Electron transport through the interface between a 3D metal and a two-dimensional electron gas with strong spin-orbit coupling

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Acknowledgements

Measurements

A. Kononov	*ISSP RAS Chernogolovka Russia*

Samples

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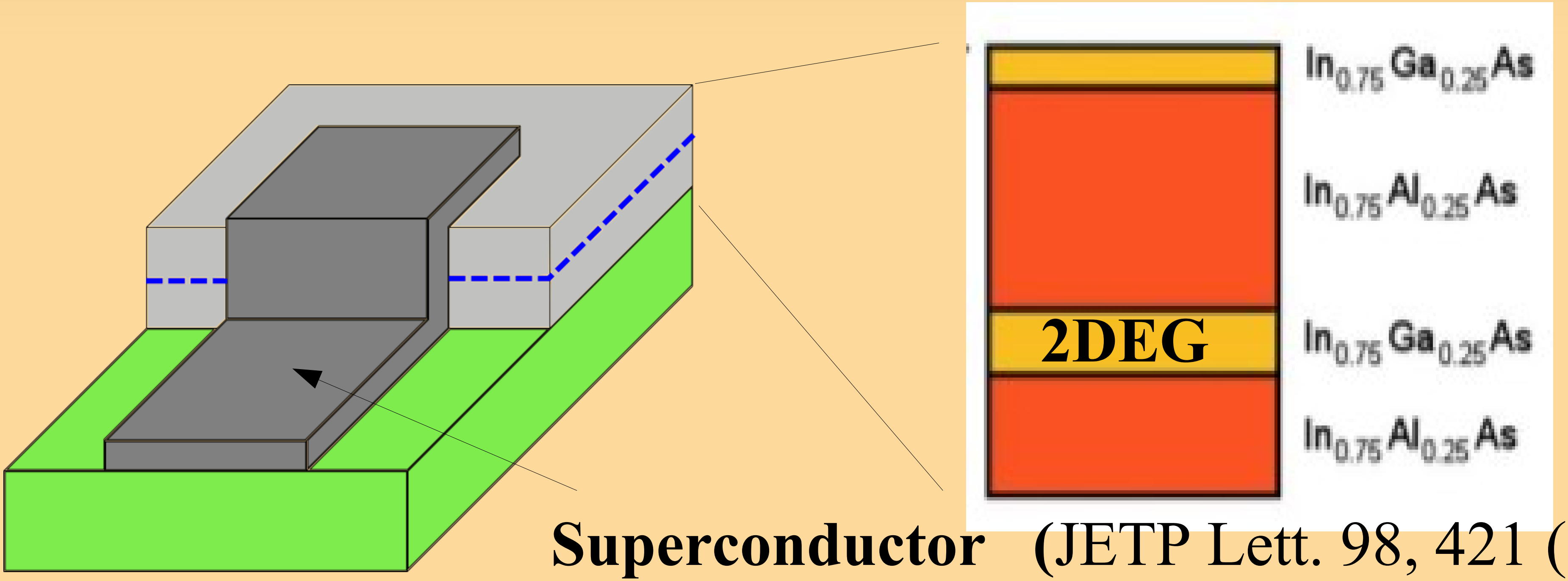
L. Sorba	*NEST INFM-CNR and Scuola Normale Superiore, Pisa, Italy*

Discussions

Ya. Fominov, A.M. Bobkov, I.V. Bobkova, V.T. Dolgopolov

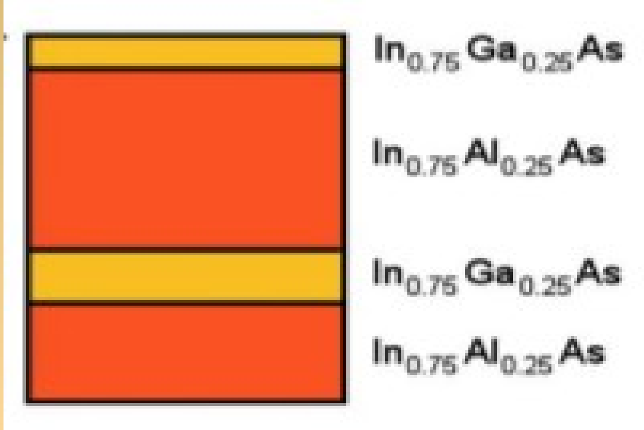
Main idea

transport through the interface between a 2DEG and a 3D metal with macroscopic order parameter



Superconductor (JETP Lett. 98, 421 (2013))
or **Ferromagnet** (Phys. Rev. B 89, 075312 (2014))

InAlAs / InGaAs / InAlAs structures



The active layer is composed of a 20-nm-thick In0.75Ga0.25As quantum well sandwiched between a lower 50-nm-thick and an upper 120-nm-thick In0.75Al0.25As barrier
(Thin Solid Films 484, 400 (2005), Phys. Rev. B 77, 235307 (2008))

1. **High mobility at low carrier density**

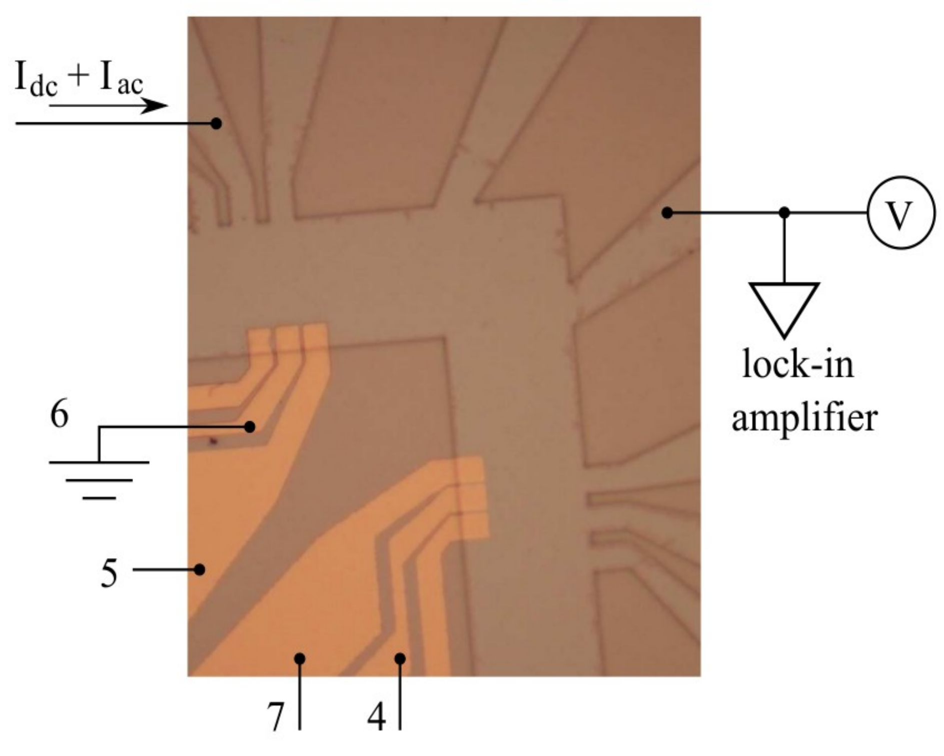
(5×10^5 cm^2 /V s at 4.1 $\times 10^{11}$ cm^{-2})

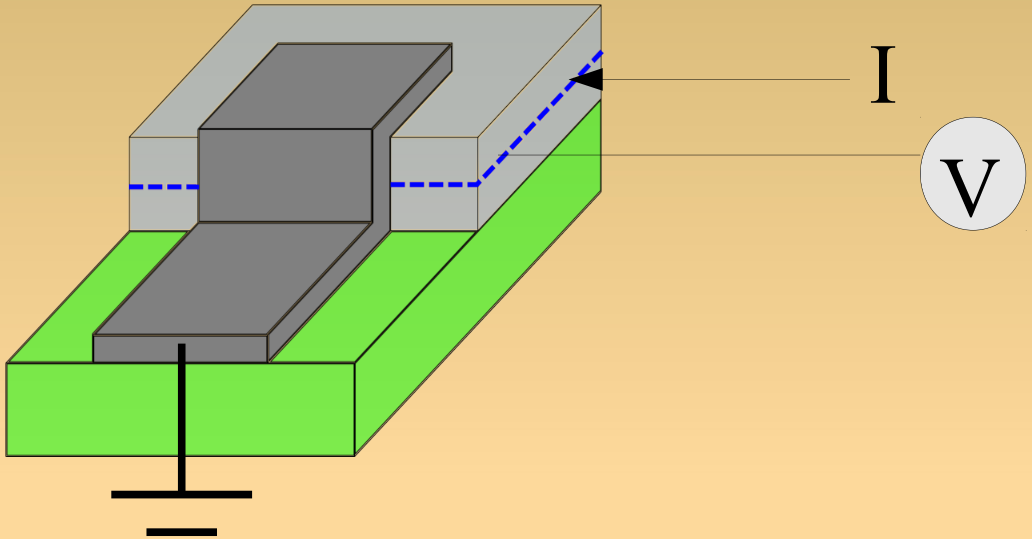
2. **Strong Rashba-type spin-orbit coupling**

($\alpha > 10^{-11}$ eVm at 1 $\times 10^{11}$ cm^{-2})

J. Phys.: Condens. Matter 20, 472207 (2008) in low fields,
our Phys. Rev. B 86, 125304 (2012) in the QH effect regime.

Samples and technique



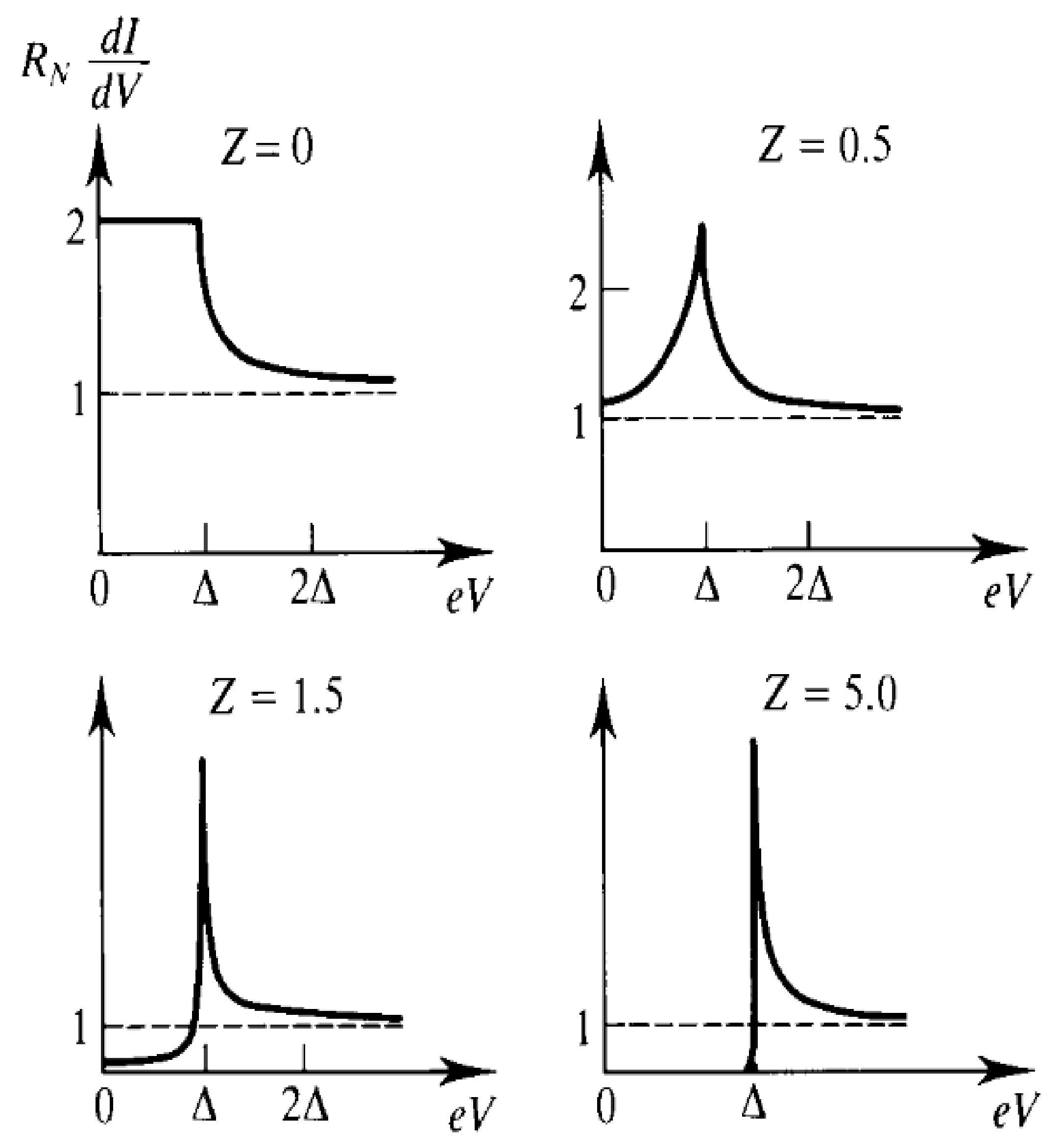


The 100 μm width, corner-shape mesa has a number of leads to Ni-Au Ohmic contacts.

