. Under the conditions of a strongly pumped cavity at $2^{o}K$ it should not be a surprise if these magnetic properties reappear in the measured Q.

Lattice Models and Defects

The proton's mass removes it from the dynamics of the more massive ions of the metallic lattice, but it is still much more massive than the valance electrons. The proton is much more agile than the lattice ions and has to be treated as a very light ion. In the BCC lattice which is found in iron and niobium the interstitial sites are not regular but distorted and have a lower symmetry than either a regular octahedron or tetrahedron interstitial site. Sites containing a proton are expected to relax to even lower symmetry, which can enhance magnetic properties. So lattice theories like density function theory for calculating properties typically require a number of corrections to produce energetically accurate results. A more appropriate attack on this problem is to consider two quantum problems. That of the allowed bound states of the proton, which has already been treated and the sum over the allowed electronic interactions that leave the state bound. These are factors than can be calculated with less difficulty and fewer assumptions. Then comes the proton associated with the array of lattice defects that are available, which are more energetically favorable than interstitial sites. The protons in these defects at low temperature may dominate any magnetic coupling with the resonant fields of the cavity. The field dependent Q loss/gain problem when niobium contains hydrogen is a completely quantum mechanical problem and has nothing in common with classical or semi-classical approximations used to compute surface resistance values of cavities. As a problem the accelerator cavity properties has much more in common with cavity quantum experiments that study single trapped atoms.

Mechanisms for Improving Q

There are two general wasys for improving Q in a niobium cavity. The first is to apply a higher T_c coating on the inner cavity wall and the second is to reduce the cavity temperature. If during operation there is a **B** field dependent improvement in Q there is only one possible source for that improvement. The value of T_c will not be altered by a relatively small field change and that leaves only the cooling of the inner wall. There are two possibilities for this cooling. The conduction cooling through the Nb wall has been improved or there is a mechanism to extract heat from the cavity inner wall. The heat loss would require converting heat into the oscillating field within the cavity as this is the only sink for the energy in a sealed resonator. This second mechanism is a form of refrigeration and can only exist if there are lower level states that are available, which can coherently couple to the oscillating field of the cavity. This last possibility can occur if there are spins states available which can both absorb thermal energy and return it coherently as an electromagnetic field to the cavity. The strongest **B** field coupling will be to the available electron spins, for example a hydrogen atom trapped in a vacancy or micro-void. A proton on an interstitial site has two possible states on that site. The low level state is $l = 0$ and there is also a bound state for $l = 1$ state. Finally there are the nuclear spins and these are dominated by the $9/2$ nuclear spin of niobium. All of these can magnetically couple to the dynamic

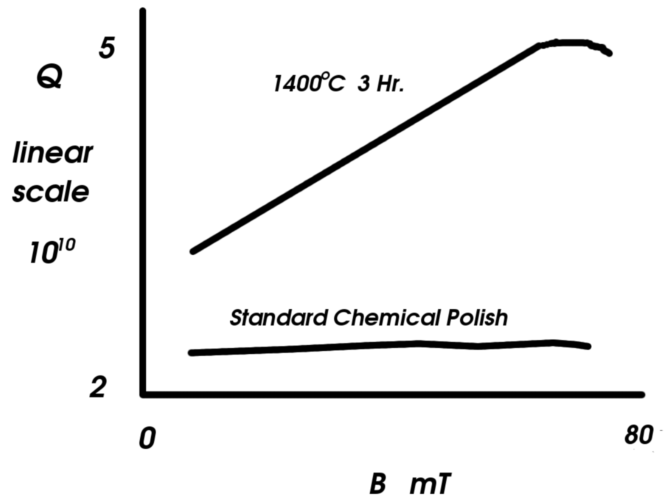

FIGURE 1. A linear schematic sketch of the increasing *Q* with applied B field for the cavity with the accidental coating made at 1400^oC, taken from reference [3] figure 7. The lower curve is the starting state of the cavity with the standard BCP chemical polish. The lower curve is essentially flat showing little field dependence affecting *Q*. The lower curve is 50% less than the lowest Q value measured for the 1400^oC heat treatment. Whatever the loss mechanisms that were removed by the heat treatment they were sufficient to suppress the gain mechanism. In terms of energy stored in the cavity this represents a 250% increased in stored energy in a useful form over the cavity that was not heat treated. The error in measuring *Q* are $\pm 1 \times 10^{10}$. A low temperature bake at 120^oC for 12 hours generates as slight decrease in the upper response over the entire range of *B*. The increasing *Q* in the upper curve probably reflects the nearly linear decrease in cavity wall temperature as the B field is increased.

