Resistively-detected NMR lineshapes in a quasi-one dimensional electron system

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FIG. 1. (a)-(b) Schematic of potential barrier seen by up-spin and down-spin electrons without (solid line) and with (dashed line) the presence of positive and negative nuclear polarization, respectively. The chemical potential window sits at $\nu_{QPC} < 1$, so that only the up-spin channel affects the transport. (c) Differential diagonal resistance $R_d \equiv dV_d/dI_{AC}$ curve versus split gate bias voltage ($V_{CG}$) at a field of 4.5 T (black) and 4.25 T (red). The left and right split gate are biased equally. The center gate voltage $V_{CG}$ is fixed to $-0.425$ V and $-0.4$ V, respectively. Upper inset displays a schematic drawing of device. Cross marks represent Ohmic contact pads. Triple Schottky gates deposited on top of the Hall bar defined a quantum point contact (see SEM image). The lithographic gap/width between (of) a pair of split gate is 600(500) nm. An extra gate (center gate) with lithographic width of 200 nm is deposited in between the split gates. An excitation current $I_{AC} = 1$ nA with $f = 13.7$ Hz is applied to the device for transport measurement. Lower inset shows typical $R_d$ time trace during current-induced dynamic nuclear polarization with $I_{AC} = 10$ nA.

We observe variation in the RDNMR lineshape spectra on both flank of the $\nu_{QPC} = 1$ plateau as displayed in Fig. 2 and 3. Let us start with the RDNMR spectra for $\nu_{QPC} < 1$ case observed at a field of 4.5 T shown in Fig. 2(a), measured from $V_{SG} = -0.41$ up to $V_{SG} = -0.7$ V. For ease of comparison, we plot the resistance variation $\Delta R_d$ with respect to the off-resonance resistance at $f = 33$ MHz. The salient feature appears in a narrow portion of the split gate bias voltage region, $-0.50 \leq V_{SG} \leq -0.41$ V, very close to the $\nu_{QPC} = 1$ plateau. The spectra have a curious dispersive lineshape, strikingly resemble the dispersive lineshape previously observed in a number of reports on a 2D quantum Hall system in the vicinity of $\nu_b = 1$. The lineshape we observe in our system is found to be highly sensitive to the rf power such that the resistance peak resonance line vanishes at a relatively high rf power of -15 dBm.

The corresponding signal amplitude normalized to the off resonance resistance $|\Delta R_d|/R_d$ is displayed in Fig. 2(b). All the signal amplitude observed here falls below 1%, similar to the previous reports in Ref. 28, 29. Starting from the observable signal closest to the plateau $V_{SG} = -0.41$ V, the dip amplitude shows a sharp upturn and reaches a maximum value at $V_{SG} = -0.44$ V. It is then followed by a downturn and takes on a minimum value at $V_{SG} = -0.50$ V, precisely at the transition between dispersive-to-single lineshape. The peak amplitude has a smaller amplitude than the dip amplitude and shows a monotonically decrease from $V_{SG} = -0.42$ V and eventually vanishes at $V_{SG} = -0.51$ V. The spectrum evolves into an expected single dip lineshape for $V_{SG} \leq -0.51$ V with the signal amplitude gradually increases. It can be partially explained by an increase in the current density locally in the constriction. Altogether, the facts that the lineshapes, signal amplitudes, as well as resonance point variations with the split gate bias voltage constitute firm evidence that the nuclei is polarized locally in the QPC.