Several superconductor (Nb or NbN) stripes (yellow, denoted by numbers) are placed to overlap with two perpendicular mesa edges. The width of a single stripe is equal to 20 μm in the overlap region.

In every overlap region, S-N junction is formed between the Nb (NbN) electrode (S) and the 2DEG edge (N) at the mesa step.

Superconductor: Andreev reflection (BTK)



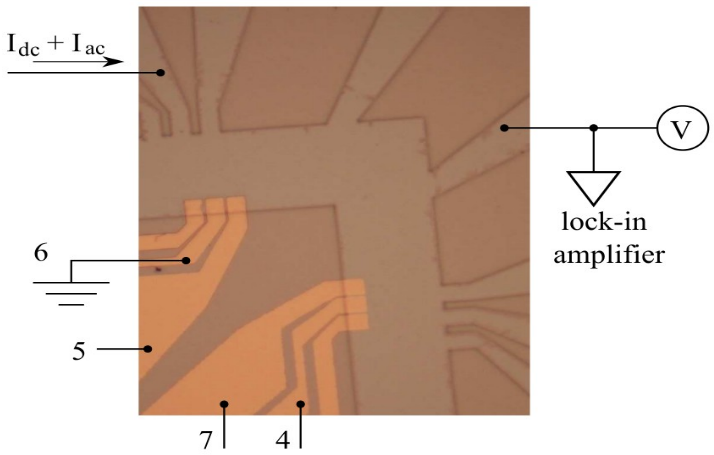
BTK:
G.E. Blonder, M. Tinkham,
T.M. Klapwijk,
Physical Review B. 25, 4515, (1982)

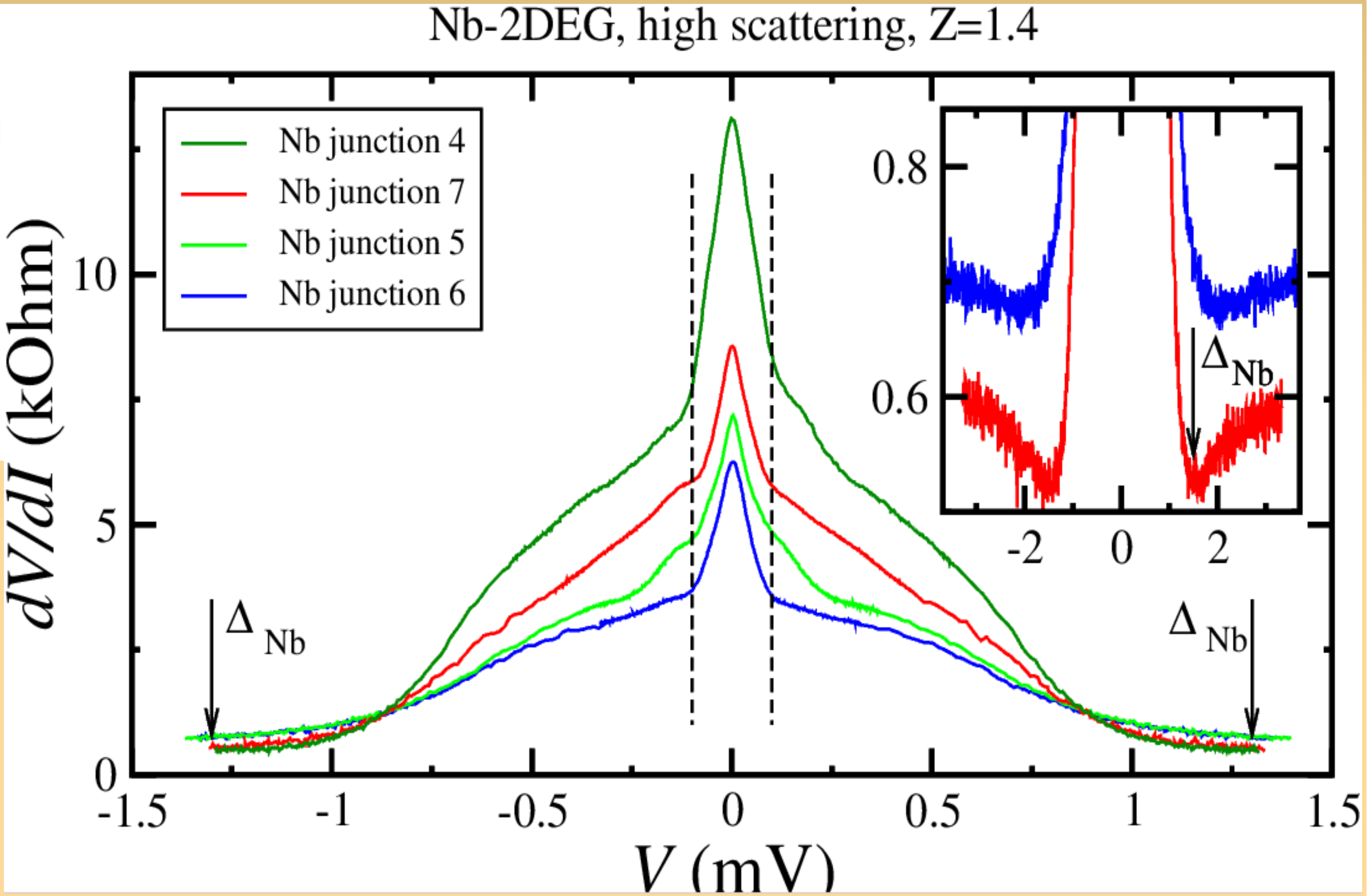
M. Tinkham, Introduction to
Superconductivity
(2d ed., McGrawHill, New York, 1996).

I. E. Batov, Th. Schpers, A. A. Golubov,
and A. V. Ustinov,
J. Appl. Phys. 96, 3366 (2004).

I-V curves for the Nb-2DEG interface

The most important experimental finding is a well developed dV /dI resistance peak of the same width (denoted by dashed lines) at low biases



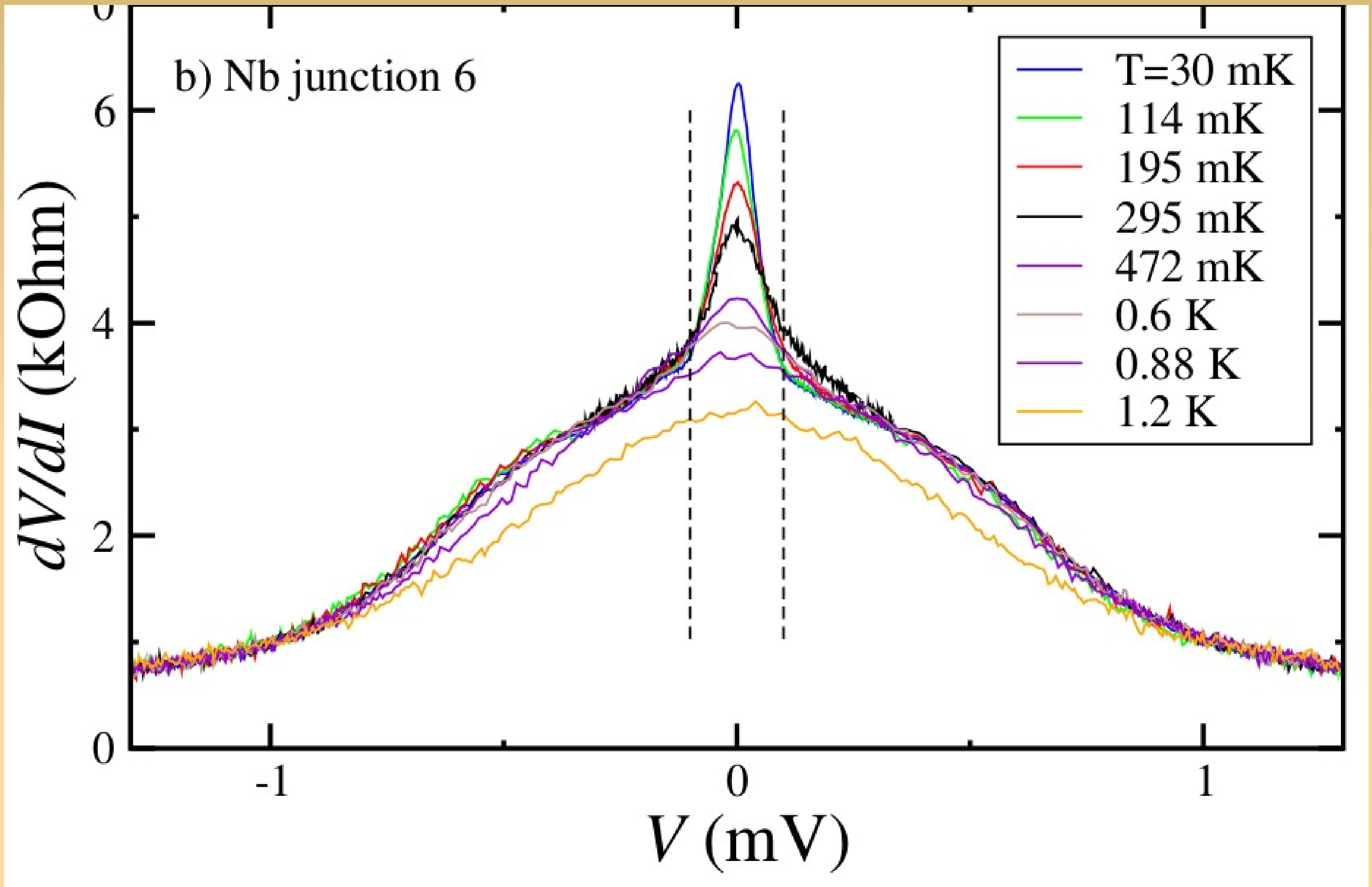


The peak width ≈ 0.2 mV
is the same
for different S-N junctions,
so it is independent of the
disorder at the interface.

In the case of **Nb** electrode, the scattering is dominant T=0.3 => Z=1.4

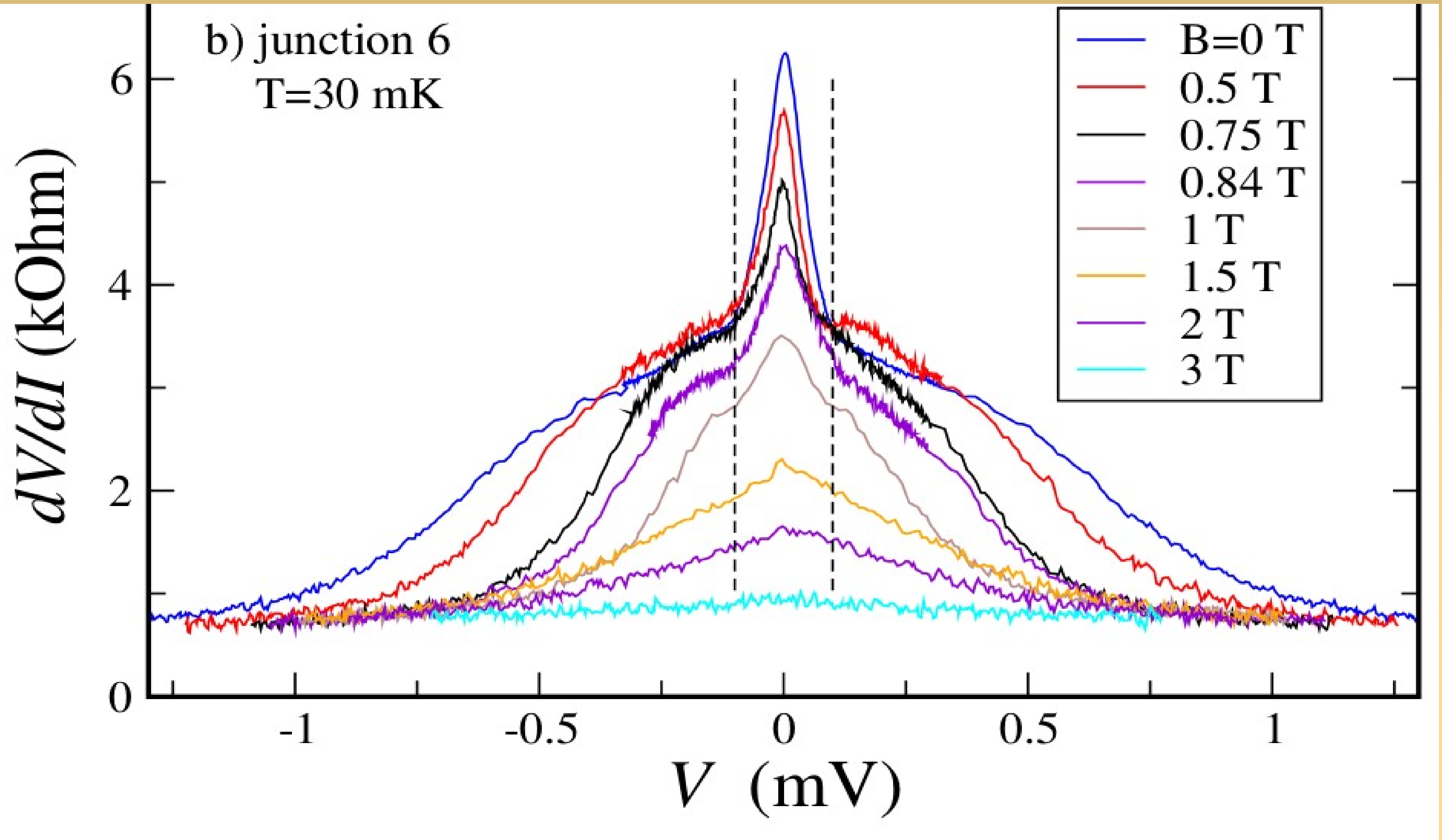
(T= 1 / (1 + Z^2)) (BTK)

