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**LDRD PROJECT NUMBER**: 213054
**LDRD PROJECT TITLE**: Enhance coherence time in intensely driven quantum systems
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**PROJECT MANAGER**: Zhiyong Li

## ABSTRACT:

Not long ago, it was shown that a discrete time crystal can be realized if a quantum system is periodically driven to a non-equilibrium state. Proof-of-concept experiments are reported by two groups using trapped ions and nitrogen-vacancy centers in diamond, respectively. The concept of discrete time crystals vividly demonstrates that the coherence time of a quantum system may be enhanced by driving the system out of equilibrium.

In this project, we want to test this novel concept in another canonical quantum system, the quantum Hall system in a two-dimensional electron gas (2DEG). Compared to other systems, quantum Hall magnetism (QHM) in high quality, industry-compatible GaAs/AlGaAs heterostructures allows for detailed and quantitative studies in a particularly simple and clean environment. This detailed knowledge should help achieve longer coherence times in a driven QHM system.

This report will detail the results from a recent study on the stability of the quantum Hall skyrmions (QHS) state at a Landau level filling close to $\nu = 1$ by measuring its current-voltage (I-V) breakdown characteristics under radio-frequency (RF) radiations. We observe that the critical current increases visibly when the RF frequency is right at the Larmor frequency of $^{75}$As nuclei, where the hyperfine interaction between electron and nuclear spins perturbs the QHS state most significantly. We believe that this observation is consistent with the novel concept that the coherence time of a quantum system may be enhanced by driving the system out of equilibrium.

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INTRODUCTION AND EXECUTIVE SUMMARY OF RESULTS:

## INTRODUCTION:

Symmetry is a wonder in nature. It permeates everything around us, from the reflective symmetry in a butterfly's wings, to the rotational symmetry in a starfish, to the fractal symmetry in Romanesco broccoli. In physics, symmetry and symmetry-broken phenomena have been a prevalent theme. For example, a liquid to solid phase transition occurs when the translational symmetry is broken, resulting in a repeating pattern of unit cells in the three-dimensional space.

Not long ago, Frank Wilczek postulated that a time crystal ought to occur if the time translational symmetry is broken [1]. Although extremely elegant in concept, it was soon realized [2] that an equilibrium time crystal is impossible to realize, as it violates fundamental thermodynamic laws. Fortunately, several recent publications [3-5] showed that *a discrete time crystal can be realized if a quantum system is periodically driven to a non-equilibrium state*. The concept of discrete time crystals vividly show that the coherence time of a quantum system may be drastically enhanced by driving the system out of equilibrium (as shown schematically in Fig. 1), which may find wide applications in many national security areas such as ultra-sensitive magnetometers for navigation and quantum memory for information processing.

Proof-of-concept experiments on discrete time crystals recently were reported by two groups using trapped ions and nitrogen-vacancy centers in diamond, respectively [6,7]. In both experiments, the spin state, or the Hamiltonian, is periodically manipulated and applied to the system, and the hallmark of a subharmonic (i.e., period doubling) temporal response was demonstrated. Encouraged by these successes, we propose to create a time crystal using quantum Hall ferromagnetism in high quality semiconductor, industry-compatible GaAs/AlGaAs superlattice structures. If successful, this material system should allow us to achieve unprecedented sensitivity in magnetometer for magnetic navigation, and robust, high-density, and energy-efficient quantum memory for semiconductor quantum information processing.

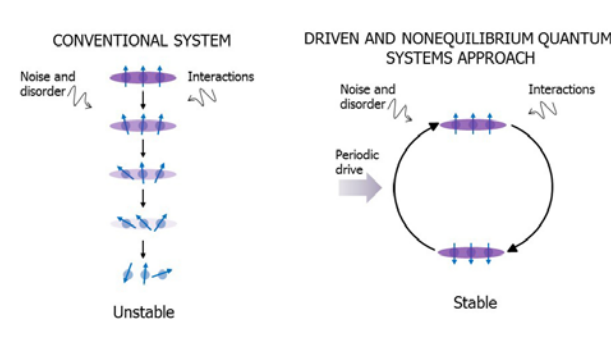


**Fig.1.** This image by DARPA shows that a quantum system can become more stable by driving the system out of equilibrium.

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In the following, we will first introduce the concepts of quantum Hall effect and quantum Hall magnetism (QHM) in a two-dimensional electron gas (2DEG) realized in GaAs/AlGaAs heterostructures, a particularly simple and clean system compared to other material systems. We then will show that these quantum Hall magnetic phases are ideal candidates for proof-of-principle demonstrations of the enhanced stability of driven and non-equilibrium quantum systems. Lastly, we will propose applications that utilize these proof-of-principle quantum systems, which we believe are of interest to national security.

## Quantum Hall effect in two-dimensional electron systems:

The Hall effect, in which a voltage buildup in the plane of the metal at right angles to the current path is linear in an applied magnetic (B) field, was discovered by Edwin Hall in 1879 while doing his thesis work at Johns Hopkins University. Later, the Hall effect was explained by invoking the Lorentz force. The Hall effect is now widely used to determine the density and type (electron or hole) of charge carriers in metals and semiconductors.