field of the cavity if there is a residual field lifting their degeneracy. The strongest coupling will be to the electron spins by about three orders of magnitude greater than the nuclear spins. How these two spin systems behave jointly is not known. Whatever the coupling is to the nuclear spins of niobium it will always be the background contribution no matter what the prior surface treatment. The visibility of the nuclear spin contribution will only be evident when the loss mechanisms have been suppressed so this spin system contribution can be detected. The experimental data from cavity measurements suggests that the coupling is principally to something that can be easily affected by heat treatment, surface processing and the simple low temperature 120^oC bake. This variable behavior implies strong loss effect associated with the electron spins and hydrogen rather than the nuclear spins. The characteristic of an oscillator tank circuit are such that as losses are removed then the next strongest process will dominate whether it is a loss or a gain mechanism.

The dynamic spin refrigeration effect is not simply the $\omega \neq 0$ form of a dilution refrigeration. We have observed this conversion of thermal energy to electromagnetic energy in iron based system [5] [6] [8] [9] and others have seen it operate in different systems [10]. The energy diagram for an active system is shown in Figure 2. The available spin on cavity surface becomes coupled through a coherent long wave length magnetic excitation. The requirement on the free spins in order to form the long range low mass coupling is that the spins are not connected by a director or indirect electrostatic or quantum state constraint. Any constraint of this type would couple in the mass of the particle to the effective mass of the spin wave. Spin waves that are studied on a micron level have an effective mass on the order of the electron mass. These micron wavelength spin waves are like spin chains which are strongly coupled. If there is no direct electromagnetic coupling then the spin wave will have an effective mass determined by the speed of light of the medium and the energy of the spin splitting. The resultant small mass for these large scale spin waves requires a relativistic description.

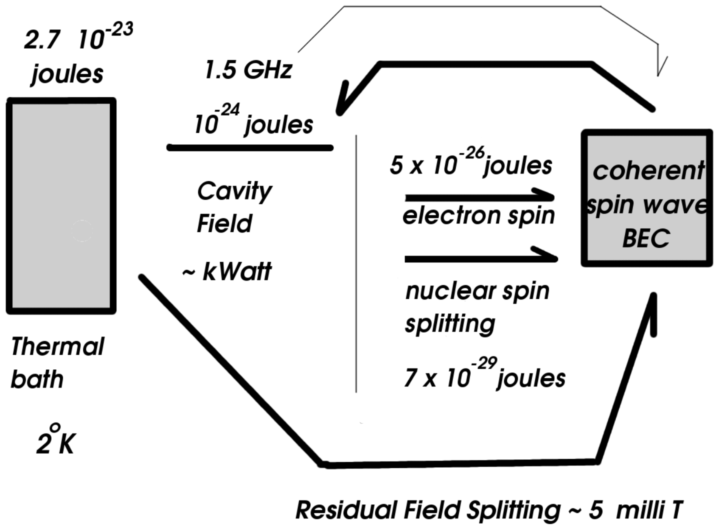

FIGURE 2. Energy states available at 2^oK and a background B field of 5 milli Tesla which splits the spin states. The thermal bath energies available as compared to the cavity photon energies is significantly greater. This allows energy to be extracted from the walls to the available spins within the London penetration depth to build up a coherent oscillation to pump energy back into the cavity while cooling the inner cavity walls.

Large Scale Quantum Spin Wave

Even though the **B** fields are tremendously reduced by the Meissner effect in the boundary regions, residual fields on the order of 5 milli Tesla or less will split available spin states. The residual fields will be a combination of external fields trapped on cooling and internal fields generated by aligned free spins within the London layer on the surface of the cavity. A collective mode with other spins within a single cell or multiple cells can be coherently coupled because of the very long characteristic length of the magnetic excitation. The symmetry of the driven **B** field in the resonant cavity is azimuthal around the axis of the cavity and tangential to the cavity surface. The scale of the excitation, ϵ, is computed from the local splitting field **B**, spin **S**, the gyromagnetic ratio g, Planck's constant $\hbar$ and the speed of light c [9].

$$\epsilon = \frac{\hbar c}{2 g \mu S\, B} \tag{1}$$

For an electron at 5 milli Tesla this yield a linear dimension of approximately *100* meters and for a nuclear spin it would be in the $\sim\, 10^5$ meters. Associated with this very long characteristic size of the excitation is a very small effective mass.

$$m = \frac{\hbar}{\epsilon c} \tag{2}$$

Because of this tremendously reduced mass, $\sim\, 10^{-12}$ of an electron mass for an electron spin, the requirements for forming a Bose-Einstein condensation from the magnetic excitons at 2^oK for the electron spins is not a strong restriction. In equation 3 k_b is Boltzmann's constant and n is the number density of excitons required for the BEC.