Temperature dependence (Nb-2DEG)



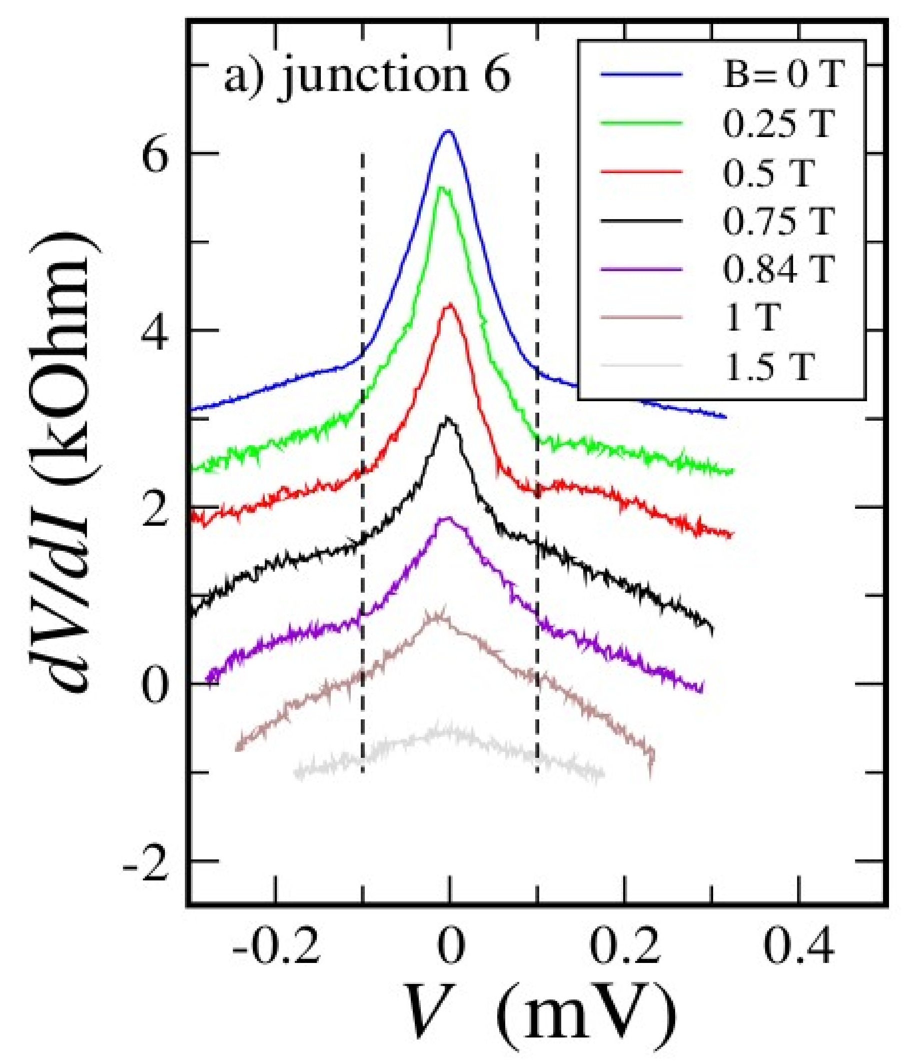
The dV /dI resistance peak only exists at low temperatures.
It disappears completely at 0.88 K, while the curve is practically insensitive to the temperature below this value.

In-plane magnetic field behavior (Nb-2DEG)



High field B suppresses the nonlinearity of the dV /dI −V curve, as expected: the dV /dI −V curve is fully linear above B = 3 T, reflecting constant, bias-independent normal resistance of the junction.

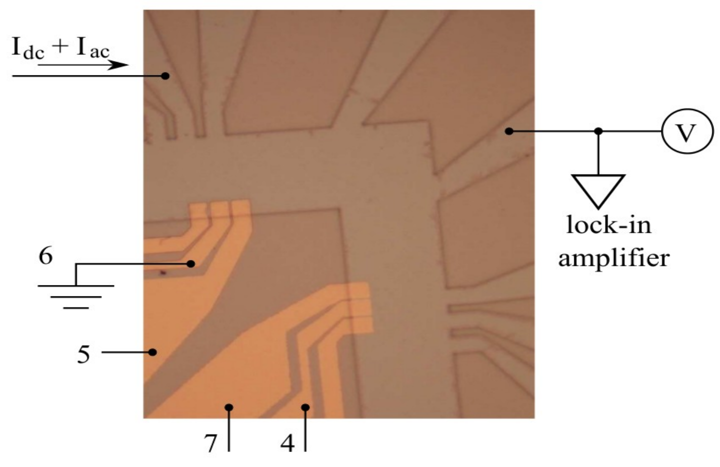
In-plane magnetic field behavior (central peak region, Nb-2DEG)

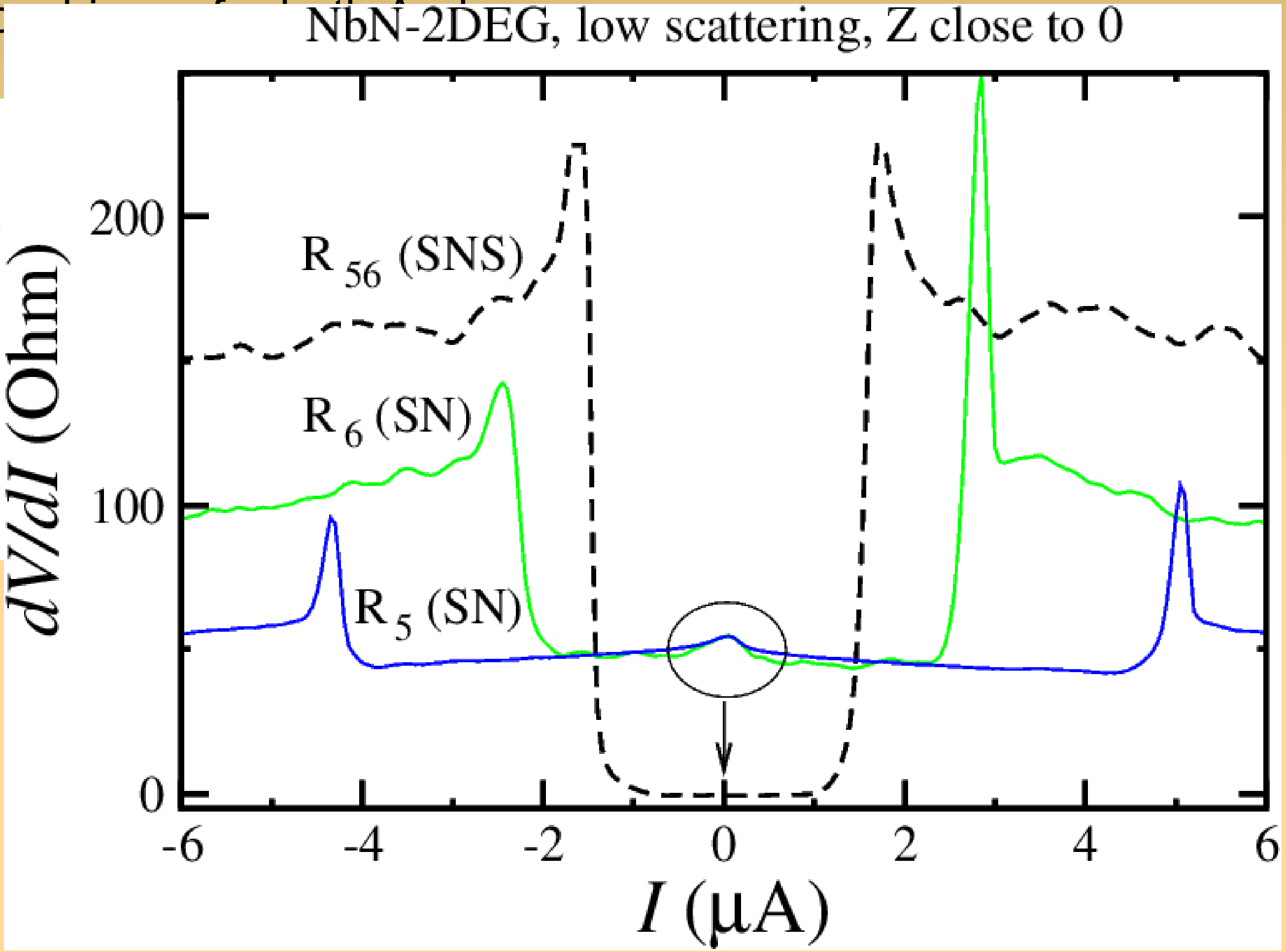


The dV /dI resistance peak disappears completely at 1.5 T.

I-V curves for the NbN-2DEG interface

The most important experimental finding is a well developed dV /dI resistance peak at lo




NbN-2DEG, low scattering, Z close to 0

In the case of **NbN** electrode, the limit of low scattering at the S-N interface is realized, Single-particle transmission T is about 1, barrier strength Z (BTK) about zero.

$(T = 1 / (1 + Z^2))$ (BTK)

Mail experimental results

1. Strong increase of the resistance within 0.2 mV bias interval indicates a **suppression of the Andreev reflection** within a narrow energy range

2. This effect is **independent** of the superconductor materials and interface disorder.

Discussion

The only relevant energy scale in this case is the Rashba splitting Δ_{SO} (about 1K) in the 2DEG spectrum.

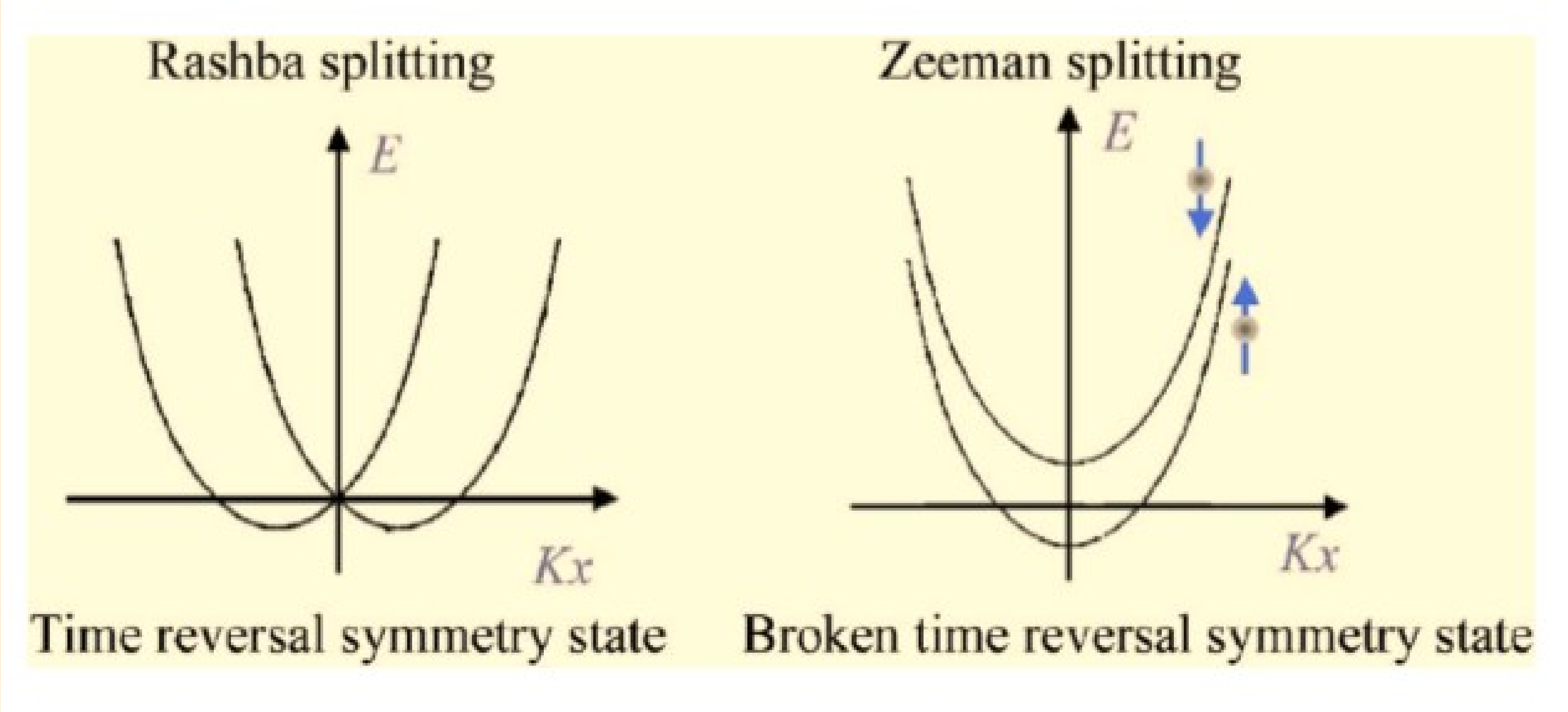
This conclusion is qualitatively supported by the strong temperature dependence at $T << T_c$:
if temperature T exceeds Δ_{SO} , the spectrum is restored, and therefore the Andreev reflection.