In 1980, Dr. von Klitzing and his colleagues discovered the integer quantum Hall effect (IQHE) in high-quality silicon metal-oxide-insulator field-effect transistors [8]. In this new quantum regime, the Hall resistance displays a precisely quantized Hall plateau, with the diagonal resistance a vanishingly small value, whenever the Landau level filling factor, defined by $\nu = nh/eB$, is an integer. Here, n is the electron density, h Planck's constant, and e electron charge. The quantized Hall value is given by $(h/e2)/\nu$.

Soon after the observation of the IQHE, it was realized that the extreme accuracy in the quantum Hall effect is a topological effect [9]. Consequently, the quantization of the Hall resistance is insensitive to specific material systems, disorder, etc. This extreme accuracy has an important impact on metrology of fundamental constants [10].

## Quantum Hall ferromagnetism:

In addition to the rich phenomena displayed in charge transport in the quantum Hall effect, the quantum Hall system has been an ideal material platform for studying quantum magnetism, which remains poorly understood in conventional materials. For example, at Landau level filling $\nu = 1$, the strong electron-electron interactions give rise to a quantum Hall ferromagnetic ground state [11], in which all the electron spins are parallel pointing to the same direction of external magnetic field. Moreover, due to the quenched kinetic energy at this state, all the states in the lowest Landau level are degenerate, making the quantum Hall ferromagnet the world's best understood ferromagnet [11]. It is this precise knowledge that we expect to help provide a better understanding of a strongly driven quantum system.

More fascinatingly, the low energy charged excited states of this quantum Hall ferromagnet are topological defects, termed skyrmions [12] (a current hot topic). Due to strong electron-electron correlations, it is energetically prohibited to have a single spin flipping. Instead, the system forms spin textures carrying a topological quantum number and a quantized net charge. It has been proposed that skyrmions can offer great potential for future quantum information processing [13].

**Quantum Hall antiferromagnetic superlattice as a material platform to realize time crystals:**

Quantum Hall ferromagnetism physics becomes much richer in bilayer GaAs heterostructures due to intra-layer as well as interlayer correlations [14]. This is particularly true at the total filling factor $\nu=2$, or $\nu=1$ in each layer. There, the system retains a fully developed quantum Hall effect, with a well-defined energy gap $\Delta$, so that the bulk of the system remains localized at low temperatures. What is more exciting is that, depending on the separation between the two layers and strength of electron-electron interactions, three phases have been proposed in this state: a quantum Hall ferromagnetic phase, a canted antiferromagnetic phase, and a paramagnetic phase [15], as shown schematically in Fig. 2. The canted antiferromagnetic phase is of particular interest. In this region, the total spin in each layer acquires a component in the x-y plane (or perpendicular to the magnetic field). As a result, the z component of each electron spin is smaller than its maximum value of 1/2. At the same time, the sign of the x-y plane component alternates from layer to layer, due to interlayer antiferromagnetic exchange interactions. Later, it was shown that this canted phase also exists in a superlattice system [16].

We notice here that this canted antiferromagnetic phase is similar to the model system of a one-dimensional chain of trapped ions proposed in the paper by Yao et al [5]. Extending this similarity, we hypothesize that the canted antiferromagnetic phase in a GaAs/AlGaAs superlattice will allow us to realize a discrete time crystal in the quantum Hall magnetic state. For example, Figure 3 shows a schematic diagram of period doubling in the spatial-temporal order [17] when a quantum Hall canted antiferromagnetic superlattice is periodically driven.

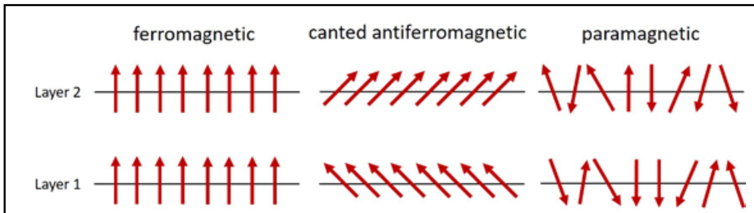


**Fig.2** Three possible magnetic phases in a bilayer GaAs heterostructure. The total filling factor $\nu$ is 2, with $\nu = 1$ in each layer.

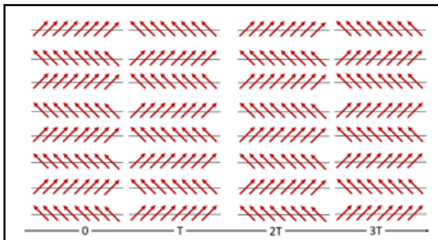


**Fig.3** Periodically driven canted antiferromagnetic phase that exhibits a spatial-temporal order.

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Magnetism in quantum Hall systems, including quantum Hall ferromagnetism and canted anti-ferromagnetism, allows for studies of various magnetic states in a particularly simple and clean environment, which experimentalists have great control over. As an example, a very successful theoretical study [18] led to a detailed understanding of nuclear spin relaxation and coherence times due to their couplings with electron spins in various phases formed by quantum Hall ferromagnets (including some involving skyrmions). Particularly encouraging is the finding that these times are very sensitive to the (low-energy) excitation spectra of these magnets (which in turn can be controlled rather easily, for example via 2DEG density and g-factor, by experimentalists), and can become very long. We are thus optimistic that in a driven system, similar control and long coherence times can be achieved.

The proposed work represents game-changing scientific breakthroughs in quantum systems that could profoundly impact the future security of our nation. It adds to our strong and growing Advanced Science and Technology Mission Foundation in an area where we have an exceptionally strong leadership position in the physics behind the proposed architecture.