We plot in Fig. 2(c)-(d) the raw RDNMR spectra for the two most extreme cases $V_{SG} = -0.70$ and $V_{SG} = -0.41$, respectively. In order to extract the Knight shift for each spectrum, here we plot in Fig. 2(d) (red dots) the reference signal taken close to $\nu_b = 2$ with nearly zero Knight shift. The spectrum is fitted with a Gaussian function, centered at 33.057 MHz and FWHM of 0.039 MHz. The corresponding signal amplitude normalized to the off resonance resistance $|\Delta R_d|/R_d$ is displayed in Fig. 2(b). All the signal amplitude observed here falls below 1%, similar to the previous reports in Ref. 28, 29. Starting from the observable signal closest to the plateau $V_{SG} = -0.41$ V, the dip amplitude shows a sharp upturn and reaches a maximum value at $V_{SG} = -0.44$ V. It is then followed by a downturn and takes on a minimum value at $V_{SG} = -0.50$ V, precisely at the transition between dispersive-to-single lineshape. The peak amplitude has a smaller amplitude than the dip amplitude and shows a monotonically decrease from $V_{SG} = -0.42$ V and eventually vanishes at $V_{SG} = -0.51$ V. The spectrum evolves into an expected single dip lineshape for $V_{SG} \leq -0.51$ V with the signal amplitude gradually increases. It can be partially explained by an increase in the current density locally in the constriction. Altogether, the facts that the lineshapes, signal amplitudes, as well as resonance point variations with the split gate bias voltage constitute firm evidence that the nuclei is polarized locally in the QPC.

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throughout the remaining split gate values, an indication

system[16]. The value remains constant at about 12 kHz

linear fashion up until

V value continuously drops down to 12 kHz in an obviously

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18 kHz. Interestingly, its peak frequency appears to be

for the spectrum very far from the plateau at a field of

is only Knight shifted by about 8 kHz, reasonable value

V

erence signal, the observed spectrum at

V

8 kHz (red line). Note that the long tail in the higher

radio frequency side in the reference spectrum is nothing

but reflects a long T1 time[35]. Comparing with the refer-

ence signal, the observed spectrum at

V

−0.70 V is only Knight shifted by about 8 kHz, reasonable value

for the spectrum very far from the plateau at a field of

4.5 T. The dip frequency in the dispersive lineshape at

V

−0.41 V gives the largest observable shift by about

18 kHz. Interestingly, its peak frequency appears to be

substantially unshifted as it is aligned reasonably well

with the reference resonance point. RDNMR measure-

ment performed at a smaller field of 4.25 T reveals similar

lineshape patterns[30].

Fig. 2(e) displays the dip and peak resonance line

points extracted from the split gate bias voltage seg-

ment between −0.41 to −0.50 V, where the dispersive

lineshape is observed. The peak resonance line lies at

the resonance reference point with very small variation

throughout the range, substantially not Knight shifted.

On the other hand, the dip resonance line is upshifted

in a linear fashion up to

V

−0.46 V and then fol-

lowed by a slight downshift. The resulting ∆f values

extracted from panel (e) is plotted in Fig. 2(f). The ∆f

value continuously drops down to 12 kHz in an obviously

linear fashion up until

V

−0.46 V from its initial

value of 18.3 kHz at

V

−0.41 V, bearing a similarity to ∆f − B plot around

ν

b = 1 observed on the 2D system[10]. The value remains constant at about 12 kHz

throughout the remaining split gate values, an indication

that the electronic state in the QPC does not change sig-

nificantly. Similar trend is observed as well for a field of

4.25 T[37].

We now move on to discuss the RDNMR taken at the

opposite side of the plateau (ν

QPC > 1) as shown in Fig. 3. The data show similar lineshape trend, but with inver-

ted signal and much smaller amplitude than its counter-

part. At a field of 4.5 T displayed in Fig. 3(a), the

RDNMR signal is visible only in a confined split gate bias range, −0.32 ≤

V

SG ≤ −0.30 V. The spectra measured very close to the plateau are hindered by a large

resistance fluctuation in particular at the point where the diagonal resistance abruptly changes. Nevertheless, one can verify the existence of the inverted dispersive line-

shape for

ν

QPC > 1 (see the line-cuts at

V

SG = −0.313 and

V

SG = −0.302 V in Fig. 3(b) for better visual). The RDNMR signal measured at a field of 4.25 T displayed in Fig. 3(c) has less resistance fluctuation and hence offers better signal to noise ratio. The inverted dispersive lineshape appears at