The central dV /dI peak is suppressed by magnetic field, it disappears completely in 1.5 T, when Zeeman splitting equals to the spin-orbit coupling (J. Phys.: Condens. Matter 20, 472207 (2008)).

Possible mechanisms ?

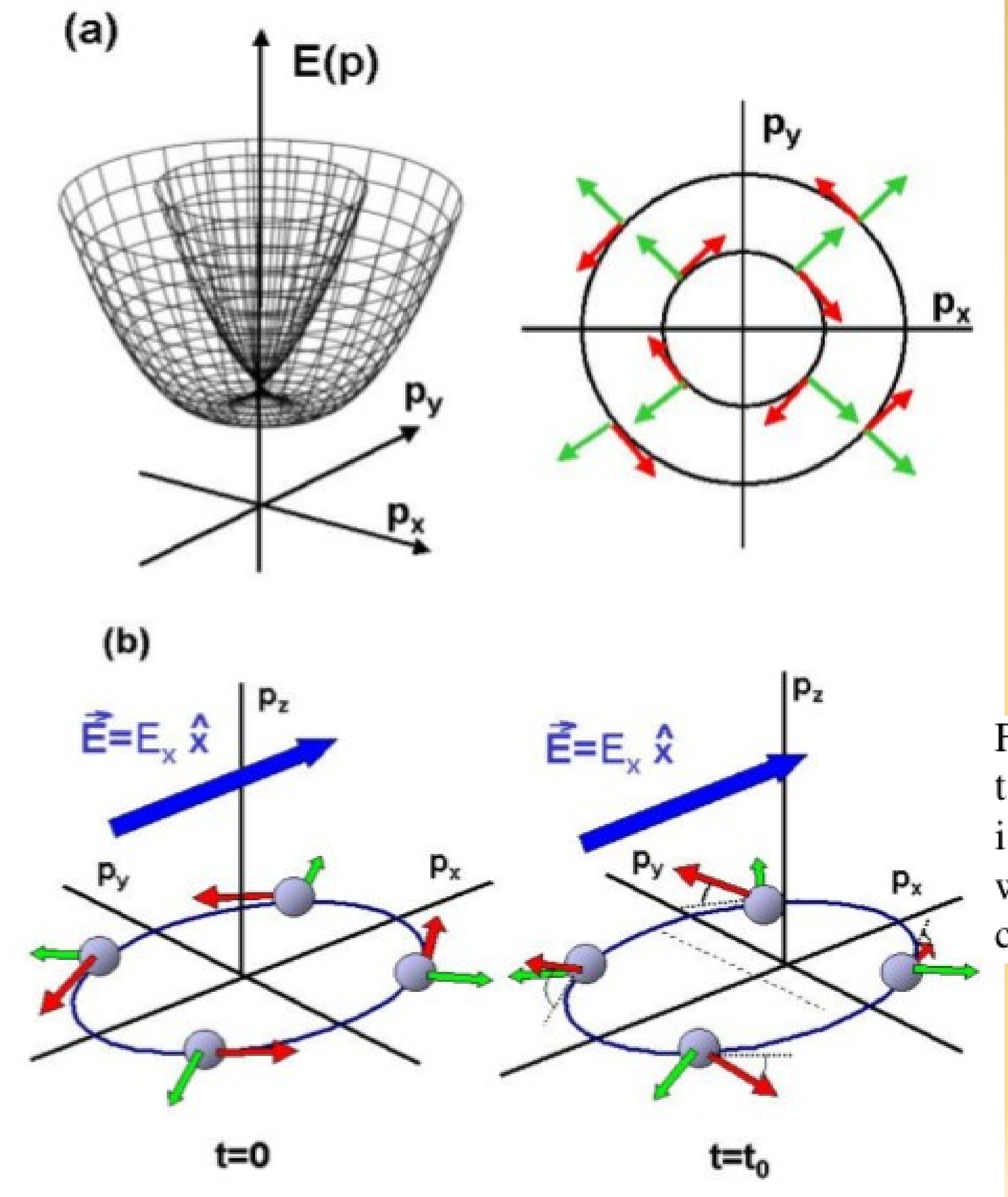
1. T. Yokoyama, Y. Tanaka, and J. Inoue, Phys. Rev. B 74, 035318 (2006).
Main conclusion: SO indeed affects the Andreev reflection, but no low-energy physics can be expected.

2. **Spin Hall effect** (experimental verification in our 2DEG:
our Phys. Rev. B 89, 075312 (2014))



Spin-Hall effect

J. Sinova, D. Culcer, Q. Niu, N. A. Sinitsyn, T. Jungwirth, and A. H. MacDonald, Phys. Rev. Lett. 92, 126603 (2004).



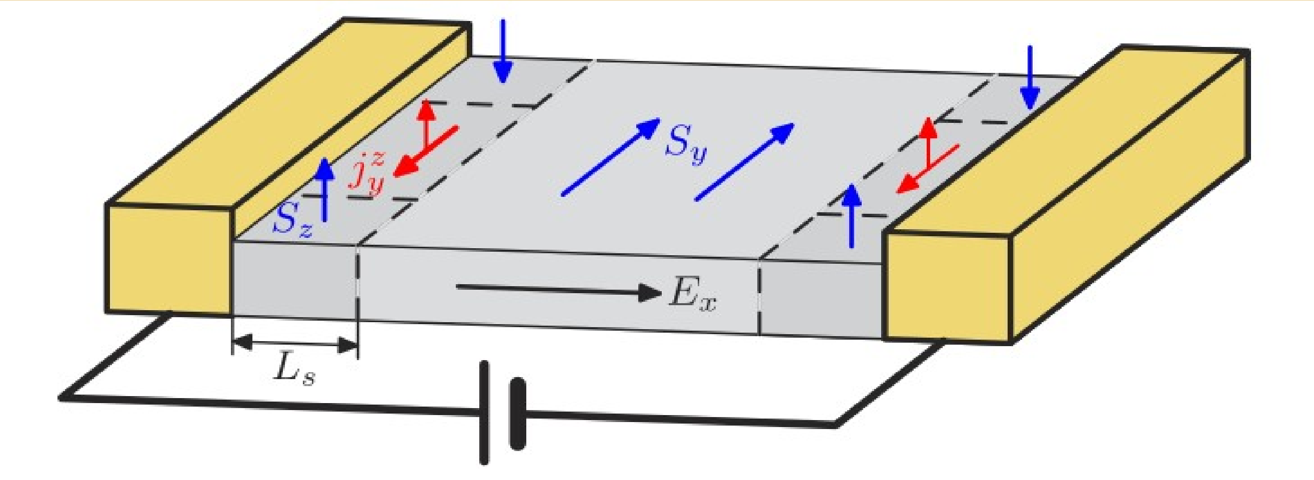
$$H = \frac{p^2}{2m} - \frac{\lambda}{\hbar}\vec{\sigma}\cdot(\hat{z}\times\vec{p}),$$

Fermi surface (circle) is displaced an amount $|eE_x t_0/\hbar|$ at time t_0 (shorter than typical scattering times). While moving in momentum space, electrons experience an effective torque which tilts the spins up for $p_y > 0$ and down for $p_y < 0$, creating a spin current in the y direction.

Spin Hall effect

E. G. Mishchenko, A. V. Shytov, and B. I. Halperin, Phys. Rev. Lett. 93, 226602 (2004).

A. Khaetskii, arXiv:1401.7684.



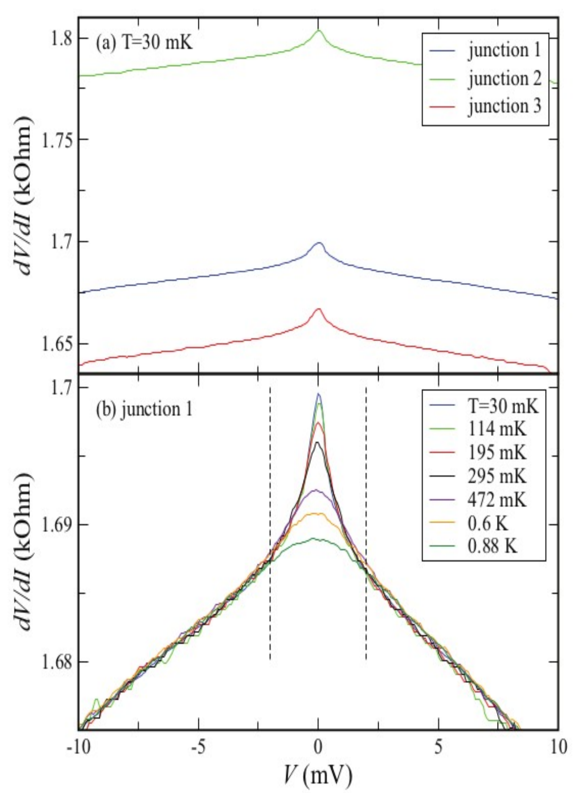
$$H = \frac{p^2}{2m} - \frac{\lambda}{\hbar}\vec{\sigma} \cdot (\hat{z} \times \vec{p}),$$

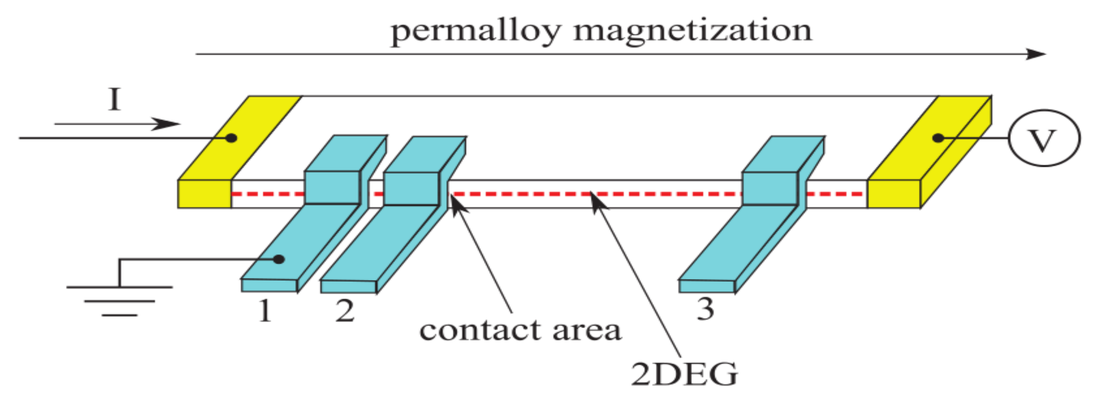
J. Sinova, D. Culcer, Q. Niu, N. A. Sinitsyn, T. Jungwirth, and A. H. MacDonald, Phys. Rev. Lett. 92, 126603 (2004).