## EXECUTIVE SUMMARY OF RESULTS:

The goal of this proposal is to demonstrate that the coherence time of quantum Hall magnetic phases in high quality GaAs/AlGaAs superlattice structures can be enhanced with intense driving electromagnetic fields. We have succeeded this goal by demonstrating an enhanced stability of the quantum Hall skyrmions state under radio-frequency radiation. This success has important implications in future developments of achieving unprecedented sensitivity in magnetometers for magnetic navigation, and robust, high-density, and energy-efficient quantum memories for quantum information processing.

## DETAILED DESCRIPTION OF RESEARCH AND DEVELOPMENT AND METHODOLOGY:

We have examined quantum Hall (QH) magnetism under intense driving electromagnetic fields in steps with increasing complexity. In Year 1, we focus on understanding the QH ferromagnetic and skyrmions system at Landau level filling $\nu = 1$ in a single GaAs quantum well without and with intensively driving electromagnetic stimuli. In Year 2, we study the canted QH antiferromagnetic system at $\nu = 2$ in double quantum well systems.

To study the QH ferromagnetism, we follow the well-developed resistively detected nuclear-magnetic resonance (NMR) method [19]. In this type of measurement, the 2D electron spins are tilted through the electron – nuclear hyperfine coupling when the applied radiofrequency (RF) wave frequency in the pick-up coil around the sample matches the resonance frequency of the nuclei. This, in turn, causes a measurable change in magnetoresistance. A typical result of this measurement is shown in right panel of Fig. 4, where electrical detection (via sensitive electron resistance measurement) of NMR on $^{75}$As nuclei in a GaAs/AlGaAs quantum well is demonstrated.

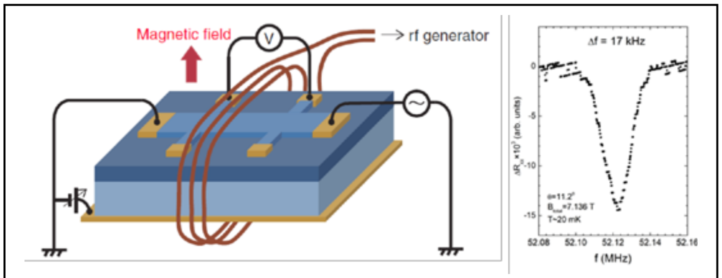


**Fig.4** Left panel: setup for resistively detected NMR measurement [20]. Right panel: $^{75}$As NMR signal at $B_{total}$ = 7.136T. The FWHM of the resonance at 52.123 MHz is ~ 17 KHz.

It is of great interest to ask the question about the stability of the QH skyrmions (QHS) state when it is driven away from equilibrium. Answer to this question can provide a useful avenue to understanding quantum coherent properties of a non-equilibrium system. Indeed, compared to trapped ions and nitrogen-vacancy centers in diamond, the quantum Hall system can be realized in industrially compatible semiconductor materials and, thus, may have important implications in practical applications. A common approach to examine the stability of a quantum Hall system is to measure its energy gap [21-23]. Another commonly exploited method is to study its breakdown behavior [24-29]. In this kind of studies, a large current is applied to the quantum Hall specimen. As the current increases over a critical value, the QH effect breaks down and the resistance of 2DEG become non-zero. The size of the critical current is related to the stability of the QH system.

In Year 2, we study the quantum Hall canted anti-ferromagnetism (QHCAF) in GaAs/AlGaAs double quantum wells. To achieve this goal, we first grow high-quality GaAs double quantum

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wells by molecular beam epitaxy (MBE). Extensive magneto-transport studies are carried out to characterize these double quantum wells to examine QHCAF. Non-linear I-V measurements have also been used to study this novel phenomenon.

The quantum well samples used in this research project are MBE (molecular beam epitaxy) grown. The schematic diagram of the single quantum well and double quantum well growth structures are shown in Fig. 5. The well width is 6nm in the single quantum well. In the double quantum wells, the GaAs quantum well width is 18 nm. The two quantum wells are separated by an AlAs barrier of 3nm thick. Because of this small separation, the tunneling between the two wells is large, and the symmetric-antisymmetric energy gap is non-zero. Ohmic contacts were made by alloying Au/Ge in a forming gas at ~ 420 $^oC$ for a few minutes. Electron transport measurements were performed in a dilution refrigerator or a pumped 3He system with a base temperature (T) of 0.02 and 0.3K, respectively. Standard low frequency (~ 13 Hz) lock-in detection techniques are used for magneto-resistance measurements. The excitation current is 10 nA.