V

SG = −0.29 V (upper Fig. 3(d)) and turns into a resistance peak lineshape at

V

SG = −0.285 V (lower Fig. 3(d)). In contrast to the case for

ν

QPC < 1 where the RDNMR signal is observed in a wide range of split gate bias voltages, the signal observed here vanishes very quickly far from the

ν

QPC = 1 plateau region. Recall that the hyperfine-mediated spin flip-flop process relies on the spatial overlap between the up-spin and down-spin channels[21]. Thus, the absence of RD-

NMR signal indicates the critical current for breakdown is higher than for

ν

QPC < 1 since the channel is opened wider[35].
nario, the Knight shift at the central region is determined by \( K_S \propto (n_\uparrow - n_\downarrow) \propto (T_\uparrow - T_\downarrow) \), where \( n_\uparrow(n_\downarrow) \) and \( T_\uparrow(T_\downarrow) \) are up(down)-spin electron density and up(down)-spin transmission probability, respectively. The Knight shift reaches a maximum value when the up-spin channel is completely transmitted \( (T_\uparrow = 1) \) while the down spin channel is completely reflected \( (T_\downarrow = 0) \). It decreases with reduction of \( T_\uparrow \), agreeing well with the experimental data shown in Fig. 2(e).

For \( \nu_{QPC} > 1 \) case, similar scenario happens. However, the Overhauser field from the polarized nuclei now affects the transmission of the down-spin channel while the fully transmitted up-spin channel is left unaffected. The nuclear polarization influences the transmissivity of the down-spin channel in an opposite way than that of the up-spin channel. This is the reason why the RDNMR spectrum gets inverted as experimentally confirmed in Fig. 3 and noted in Ref. [29].

To summarize, here we observe four variation of the RDNMR lineshapes in a gate-defined QPC. Of particular interest is the emergence of the dispersive lineshape in the RDNMR signal when the bulk filling factor is set to \( n_B = 2 \) and the QPC filling factor to the vicinity of the \( \nu_{QPC} = 1 \) plateau. It can be accounted by considering simultaneous occurrence of two hyperfine-mediated spin-flip scattering events due to current-induced dynamic nuclear polarization. These phenomena give rise to localized regions with opposite nuclear polarization in the QPC. Although both of them are in contact with electrons in the QPC, they polarize in a region with different degree of electron spin polarization. Our experimental results further cemented the idea that the observation of the dispersive lineshapes on the 2D system, in particular

FIG. 3. (a) 2D color map of \( ^{75}\text{As} \) RDNMR traces at the lower flank of the \( \nu_{QPC} = 1 \) plateau \( (\nu_{QPC} > 1) \) measured at a field of 4.5 T. (b) Raw RDNMR traces sliced at \( V_{SG} = -0.313 \) (upper) and \( V_{SG} = -0.302 \) (lower) V, respectively. (c) 2D color map of \( ^{75}\text{As} \) RDNMR traces at the lower flank of the \( \nu_{QPC} = 1 \) plateau \( (\nu_{QPC} > 1) \) measured at a field of 4.25 T. (d) Raw RDNMR traces sliced at \( V_{SG} = -0.29 \) (upper) and \( V_{SG} = -0.285 \) (lower) V, respectively.