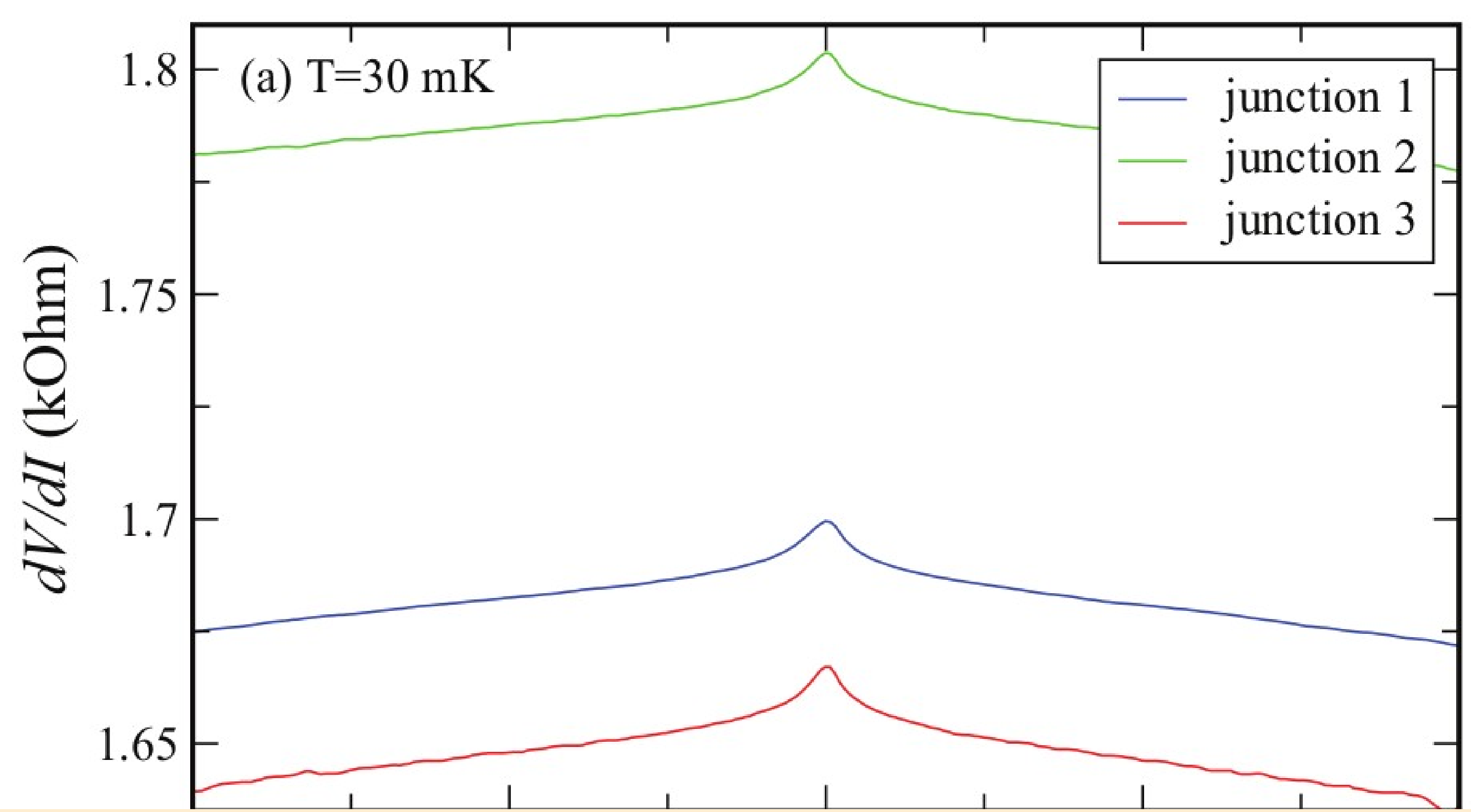
J. Schliemann and D. Loss, Phys. Rev. B 69, 165315 (2004); J. I. Inoue, G. E. W. Bauer, and L. W. Molenkamp, ibid. 67, 033104 (2003); A. A. Burkov, A. S. Nunez, and A. H. MacDonald, ibid. 70, 155308 (2004).

E. I. Rashba, Phys. Rev. B 70, 201309(R) (2004)   E. I. Rashba, Physica E 34, 31 (2006).

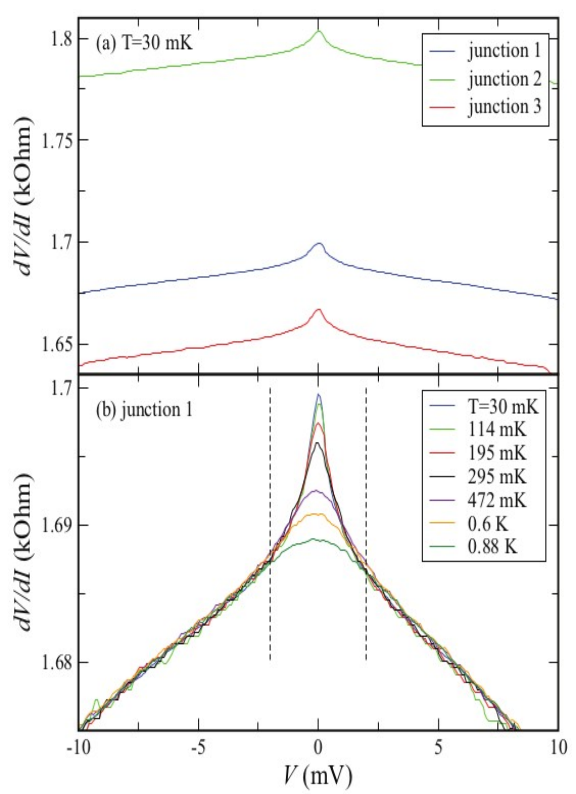
I-V curves for different ferromagnetic junctions

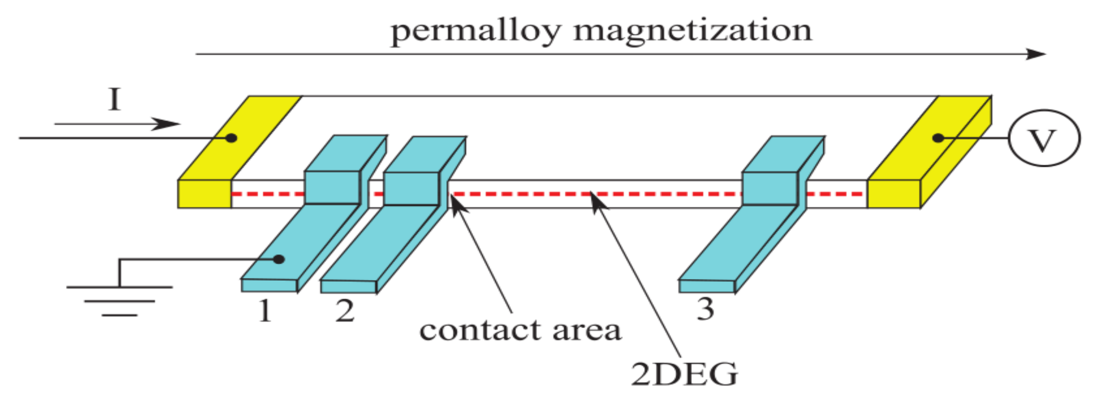


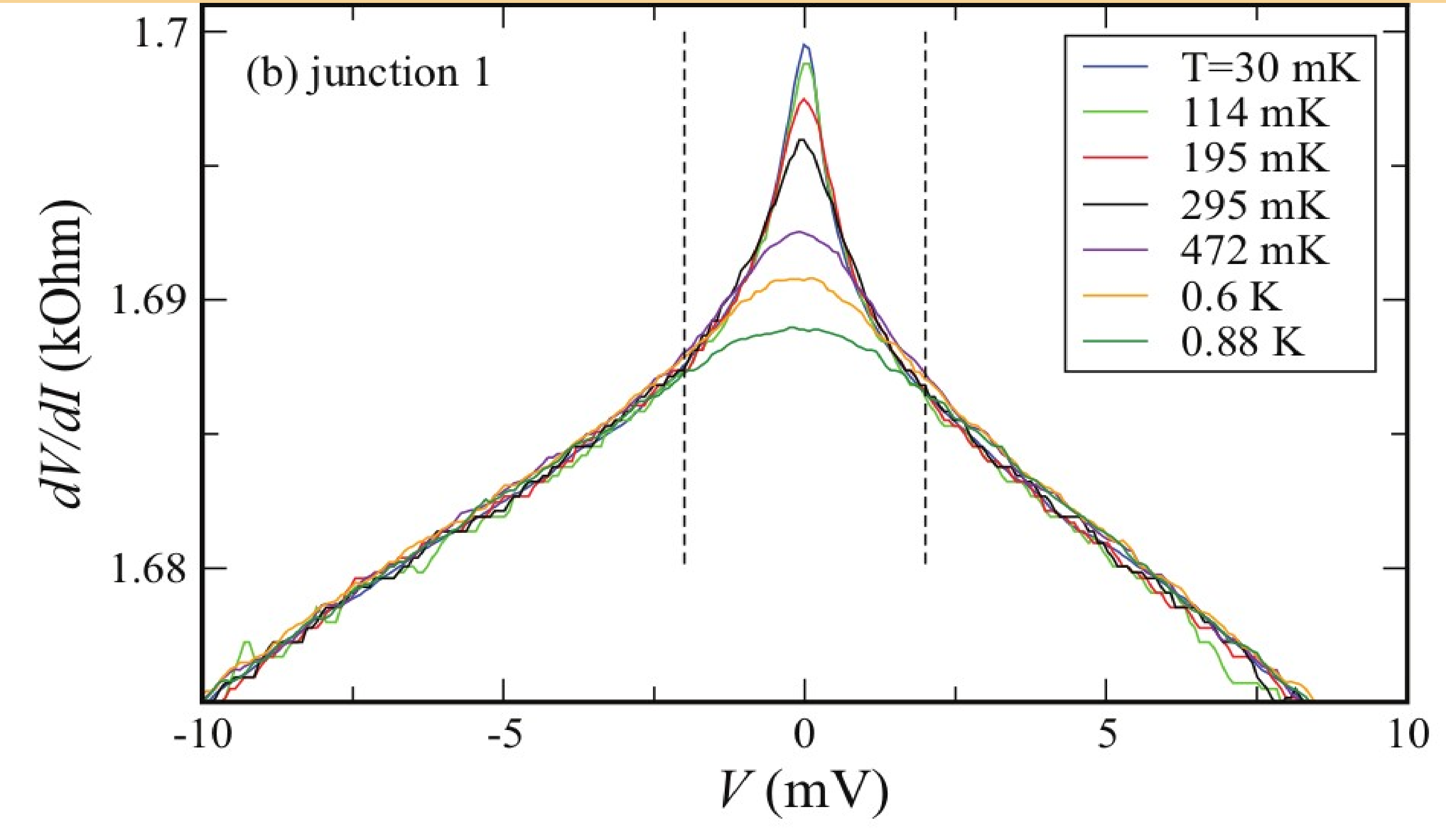




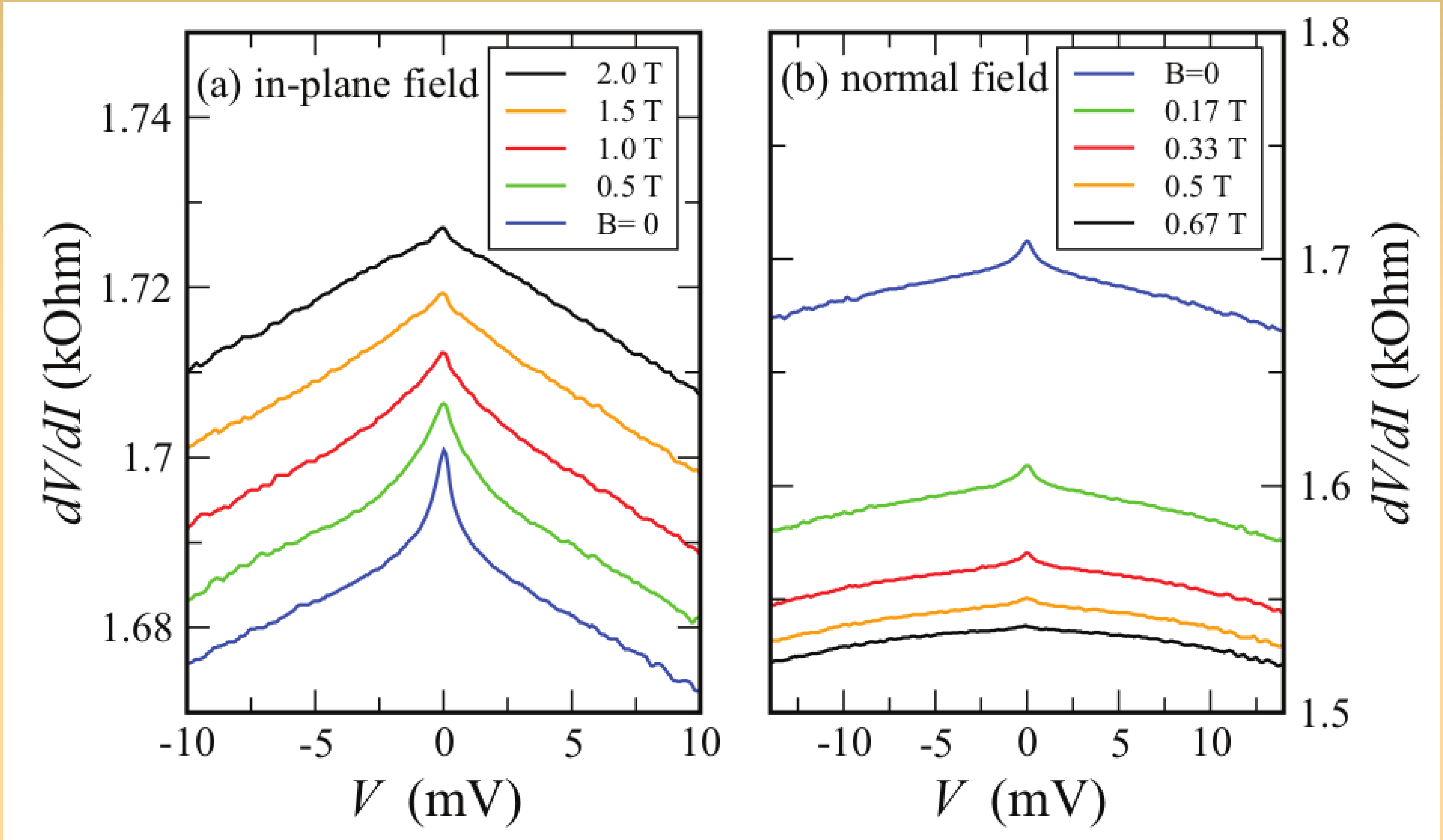
I-V curves (temperature dependence)