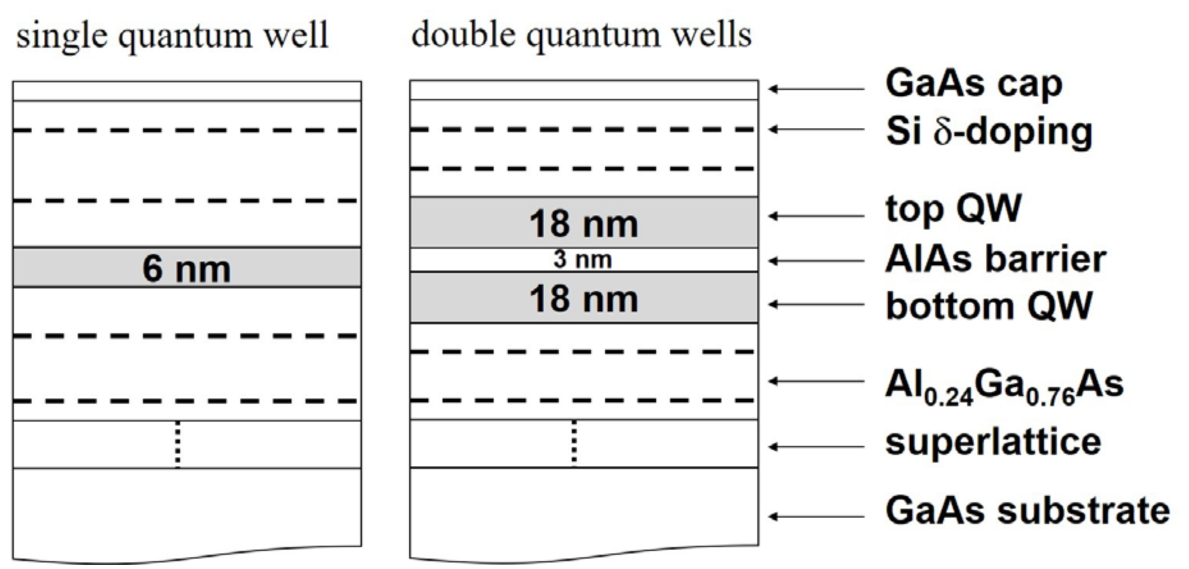


**Fig.5** Left panel: growth structure of a single quantum well. The thickness of the quantum well is 6 nm. Right panel: growth structure of a double-quantum well specimen. The thickness of the quantum well is 18 nm. The separation between the two wells is 3 nm.

## RESULTS AND DISCUSSION:

### MAGNETO-TRANSPORT CHARACTERIZATIONS IN SINGLE QUANTUM WELL

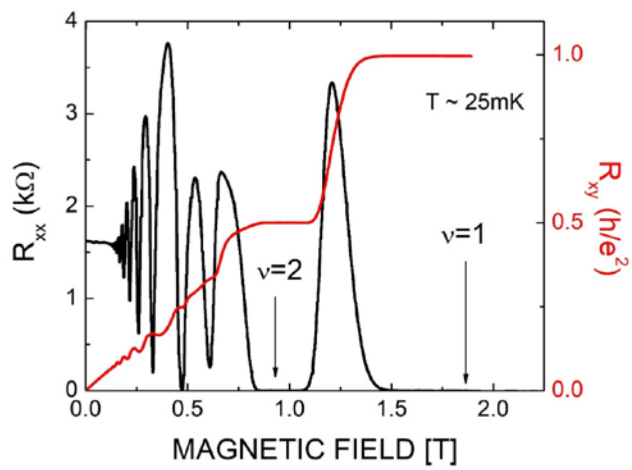


**Fig.6** shows the diagonal resistance $R_{xx}$ (black curve) and Hall resistance (red curve) of our narrow GaAs quantum well as a function of magnetic field at a temperature of T = 25 mK. Well-developed quantum Hall effect is observed at Landau level filling ν = 1 and 2, marked by arrows.

The specimens used in this experiment are narrow GaAs quantum wells (QWs) sandwiched between two $Al_{0.24}Ga_{0.76}As$ barrier layers of thickness 200 nm. The well width is 6 nm. The two-dimensional electron gas (2DEG) has a density of n ~ 4.5 × $10^{10}$ $cm^{-2}$ and mobility of ~1 × $10^{5}$ $cm^{2}$/Vs, after a brief red light-emitting diode (LED) illumination at low temperature (T). A standard low-frequency lock-in technique is used to measure the magnetoresistance $R_{xx}$ and Hal resistance $R_{xy}$ with an ac excitation current of 10 nA. Two quantum-well samples were studied, and the results are consistent with each other. Here, we will present the results from one sample.

Fig.6 shows the diagonal resistance $R_{xx}$ and Hall resistance $R_{xy}$ traces measured at *T* ~ 25 mK. At low magnetic fields, the Shubnikov-de Haas oscillations are clearly seen. In this regime, the spin degeneracy is not lifted and only the even Landau level filling states are developed. At higher magnetic fields, the spin degeneracy is lifted, and the developing ν = 3 state becomes visible. At even higher magnetic fields, well developed IQHE states are observed at ν = 1 and 2, $R_{xx}$ is vanishingly small and $R_{xy}$ is quantized to the expected values.

### MAGNETO-TRANSPORT CHARACTERIZATIONS IN DOUBLE QUANTUM WELLS

Magnetotransport has been utilized to characterize GaAs double quantum well structures. Fig. 7a shows the $R_{xx}$ data in one specimen, taken at T = 0.3K. Shubnikov-de Haas (SdH) oscillations with a clear beating patten is seen, due to occupation of both the symmetric (S) and antisymmetric (AS) electrical subbands. Fast Fourier analysis of these SdH oscillations yields two peaks at 1.27T