The results presented in Fig. 2-3 provide important insights into mechanisms leading to the dispersive lineshape observed in the vicinity of \( \nu_{QPC} = 1 \) plateau. Fig. 4 displays all possible hyperfine-mediated spin-flip scattering events where the QPC filling factor is tuned slightly less than 1 for two different alternating current cycles. The forward and backward spin-flip scattering could occur simultaneously within the QPC. The forward scattering occurs at the central region of the QPC where the degree of electron spin polarization is finite, not zero. On the other hand, the backward spin-flip scattering occurs slightly outside the central region where the electron spin polarization is zero. Those scattering events polarize the nuclei in opposite direction and spatially separated. On sweeping of rf with increasing frequency, the positive nuclear polarization is destroyed first due to Knight shift. It results in an increase in the transmissivity of the up-spin channel. On further sweeping the rf, the positive nuclear polarization starts to build up and negative nuclear polarization is destroyed. This results in a decrease in the transmissivity of the up-spin channel. The backward spin-flip scattering is highly suppressed when the QPC filling factor is further tuned to \( \nu_{QPC} < 1 \), leaving only positive nuclear polarization build-up at the central region of the QPC. The RDNMR spectrum switches from dispersive-like to dip resonance lineshape. In this sce-
around $\nu_b = 1$, should reflect the nuclear spin interaction with two electronic sub-systems as suggested by the authors in Ref. [7] [10].