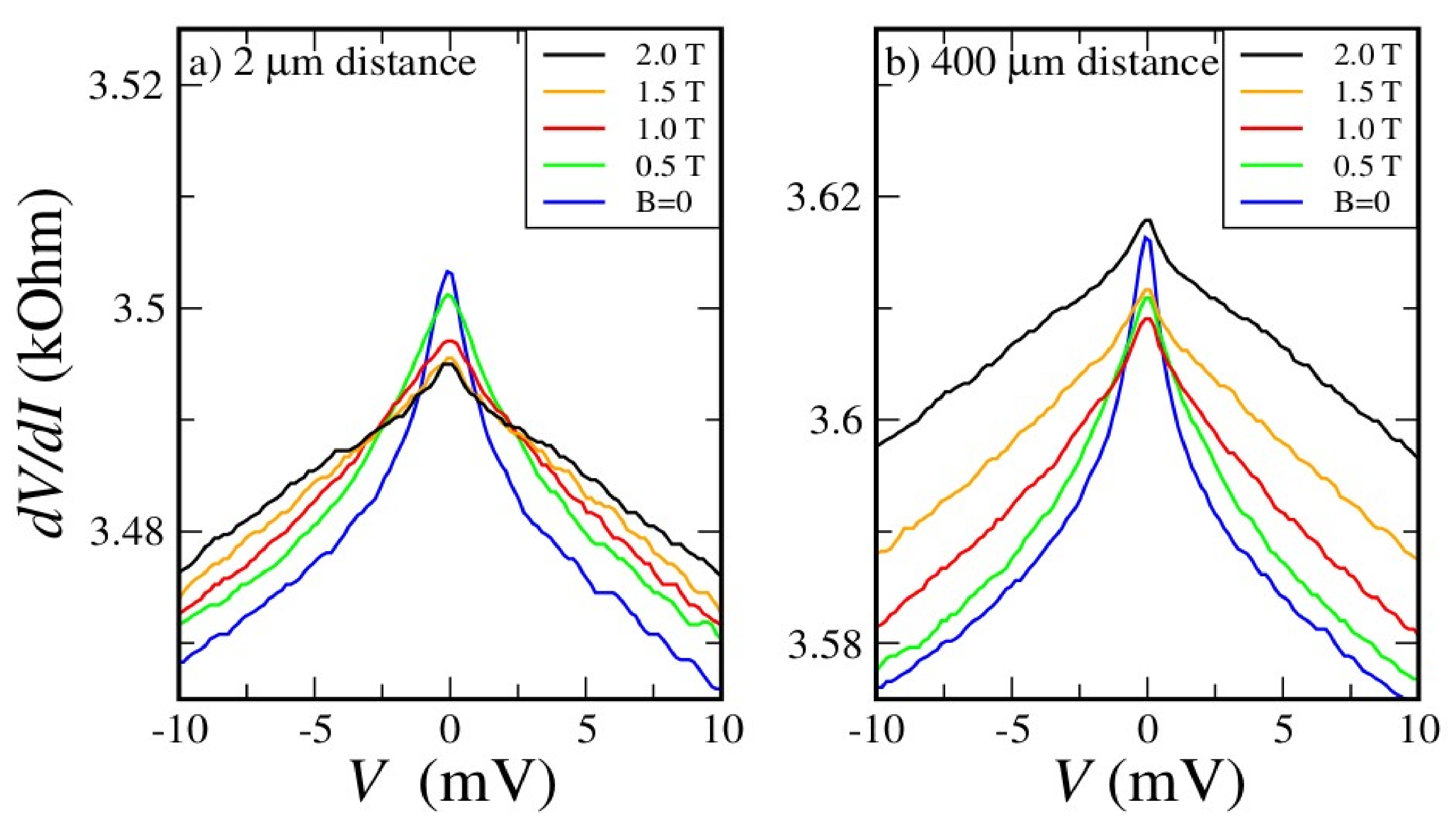


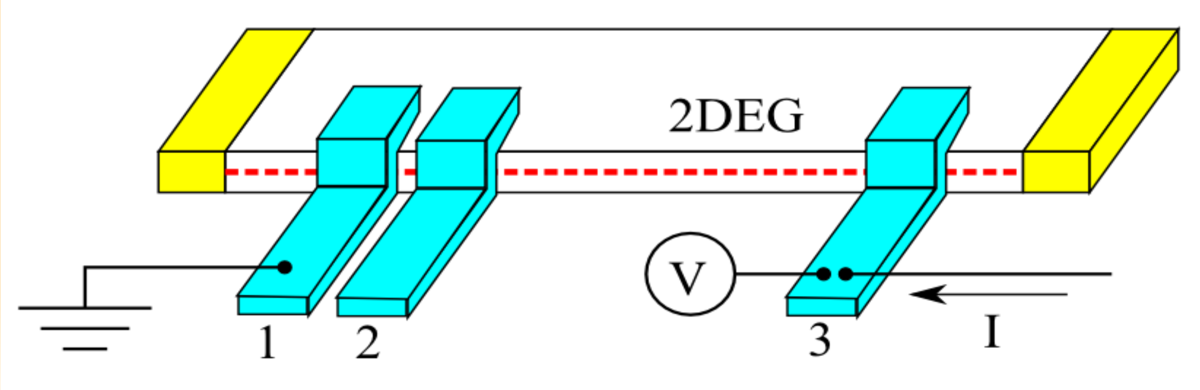
Magnetic field dependence for the ferromagnetic contact



Interface effect?

Two-point I-V in-plane magnetic field





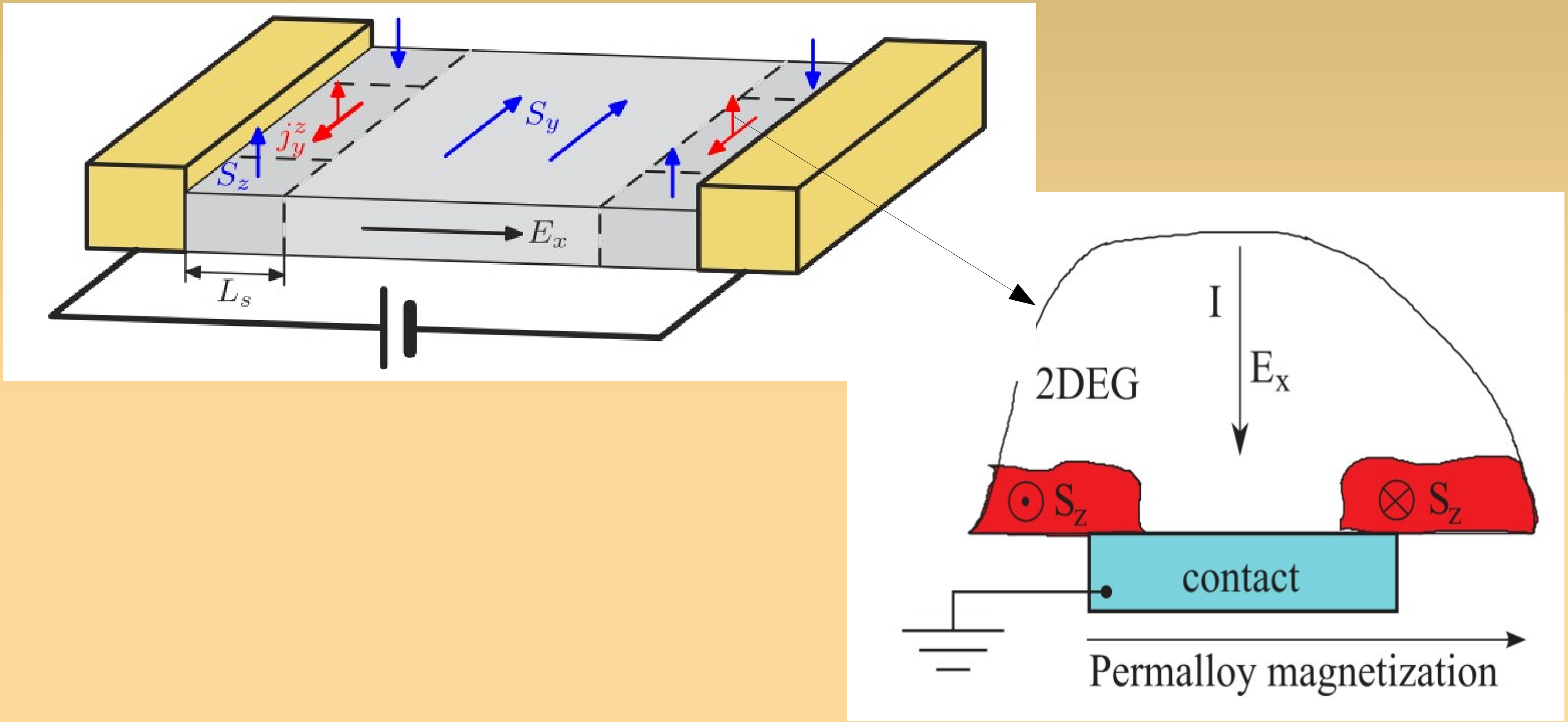
Main experimental results

1. **We observe strongly non-linear transport around zero bias at millikelvin temperatures.**

2. The observed nonlinearity is fully suppressed above some critical values of temperature, magnetic field, and current through the interface.

3. **This behavior is universal for different contacts.**

Vicinity of the contact



When we increase the current through the interface, this out-of-plane spin polarization can be transferred to the permalloy magnetization as a magnetization torque

If we consider the finite 2DEG thickness, we obtain quite reasonable critical current density of 10^4 –10^5 A/cm^2 . (Y. Tserkovnyak, A. Brataas, G. E. W. Bauer, and B. I. Halperin, Rev. Mod. Phys. 77, 1375 (2005).)