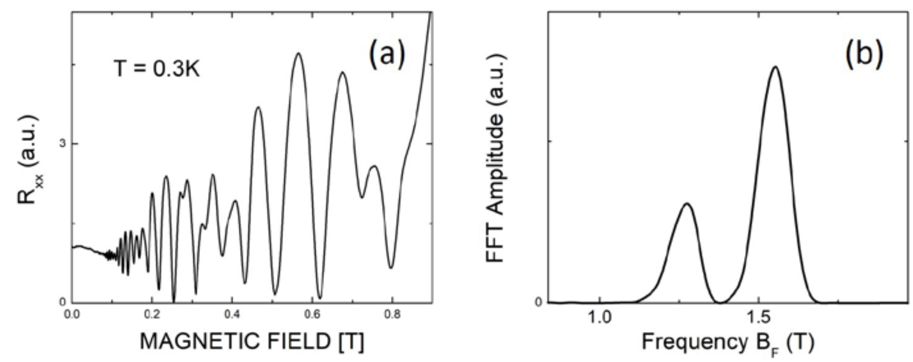


**Fig.7** (a) shows the diagonal resistance $R_{xx}$ of our GaAs double quantum wells specimen as a function of magnetic field at a temperature of T = 0.3 K. A beating pattern is clearly seen in the Shubnikov-de Haas oscillations. (b) shows the Fast Fourier amplitude versus frequency of the SdH oscillations. Two peaks are observed at B = 1.27 and 1.55T.

and 1.55T, respectively. They correspond to electron densities of $0.61\times10^{11}$ cm$^{-2}$ and $0.75\times10^{11}$ cm$^{-2}$, respectively. The total density is $1.36\times10^{11}$ cm$^{-2}$, consistent with the high magnetic field Hall resistance measurements as shown below. With these two densities, we calculate the energy separation of the symmetric and anti-symmetric electrical levels, $\Delta_{SAS}$ = 0.464 meV (or 5.5K) [30]. This value is consistent with the value of 0.462 meV obtained from our k.p band calculations.

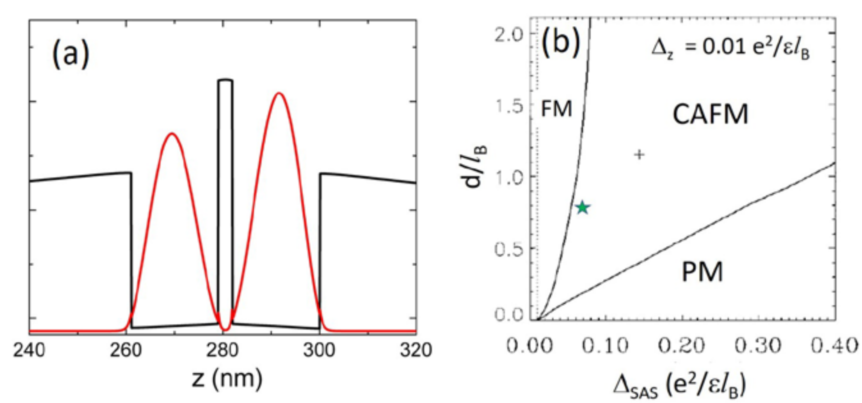


**Fig.8** (a) shows results of the k.p calculations of our double quantum wells structures. The red curve represents the electron density distribution in two wells. (b) Comparison of our device parameters with theoretical predictions in Ref. [31]. The star represents our specimen.

Self-consistent k.p band calculations are carried out for our double quantum well structures. The obtained quantum well potential profile and electron density distribution are shown in Fig. 8a. The energies of the two lowest electrical subbands, the symmetric and antisymmetric bands, are at -2.624 and -2.162 meV, respectively. Here, the Fermi level is fixed at the zero energy. Consequently, the separation between the symmetric and antisymmetric bands is $\Delta_{SAS}$ = 0.462meV, consistent with our SdH oscillations analysis.

In Fig. 9, we show the magnetoresistance $R_{xx}$ (black curve) and Hall resistance $R_{xy}$ (red curve) in high magnetic fields. Well-developed quantum Hall states are observed at Landau fillings $\nu = 4$ (B = 1.39T) and 2 (marked, B = 2.78T). A developing $\nu = 1$ quantum Hall states is seen at B = 5.56T, evident by a $R_{xx}$ minimum and a developing Hall plateau. We believe that this quantum Hall state should become fully developed at lower temperatures. From the positions of the integer quantum Hall states at $\nu = 2$ or 4, an electron density of $n \cong 1.35\times10^{11}$ $cm^{-2}$ is calculated. This value is consistent with the FFT analysis.

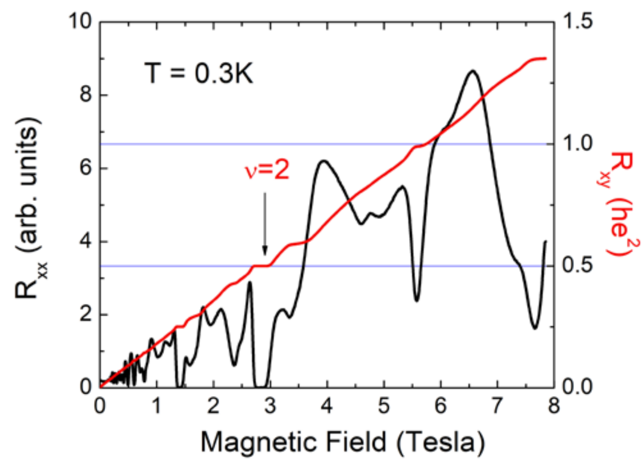


**Fig.9** shows the magnetoresistance $R_{xx}$ (black curve) and Hall resistance (red curve) of our GaAs double quantum well specimen as a function of magnetic field at T = 0.3 K. Well-developed quantum Hall effect is observed at Landau level filling $\nu = 4$, and 2 (marked by arrow).