$$T_{BEC} \simeq 3.312 \frac{\hbar^2}{m k_b} n^{\frac{2}{3}} = 3.312 \frac{\hbar c \epsilon}{k_b} n^{\frac{2}{3}} \tag{3}$$

With ϵ on the order of 100 meters and $T_{BEC} \rightarrow 2^oK$ the number density is less than 5 for the condensate to form. This indicates that forming a Bose-Einstein condensation will readily occur. That will produce the coherence with the cavity field and when it builds to sufficient amplitude it can pump energy back into the cavity field while cooling the cavity wall. The long coherence length is possible because the exciton are boson which can collect in great numbers with an amplitude which is not vanishing at the source. We have detected both longitudinal magnetization and transverse magnetization in these long wave length spin waves in ferromagnetic materials which form high temperature Bose-Einstein condensates [5] [7]. These excitations show the ability to increase in number by converting thermal energy or electrical white noise into a larger coherent magnetic excitation.

The key feature is that the free spins within a cell can be coherently pumped with a magnetic excitation that can build and feed energy back into cavity extracting thermal energy from the cavity walls. The scale of a single cavity or multiple cavity sections is an important consideration because of the narrow splitting in the spin energies the scale of the coherent spin coupling range will be large and much larger that these structures. Because the scale of the excitation spans the cavity size it will be coherent over the entire volume. This allows all spins to contribute equally. Surface hot spots when they develop will now have a mechanism that will enhance their local cooling.

The reverse of this process would allow pumping into these states, which will extract energy from the main electromagnetic mode and this energy will dissipate as heat. This would occur when the cavity temperature was low enough to shut down the cooling process. This is a magnetic loss mechanism that cannot be described by surface resistance. Stabilizing either the forward or reverse process over time will probably depend on the spins that are carrying the excitation. If it is hydrogen and the hydrogen is not permanently trapped then the effect will vary in time. The problem with hydrogen is that diffusion is not shut down at even 2^oK and the bulk of the niobium wall is a large reservoir that can supply hydrogen to the internal surface of the cavity if it has not been removed. Hydrogen stably trapped within defects of a surface film would solve part of the transient motion of hydrogen within the surface layer if they were also magnetically active.

If the nuclear spins of niobium are the active spin system then the presence of hydrogen may be sufficient to suppress the nuclear moments participating in reducing the cavity Q. From the current set of experiments there is no way to make this deduction.

Thermal Characteristics of a Free Surface

Thinking of the Q measurements as an extremely sensitive thermometer raises the question of the thermal capacity and thermal diffusivity away from the surface. Geometry restricts phonon flow in only three direction and two of those lie in the plane of the surface and the third is directed towards the helium bath. This is a limiting form of the Kapitza thermal resistance. That two to one ratio in allowed propagation vectors implies that the surface heat capacity can be significant. This will be enhanced by the natural coupling of surface phonon which will resist scattering from a smooth surface into the interior. The free surface can be partially decoupled from the helium cooling bath that allows for both enhanced surface heating and cooling. The surface state heat capacity will be limited because it is the only free surface involved. The local surface thermal transients may easily exceed transients in the bulk due to RF heating and the quantum cooling process. So now the Q measurements is a sensitive local thermometer of the excess energy in surface modes and the mechanisms used to absorb the energy from these modes. We can expect the sensitivity of the Q measurements to be at least twice as sensitive to changes in surface temperature as compared to a bulk change in temperature.

To estimate the surface temperature change the coefficient $\partial Q/\partial T$, that is determined by measuring the Q change by changing the helium bath temperature, can be then used to relate measured $\Delta Q_{measured}$ changes to surface temperature changes, $\Delta T_{surface}$.

$$\Delta T_{surface} \sim \frac{\Delta Q_{measured}}{2\frac{\partial Q}{\partial T}} \tag{4}$$

In the case our example $\partial Q/\partial T = 10^{11}\ K^{-1}$ [2]. With a change in the field dependent Q from $3\ to\ 5\ \times 10^{10}$ from figure 1, which results in a surface temperature reduction of $.1^oK$.

Accelerator as a Simulator for CMB Perturbations

MASER action is now a familiar concept, but pumping a MASER using a 2^oK thermal source is not commonly discussed [17] [18]. The debate will be whether there is an assist in the pumping of the MASER or simply an improvement in efficiency just due to the wall cooling. This is an important point because it is a mechanism to take low energy quanta and collectively produce a higher energy microwave. In laboratory experiments using ferromagnetic medium this type of conversion is detected.