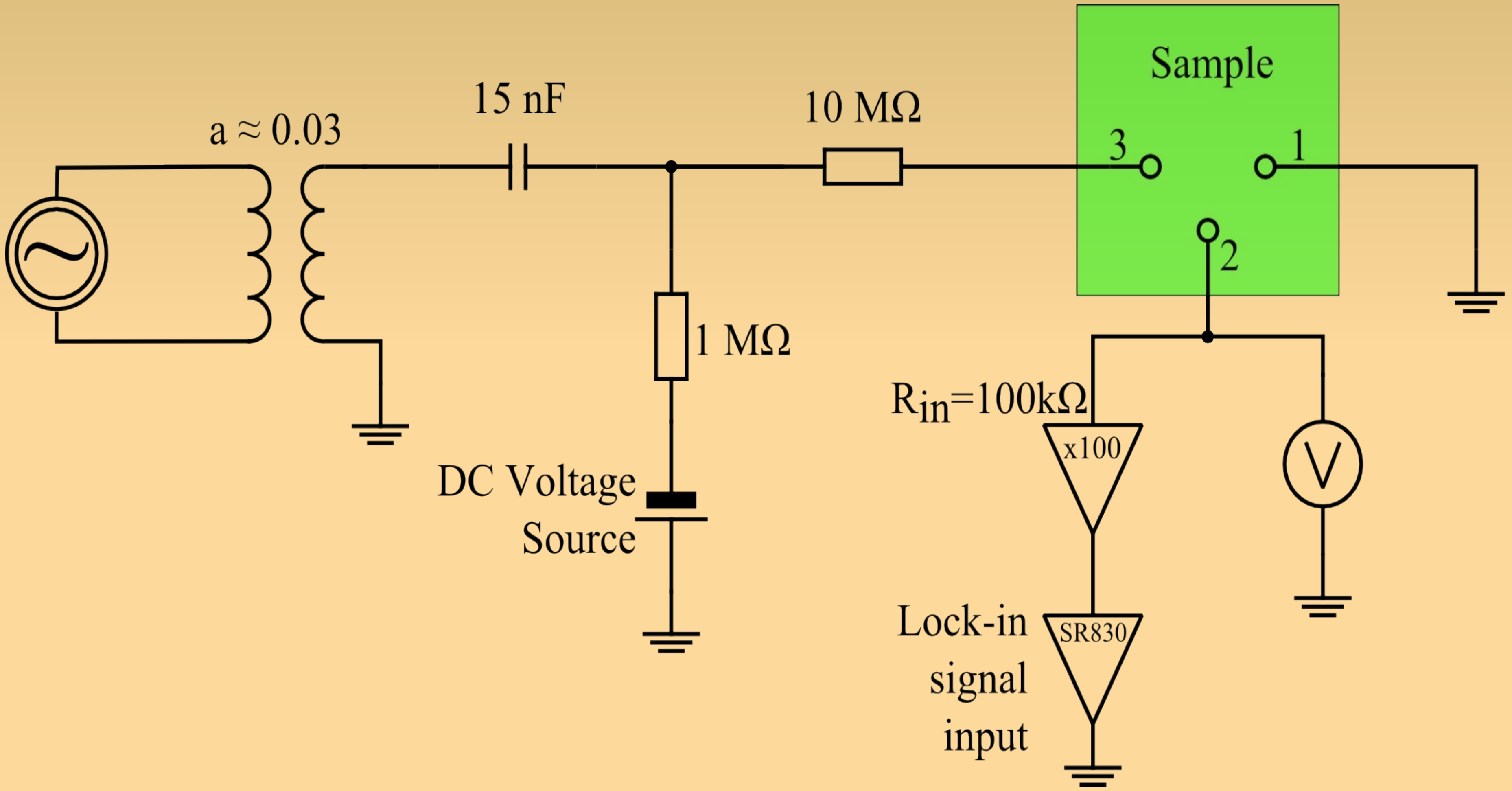
Conclusion

We experimentally investigate transport properties of a single planar junction between a superconductor and the edge of a two-dimensional electron system in a narrow In0.75Ga0.25As quantum well with strong Rashba-type spin-orbit coupling.

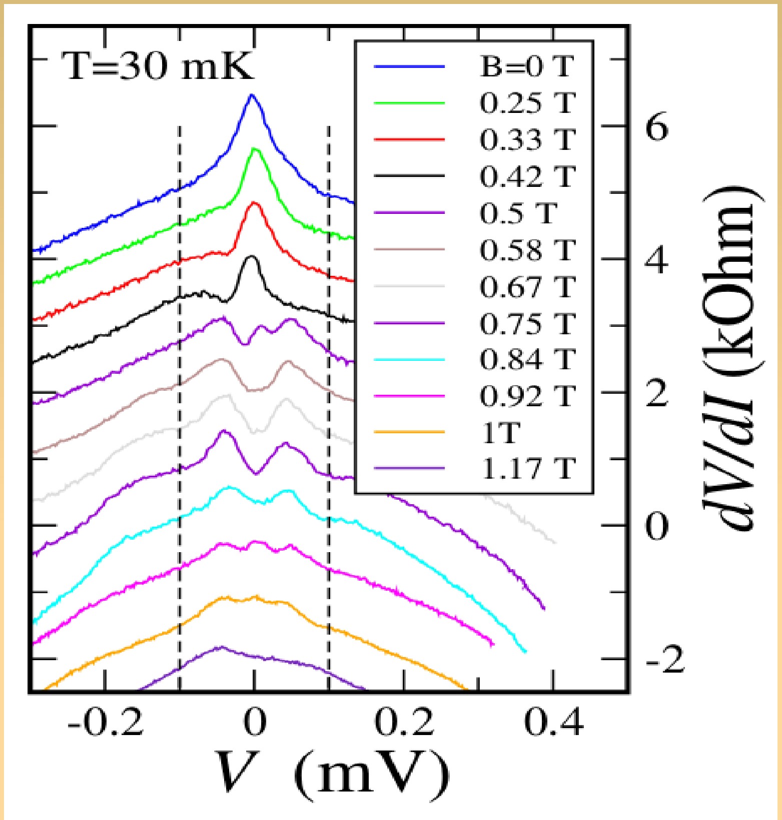
We demonstrate suppression of Andreev reflection within a narrow energy range below the superconducting gap. This effect is shown to be independent of the superconductor material and the interface disorder.

We connect the observed suppression with a strong spin-orbit coupling on the normal side of the junction.

Experimental details



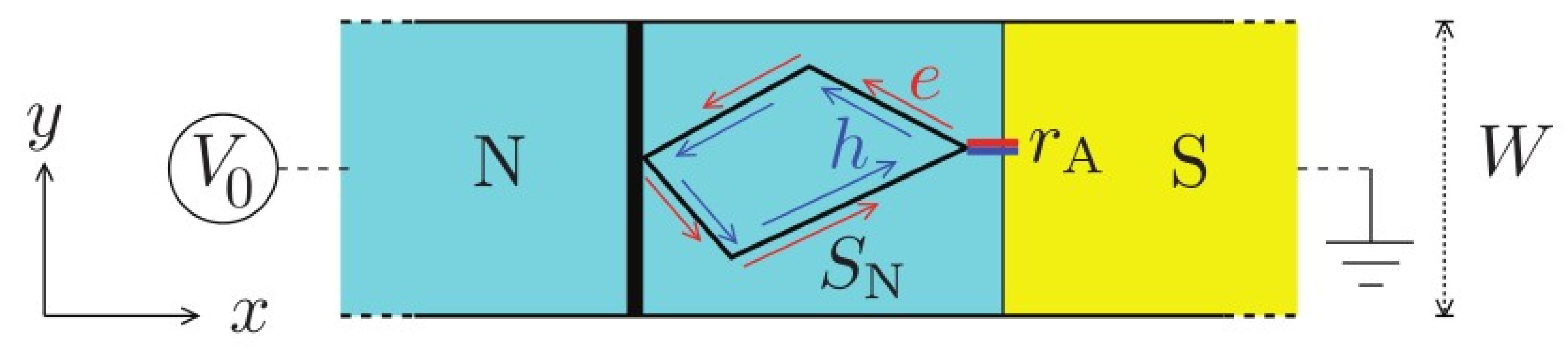
In-plane magnetic field behavior



non-monotonous evolution of the effect in low in-plane magnetic fields

Disorder-induced Andreev reflection? (New Journal of Physics 14 (2012))

Disorder-induced Andreev reflection

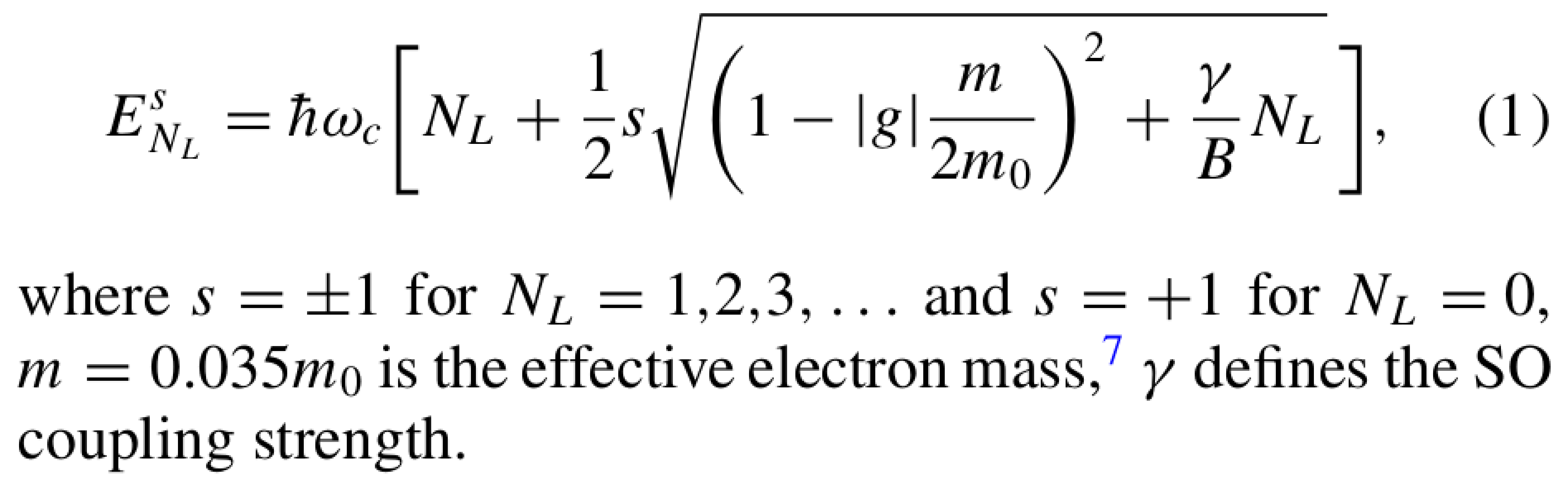


A bias voltage V0 applied to the normal metal (N) drives a current I into the grounded superconductor (S). Electrons and holes (e, h) are scattered by disorder or a tunnel barrier in N and converted into each other by Andreev reflection at the NS interface, as described by the scattering matrices SN and rA .

Particle–hole symmetry ensures that the phase shifts accumulated by e and h along a closed trajectory cancel, irrespective of whether time-reversal symmetry is broken or not. Such phase conjugate series of scattering events permit weak (anti)localization to persist in a magnetic field.

New Journal of Physics 14 (2012)