Moreover, from the magnetic field position of the $\nu = 2$ quantum Hall state, one can calculate the values of the parameters such as the Zeeman energy $\Delta_Z = g\mu_B B$, the magnetic length $l_B = (\hbar/eB)^{1/2}$, and Coulomb energy $e^2/\varepsilon l_B$. Here, g = 0.44 is the effective Lande factor of GaAs, $\mu_B$ the Bohr radius, ħ the Planck constant, e electron charge, and $\varepsilon = 13$ dielectric constant of GaAs. Consequently, one observes that $\Delta_Z \approx 0.01\times e^2/\varepsilon l_B$, $\Delta_{SAS} = 0.065\times e^2/\varepsilon l_B$. Together with the value of $d/l_B = 0.78$, we show that in this specimen the $\nu = 2$ quantum Hall state is in the canted antiferromagnetic (CAFM) quantum Hall state regime (as shown in Fig. 8b), by comparing these values with the theoretical predictions in Ref. [31].

## ENHANCED STABILITY OF QUANTUM HALL SKYRMIONS UNDER RADIO-FREQUENCY RADIATIONS

In a high quality 2DEG, discrete Landau levels are formed at low temperatures when a high magnetic field is applied perpendicularly. This gives rise to the integer quantum Hall effect (IQHE) [8]. In general, the IQHE can be understood under a single particle picture of Landau level quantization and disorder broadening [32]. However, this single-particle picture fails to explain the $\nu = 1$ state. Here $\nu = nh/eB$ is the Landau level filling factor, $n$ the density of 2DEG, $h$ the Planck constant, $e$ the electron charge, and $B$ the magnetic field. At $\nu = 1$, strong electron-electron (e-e) interactions and the Pauli principle force the electron spins to align with the external magnetic field, giving rise to a perfect quantum Hall ferromagnetic phase [33]. The lowest energy charged excitations of this quantum Hall ferromagnetic phase are called skyrmions, a topological spin texture [12,33,34]. The quantum Hall skyrmions (QHS) state has been confirmed in various experiments [19,21-23,35-45]. Among the methods to probe the QHS state, the resistively detected nuclear magnetic resonance (RDNMR) technique [46] is widely used. In a typical RDNMR measurement, an oscillatory radio frequency (RF) magnetic field is coupled to the, for example $^{75}$As, nuclear spins. The hyperfine interaction between the electron and nuclear spins, in turn, modifies the Zeeman energy and thus the resistance of the 2DEG at the Larmor frequency of $^{75}$As. As a result, a resonant behavior is observed in the spectrum of resistance versus RF frequency.

It is of great interest to ask the question about the stability of the quantum Hall skyrmions (QHS) state when it is driven away from equilibrium. Answer to this question can provide a useful avenue to understanding quantum coherent properties of a non-equilibrium system. Compared to trapped ions and nitrogen-vacancy centers in diamond, the quantum Hall system can be realized in industrially compatible semiconductor materials and, thus, may have important implications in practical applications. A common approach to examine the stability of a quantum Hall (QH) system is to measure its energy gap [21-23]. Another commonly exploited method is to study its breakdown behavior [24-29]. In this kind of studies, a large current is applied to the quantum Hall specimen. As the current increases over a critical value, the QH effect breaks down and the resistance of 2DEG become non-zero. The size of the critical current is related to the stability of the QH system.

Here, we present the results from a recent study on the stability of the QHS state at a Landau level filling close to $\nu = 1$ by measuring its current-voltage (I-V) breakdown characteristics under RF radiations. We observe that the critical current increases visibly when the RF frequency is right at the Larmor frequency of $^{75}$As nuclei, where the hyperfine interaction between electron and nuclear spins perturbs the QHS state most significantly. We believe that this observation is consistent with the novel concept that the coherence time of a quantum system may be enhanced by driving the system out of equilibrium.

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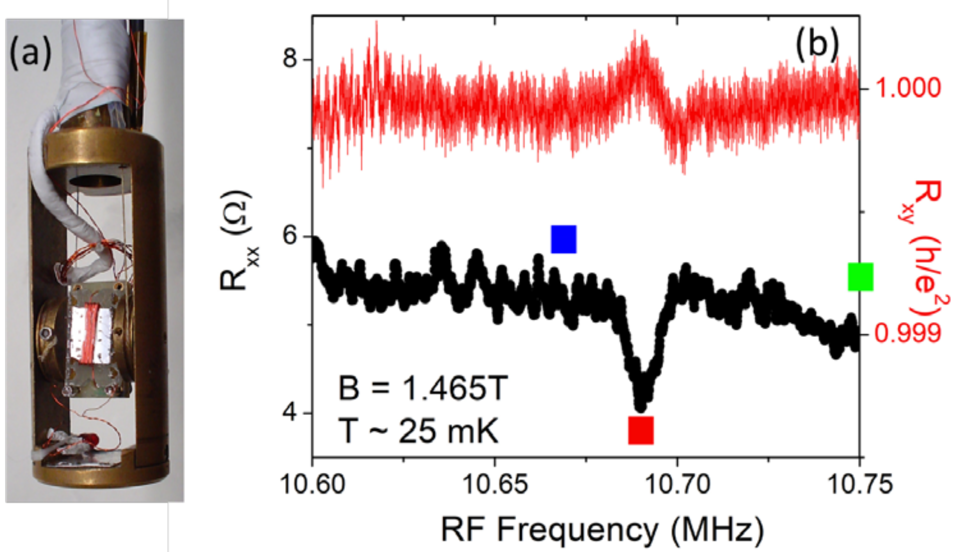