Since $2^oK < 2.75^oK\ of\ CMB$ and energy has been shown to be extracted from a reservoir of magnetic excitation, which have much lower individual energy than the microwave photons, this implies that the cosmic microwave background (CMB) is really not a true lower bound distribution for electromagnetic energy. There is a complex distribution of magnetic energy below this that can be called the cosmic magnetic background. These two energy systems can be coupled by some of the more energetic features of the universe running MASERs of their own in rotating systems. Energy can be drained away into the cosmic magnetic background and also extracted from this low energy sink under the right conditions. The only real requirements are matter and a weak residual magnetic field. One question in cosmology is to look at the 1 part in 10^5 variation the CMB over the entire sky and to try to tie the distribution of the hot and cold spots to topological structures of a finite universe [16]. If there is active energy interchange even on a long time scale between the CMB and the cosmic magnetic background then these hot and cold spots may really just be hot and cold spots rather than the repeated structures of some complex tiling of a topological model representing a finite universe.

Using the Feynman statement about looking for something small led to the nano-everything research era. The same argument when applied to energy is a bit more accurate. On the log scale there is no lower cut off in what energetic species may be found in the universe. This is particularly true for excitons associated with stable matter. The analogy would be to take the bathysphere Trieste into the deeper regions of the Marinas trench and observe the permanently nocturnal sea life. Long scale length magnetic excitation are not isolated from affecting the energy distribution in the CMB if there are astronomical pumping mechanism available to move the energy up into the microwave bands. That complicates any analysis of the origin of the noise found in the CMB spectrum.

Having a low energy sinks in the universe makes concepts such as dark matter not seem such a strange concept at all, as the energy in the cosmic magnetic background will be coupled to the distributed mass enhancing the total energy density and hence the mass of the observed matter. Large scale quantum mechanics is something that was ignored because there are few tools than can illuminate this feature in the universe. In the laboratory it is possible to use soft ferromagnetic material where the scale of the quantum structures on are on a meter scale. But in the low density of space the hydrogen distribution expands that scale with with nano and pico Tesla field levels to scales that go beyond a light year. In fact coherence on these scale should carry some different properties of their own. As the effective masses for these excitations are very small their propagation characteristic require a relativistic description. So the statistics required are relativistic quantum statistics which are seldom considered except at very high energies in large nuclei collisions.

One area of research these findings may contribute to is the search for gravity waves, which has so far yielded a null result. With an alternative low energy sink available, the mechanisms for shedding energy and angular momentum from inward spiraling binary stars no longer has to depend on a gravity wave mechanism [19]. Energy can be shed into low energy propagating magnetic excitations as well.

Conclusions

Hydrogen in niobium is becoming better understood as an interstitial component, but its behavior is not well understood in the variety of metals defects it can occupy. At low concentration it rapidly diffuses through the material as proton being activated from a shallow quantum well. Its phase diagrams for hydride formation are well know at high concentrations and its ability to destroy the lattice at free surfaces at these concentration are well known [14]. What is not as well studied are the high field interactions with the nuclear and electronic surface spin system in highly pumped RF cavity at low temperature. This cannot be studied by traditional impedance spectroscopy because the superconducting state dominates the response to any electromagnetic measurement. What is left is an indirect thermal measurement using the cavity Q when in resonance. Very small changes in surface temperature lead to large changes in the overall cavity Q. The quantum enhancement of Q has to understood in detail before optimum surface preparation can be applied to the internal surface of RF resonant niobium cavities. Considering the large scale quantum behavior of a cavity is a relatively new problem for designers. Quantum problems on a scale of meters not nanometer are not normally considered. These excitation are easily ignored if one is not aware of the conditions under which they can occur. Cooling is accomplished through the low energy spin states that can couple magnetically over a long range allowing a large numbers of excitations whose coherent statistics permit them to feed energy back into its original driving source by extracting thermal energy from the walls.

The resonant superconducting accelerator cavity becomes a simulator for the study of long wave length spin excitations that would otherwise only be studied in the low density regions of interstellar space was a fortunate accident. An accelerator cavity, module or even the entire accelerator operating in the temperature range of interstellar space with the ability of moving energy efficiently between four different modes: thermal bath, radiation field, spin transitions, and a long wave length spin waves defines a useful simulator. Low energy magnetic excitation are very difficult to study because unless their coherent numbers are large, the evidence of their existence over large volumes is not easily detected. There are no good telescope to observe them directly. Indirectly it is only possible to search for their presence by looking for loss mechanisms, maser action and by measuring mass through gravitational lensing.

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