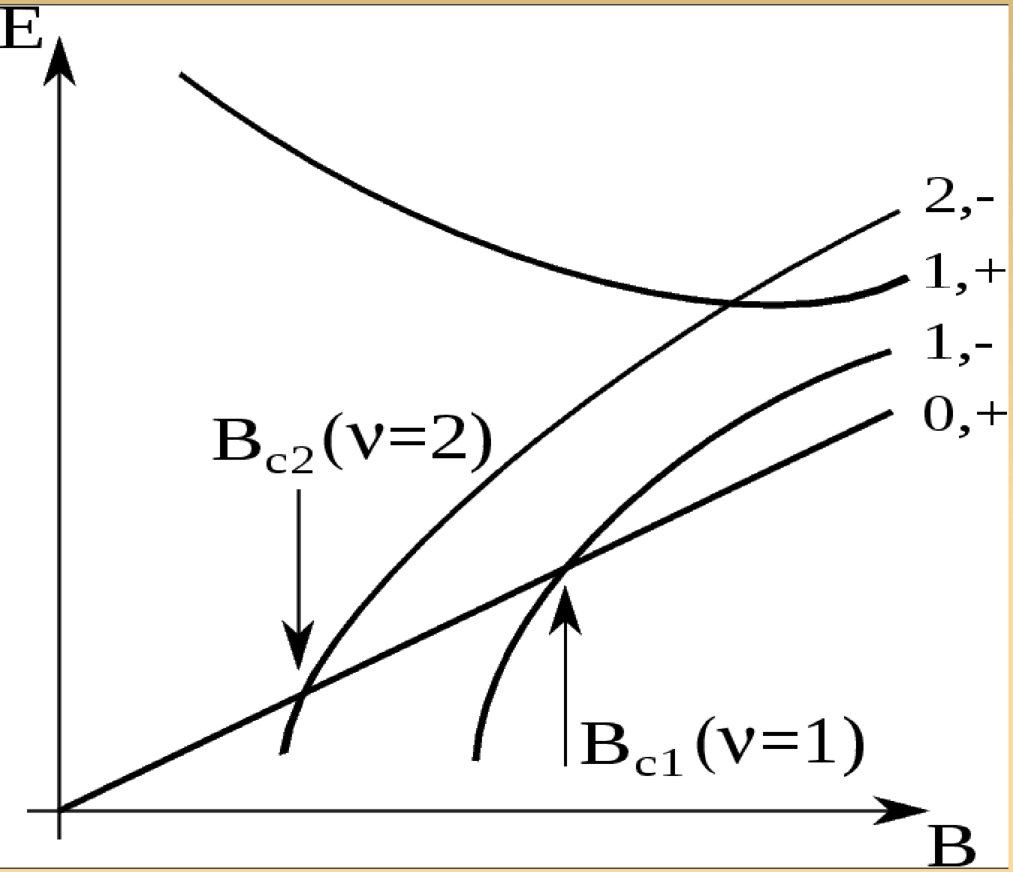
Bychkov-Rashba spectrum

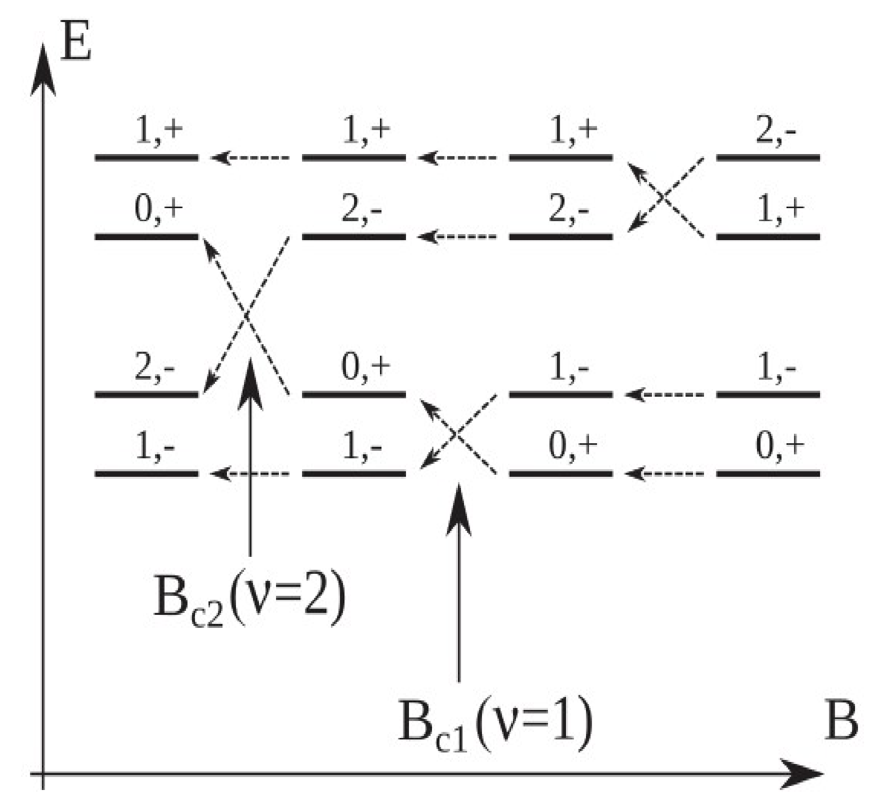


$$E^{s}_{N_L} = \hbar\omega_c\left[N_L + \frac{1}{2}s\sqrt{\left(1 - |g|\frac{m}{2m_0}\right)^2 + \frac{\gamma}{B}N_L}\,\right], \qquad (1)$$

where $s = \pm 1$ for $N_L = 1, 2, 3, \ldots$ and $s = +1$ for $N_L = 0$, $m = 0.035 m_0$ is the effective electron mass,[7] γ defines the SO coupling strength.

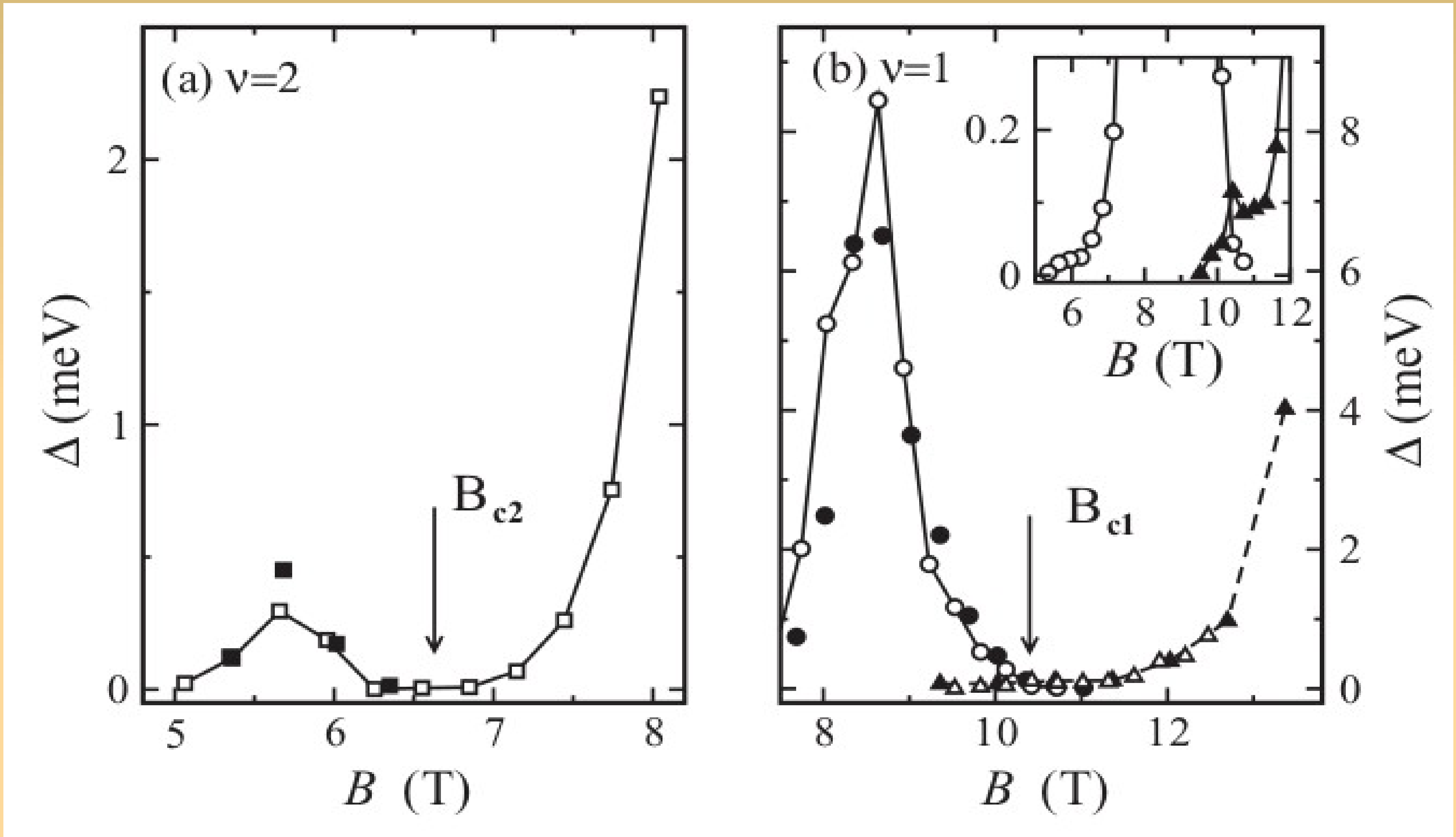
Spectrum reconstruction at low filling factors



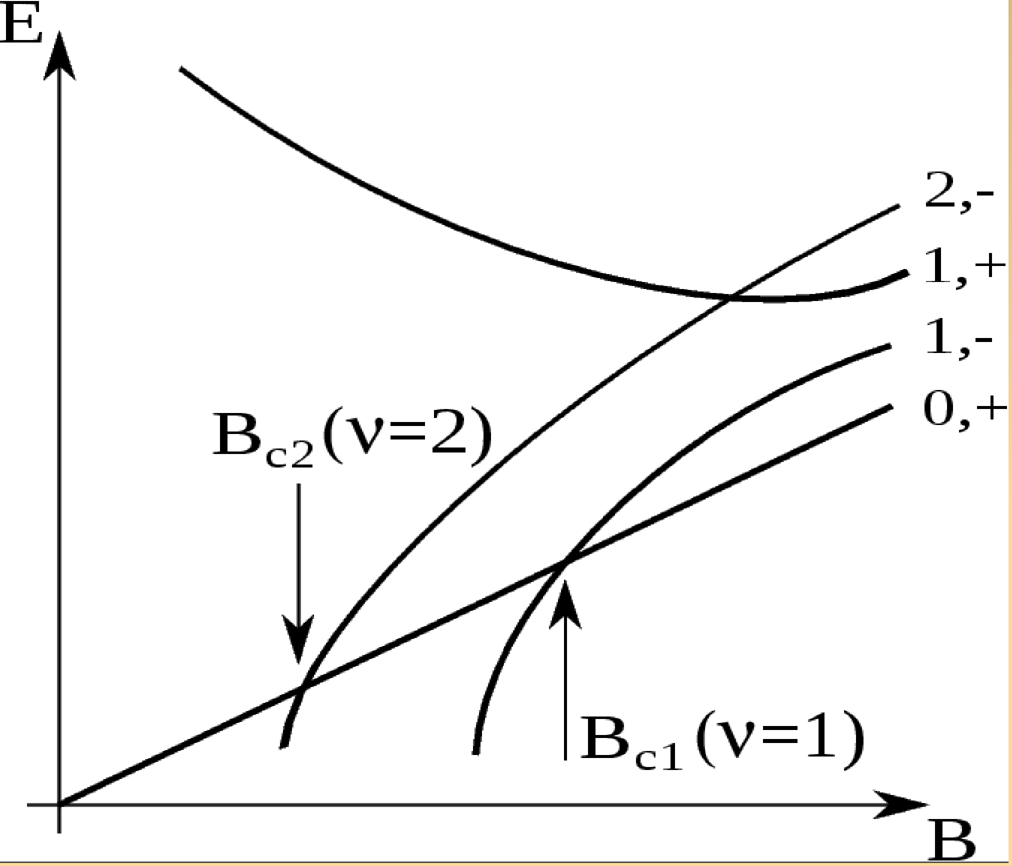


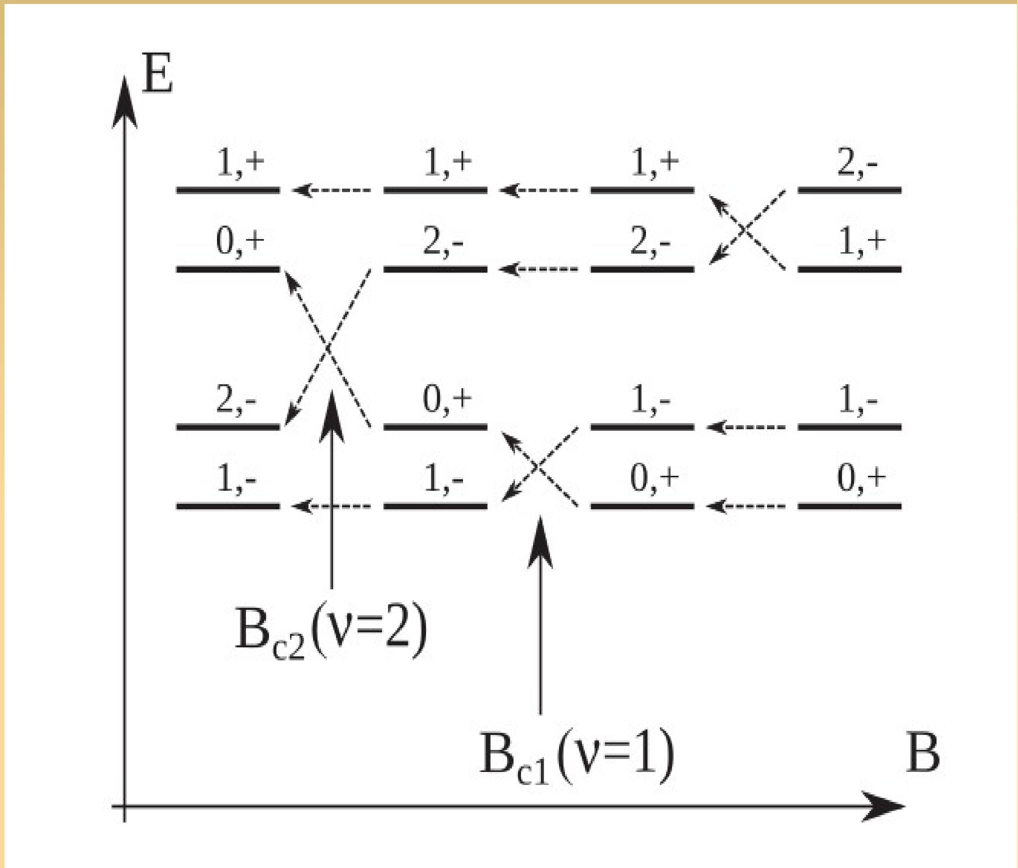
$$E^{s}_{N_L} = \hbar\omega_c\left[N_L + \frac{1}{2}s\sqrt{\left(1-|g|\frac{m}{2m_0}\right)^2 + \frac{\gamma}{B}N_L}\,\right],$$

Experimental results



Spectrum reconstruction – comparison with the experiment





Eq. (1): $B_{c1} = \gamma/(2|g|\frac{m}{m_0})$ and $B_{c2} = \gamma/(4 + 2|g|\frac{m}{m_0})$. Their comparison results in $g^* = 2\frac{m_0}{m}(B_{c2}/B_{c1}) \approx 30$ at $\nu = 1$. This

$\gamma = 2|g^*|\frac{m}{m_0}B_{c1} \approx 28$ T

$\alpha = (\frac{\hbar^3 e\gamma}{8m^2})^{1/2} \approx 10^{-10}$ eVm