**Fig.10** (a) experimental setup for the resistively detected NMR. The specimen is mounted on a plastic chip carrier. An 8-turn coil (red colored) around the sample is used to couple RF radiations to the specimen. A red LED is used for low temperature illumination. (b) shows $R_{xx}$ and $R_{xy}$ as a function of RF frequency from 10.60 to 10.75MHz. Resonant behavior is observed in both $R_{xx}$ and $R_{xy}$ at ~ 10.69MHz. The blue, red, and green dots indicate the chosen frequencies under which the I-V measurements are performed, as shown in Fig. 11.

First, we present results from our RDNMR measurements. Fig.10a shows a picture of the measurement setup. The shiny black piece on the chip-carrier is our specimen. The red NMR coil is wrapped around the middle of the specimen. Fig.10b shows the RDNMR results of $R_{xx}$ and $R_{xy}$ as a function of RF frequency (f). The magnetic field is fixed at $B$ = 1.465 T (or the filling factor of $\nu = 0.85$). f is swept from 10.6 to 10.75 MHz, at a rate of 10 kHz per step. $R_{xx}$ is roughly constant but drops quickly at f = 10.69 MHz, before it recovers its constant value. This resonant behavior is consistent with the previous work [19,36-38,41,42,44] on quantum Hall skyrmions. Surprisingly, the $R_{xy}$ trace also shows a resonant behavior at the same frequency but with a dispersive-like shape. Similar dispersive spectrum has also been observed in $R_{xx}$ in previous studies [19,36,38,41,42,44] and its origin remains unclear. Though the noise in the data prevents a quantitative comparison between the $R_{xy}$ and $R_{xx}$ spectra, nevertheless, by examining the shapes of $R_{xx}$ and $R_{xy}$ it is apparent that $R_{xx}$ is proportional to $-dR_{xy}/df$.

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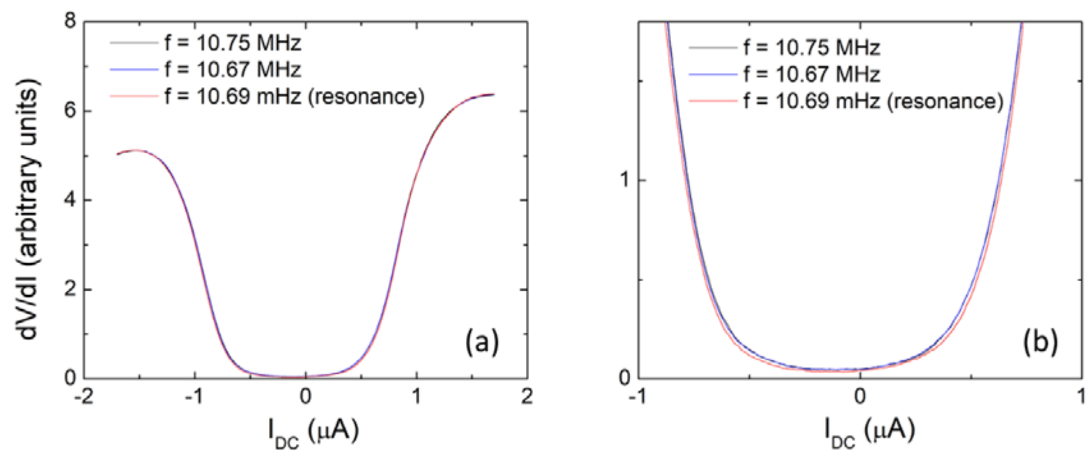


**Fig.11** (a) shows the dV/dI curves at the three selected RF frequencies of 10.67, 10.69, and 10.75 MHz. (b) the dV/dI curves zoomed in around the onset of breakdown points. It is clearly seen that the critical current (defined as the value at dV/dI = 1) is the largest at the resonance frequency of 10.69 MHz.

Having obtained the resonant behavior in our RDNMR measurements, we now show the results of I-V measurements under RF radiations, for the purpose of studying the stability of the quantum Hall skyrmions state. Three representative frequencies are chosen at f = 10.67 MHz, before the resonance, 10.69 MHz exactly at the resonant point, and 10.75 MHz away from the resonance (see Fig. 10b). In this kind of measurements, a d.c. current is added to the small a.c. bias current of δI = 10 nA and swept from -1.7 μA to 1.7 μA. A phase-sensitive lock-in amplifier is used to measure the a.c. voltage (δV) between two ohmic contacts. The obtained dV/dI is shown in Fig.11a for all three frequencies. These curves display the typical quantum Hall breakdown behavior. At low DC current, $R_{xx}$ is small, close to zero. At a critical current close to ±1 μA, $R_{xx}$ increases quickly, and then reaches a roughly constant value at higher currents. The slight asymmetry between the negative and positive currents is probably related to the edge states in the quantum Hall effect. Overall, the three curves are very similar and almost overlap each other. Yet, examining them closely in the region of the onset of breakdown, we notice that the critical current is slightly different for three curves. As shown in the zoomed plot of Fig.11b, the two off-resonant curves overlap each other, while the on-resonant curve displays a larger critical current. To quantify the difference, we define the critical current ($I_c$) at dV/dI = 1. Using this definition, we obtain $I_c^-$ = -0.789 μA and $I_c^+$ = 0.636 μA for f = 10.69 MHz; -0.780 μA and 0.623 μA for 10.67 MHz; and -