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[1] N. Kumada, K. Muraki, and Y. Hirayama, Phys. Rev. Lett. 99, 076805 (2007)
[2] X. C. Zhang, G. D. Scott, and H. W. Jiang, Phys. Rev. Lett. 98, 246802 (2007)
[3] M. Stern, B. A. Piot, Y. Vardi, V. Umansky, P. Plochocka, D. K. Maude, and I. Bar-Joseph, Phys. Rev. Lett. 108, 066810 (2012)
[4] L. Tiemann, G. Gervais, H. L. Stormer, D. C. Tsui, L. W. Engel, P. L. Kuhns, W. G. Moulton, A. P. Reyes, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. 113, 076803 (2014)
[5] L. Tiemann, T. D. Rhone, N. Shibata, and K. Muraki, Nat Phys 10, 648 (2014), letter.
[6] B. A. Piot, W. Desrat, D. K. Maude, D. Kazazis, A. Cavanna, and U. Gennser, Phys. Rev. Lett. 116, 106801 (2016)
[7] A. Kou, D. T. McClure, C. M. Marcus, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. 105, 056804 (2010)
[8] M. Kawamura, K. Ono, P. Stano, K. Kono, and T. Aono, Phys. Rev. Lett. 115, 036601 (2015)
[9] G. Gervais, “Resistively detected nmr in GaAs/AlGaAs,” in Electron Spin Resonance and Related Phenomena in Low-Dimensional Structures, edited by M. Fanciulli (Springer Berlin Heidelberg, Berlin, Heidelberg, 2009) pp. 35–50.
[10] W. Desrat, D. K. Maude, M. Potemski, J. C. Portal, Z. R. Wasilewski, and G. Hill, Phys. Rev. Lett. 88, 256807 (2002)
[11] L. A. Tracy, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Phys. Rev. B 73, 121306 (2006)
[12] K. Kodera, H. Takado, A. Endo, S. Katsumoto, and Y. Iye, physica status solidi (c) 3, 4380 (2006)
[13] C. R. Dean, B. A. Piot, G. Gervais, L. N. Pfeiffer, and K. W. West, Phys. Rev. B 80, 153301 (2009)
[14] C. R. Bowers, G. M. Gusev, J. Jaroszynski, J. L. Reno, and J. A. Simmons, Phys. Rev. B 81, 073301 (2010)
[15] W. Desrat, B. A. Piot, S. Krämer, D. K. Maude, Z. R. Wasilewski, M. Henini, and R. Airey, Phys. Rev. B 88, 241306 (2013)
[16] W. Desrat, B. A. Piot, D. K. Maude, Z. R. Wasilewski, M. Henini, and R. Airey, Journal of Physics: Condensed Matter 27, 275801 (2015)
[17] G. Gervais, H. L. Stormer, D. C. Tsui, L. W. Engel, P. L. Kuhns, W. G. Moulton, A. P. Reyes, L. N. Pfeiffer, K. W. Baldwin, and K. W. West, Phys. Rev. B 72, 041310 (2005)
[18] O. Stern, N. Freytag, A. Fay, W. Dietsche, J. H. Smet, K. von Klitzing, D. Schuh, and W. Wegscheider, Phys. Rev. B 70, 075318 (2004)
[19] K. F. Yang, H. W. Liu, K. Nagase, T. D. Mishima, M. B. Santos, and Y. Hirayama, Applied Physics Letters 98, 142109 (2011) http://dx.doi.org/10.1063/1.3579257
[20] K. R. Wald, L. P. Kouwenhoven, P. L. McEuen, N. C. van der Vaart, and C. T. Foxon, Phys. Rev. Lett. 75, 1011 (1994)
[21] D. C. Dixon, K. R. Wald, P. L. McEuen, and M. R. Melloch, Phys. Rev. B 56, 4743 (1997)
[22] T. Machida, T. Yamazaki, and A. R. Hamilton, Phys. Rev. B 65, 075303 (2002)
[23] D. C. Dixon, K. R. Wald, P. L. McEuen, and M. R. Melloch, Phys. Rev. B 56, 4743 (1997)
[24] A. Würtz, R. Wildfeuer, A. Lorke, E. V. Deviatov, and V. T. Dolgopolov, Phys. Rev. B 85, 041310 (2012)
[25] A. Würtz, A. Lorke, M. Yu. Melnikov, V. T. Dolgopolov, D. Reuter, and A. D. Wieck, Phys. Rev. B 69, 115330 (2004)
[26] A. Würtz, T. Müller, A. Lorke, D. Reuter, and A. D. Wieck, Phys. Rev. Lett. 95, 056802 (2005)
[27] S. Masubuchi, K. Hamaya, and T. Machida, Applied Physics Letters 89, 062108 (2006) http://dx.doi.org/10.1063/1.2335595
[28] A. Córcoles, C. J. B. Ford, M. Pepper, G. A. C. Jones, H. E. Beere, and D. A. Ritchie, Phys. Rev. B 80, 115326 (2009)
[29] Z. K. Keane, M. C. Godfrey, J. C. H. Chen, S. Fricke, O. Klochan, A. M. Burke, A. P. Mocklich, H. E. Beere, D. A. Ritchie, K. V. Trunov, D. Reuter, A. D. Wieck, and A. R. Hamilton, Nano Letters 11, 3147 (2011) http://dx.doi.org/10.1021/nl201211d
[30] K. Chida, M. Hashisaka, Y. Yamauchi, S. Nakamura, T. Arakawa, T. Machida, K. Kobayashi, and T. Ono, Phys. Rev. B 85, 041309 (2012)
[31] A. Singh, M. H. Fauzi, Y. Hirayama, and B. Muralidharan, Phys. Rev. B 95, 115416 (2017)
[32] Tuning the center gate bias to $-0.425(\pm0.4)$ V for a field of 4.5(4.25) T, we effectively make the channel wide so that the resistance increases gradually for $\nu_{QPC} < 1$. This gradual changes in the diagonal resistance make systematic RDNMR measurement possible for $\nu_{QPC} < 1$.
[33] See Supplemental Material at [URL will be inserted by publisher] for RF sweep rate dependence characteristics.
[34] See Supplemental Material at [URL will be inserted by publisher] for RF power dependence.
[35] K. Hashimoto, K. Muraki, T. Saku, and Y. Hirayama, Phys. Rev. Lett. 88, 176601 (2002)
[36] See Supplemental Material at [URL will be inserted by publisher] for $\nu_{QPC} < 1$ RDNMR lineshape at a field of 4.25 T.
[37] See Supplemental Material at [URL will be inserted by publisher] for RF power dependence.
publisher] for $\Delta f$ trend for $\nu_{\text{QPC}} < 1$ at a field of 4.25 T.  

[38] S. W. Hwang, D. C. Tsui, and M. Shayegan, *Phys. Rev. B* **48**, 8161 (1993).