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0.775 and 0.623 μA for 10.75MHz. Consequently, $\Delta I_c = I_c^+ - I_c^- = 1.425$, 1.403, and 1.398 μA for f = 10.69, 10.67, and 10.75MHz, respectively. Results are also listed in Table 1. It is obvious $\Delta I_c$ assumes the largest value right at the resonance frequency.

| Critical current \ RF freq. | 10.67 MHz | 10.69 MHz | 10.75 MHz |
|---|---|---|---|
| **$I_c^+$ (μA)** | **0.623** | **0.636** | **0.623** |
| **$I_c^-$ (μA)** | **-0.780** | **-0.789** | **-0.775** |
| **$\Delta I_c$ (μA)** | **1.403** | **1.425** | **1.398** |

Table 1: The critical currents (in units of μA) at various RF frequencies (in units of MHz)

This observation is surprising. Right at the resonant point, the radio frequency magnetic fields, applied to the specimen through the pick-up coil, depolarize the $^{75}$As nuclear spins and cause them to precess. This, in turn, perturbs the electron spins through the change in the hyperfine interaction. In other words, at resonance condition, the RF magnetic fields should disturb the QHS state most strongly. As a result, a less stable QHS state and, thus, a smaller critical breakdown current are expected. To speculate the physical origin of the unexpected observed result, we mention that it has been shown that the coherence time, or stability, of a quantum system may be enhanced by periodically driving the system out of equilibrium. For example, a transient superconductivity has been achieved under an intense laser pulse [47]. It is possible that the enhanced stability of the quantum Hall skyrmions state in our quantum well specimen is due to the same mechanism. In general, due to the finite Coulomb energy of short spin waves and the small nuclear Zeeman energy, nuclear spin relaxation is hard to achieve even in the limit of vanishing electron Zeeman energy [48]. However, the gapless XY magnon mode of quantum Hall skyrmions system (probably as an overdamped mode in a skyrmions liquid state) can couple strongly to the nuclear spins because of its large $S^{x,y}$ component and its gaplessness [49]. This coupling provides an efficient channel for spin transfer from the electrons to nuclei and vice versa. In our narrow quantum well, the Landé g-factor and, consequently, the ratio of Zeeman energy over Coulomb energy, are nearly zero. This favors the formation of large size skyrmions [48]. At the resonance frequency of 10.69 MHz, the nuclear spins polarization is driven out of their thermal equilibrium, and nuclear spins precess at their intrinsic Larmor frequency. Through coupling, this generates a periodically driving action on the gapless XY magnon mode and its $S^{x,y}$ component. This scenario appears to resemble the formation of a time crystal for the case of the conserved component of the total moment in the XY plane [50]. Consequently, the resonant magnetic fields may help move our quantum Hall skyrmions system toward a many-body localization and, thus, stabilize the QHS state. As a result, the critical current becomes larger in the breakdown measurements.

## ANTICIPATED OUTCOMES AND IMPACTS:

Scientifically, the quantum Hall magnetism provides a unique, clean system to study non-equilibrium quantum states, a long-standing problem in physics. Answer to this question will greatly benefit our understanding of a wide range of scientific topics such as superconductivity, superfluids, strongly correlated electron systems, localization-delocalization transition, quantum dynamics in complex systems, quantum computing, and etc. The quantum Hall magnetism has many advantages over the NV centers and trapped ions systems where previous demonstration of time crystals was made. First, GaAs/AlGaAs superlattices have been extensively studied for charge transport and optoelectronics applications, making their properties well known, robust, and controllable. Second, this III-V semiconductor system is compatible with current semiconductor industry, unlike previous time crystal demonstrations.

Technologically, the demonstration of enhancing coherence time in quantum Hall magnetism system should allow us to achieve unprecedented sensitivity in magnetometer for magnetic navigation, and robust, high-density, and energy-efficient quantum memory for semiconductor quantum information processing.

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LABORATORY DIRECTED RESEARCH & DEVELOPMENT

WHERE INNOVATION BEGINS

## CONCLUSION:

In summary, we have examined the stability of the quantum Hall skyrmions state at a Landau level filling close to $\nu = 1$, by measuring its breakdown behavior under RF radiations. We observe that critical current where the quantum Hall skyrmions state breaks down is the highest at the resonant frequency obtained in the RDNMR measurements. We argue that this enhanced stability is consistent with the proposal that the coherence time of a quantum system may be enhanced by driving the system out of equilibrium.

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## ADDENDUM: PROJECT OUTPUTS

**Publication:**

- Enhanced stability of quantum Hall skyrmions under radio-frequency radiations, W. Pan, J. L. Reno, and A. P. Reyes, Scientific Reports 10, 7659 (2020).

**Presentation:**

- New results in the quantum Hall effect, invited talk at TDLI Workshop on Fractional Quantum Hall beyond Chern-Simons Theory, Oct. 2019, Shanghai, China

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