Controlling Vortices and Cold Molecules with Magnetic Nanostructures

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Supported by: DOE Office of Basic Energy Sciences, NSF,
The Welch Foundation, Norman Hackerman Advanced Research Program
Overview

Research Programs

Magnet – Superconductor Hybrids
  Magnetic Nanorod Array in a Superconducting Film
  Magnetic Rails for Vortices

Cold Molecules
  Existing Methods to Cool Molecules
  Counter Rotating Source

Synergy and Perspectives

Conclusion
Research Programs, Funding and Main Participants

Emergent Behavior in Magnet-Superconductor Hybrids


Total funding $905,000 by DOE (2007-2010) (2010-2013)

Thanks to G. Agnolet, V. Pokrovsky, J. Ross, W. Teizer

Cold Molecules

L. Sheffield, M. Hickey, V. Krasovitskyi, D. Rathnayaka and D. Herschbach

Total funding $868,000 by NSF, The Welch Foundation, NHARP (2007-2011)

Thanks to D. Naugle, S. North, J. Bevan, M. Raizen
Question:
Can we integrate materials whose properties tend to be mutually exclusive such as ferromagnetic and superconducting materials?

Answer:
Yes, when using appropriate scales for magnetic and superconducting subsystems.

Scale is dictated by vortex core size (Cooper pair size) in a superconductor.

This question was posed as one of the ten grand challenges that S. Bader, the Chair of the Division of Materials Physics of the American Physical Society, discussed in an email to the members of this society in 2004.
**Vortex in a Thin Superconducting Film**

Characteristic lengths:
- Coherence length \( \xi \) (Cooper pair size): 1-100nm
- London penetration depth \( \lambda \)

Film thickness \( d \leq \lambda \). Vortices contain one flux quantum and have a radius of the order of the effective penetration depth \( \lambda/(\lambda/d) \).

Motion of vortices means dissipation. To prevent energy losses vortices should be strongly pinned.

Current in a superconductor acts on vortices in the direction normal to the current and applied magnetic field, similar to the Magnus force.
Magnet-Superconductor Hybrids

Superconducting film with embedded Magnetic Nanorods

Superconducting film with external Magnetic Nanostripes

Superconducting film on top of the alumina membrane with magnetic nanowires
Characterization of Magnetic Nanostructures

Atomic Force Microscope picture of Ni nanocolumn array with period 2 microns, column diameter 70nm and height 350nm;

Magnetic Force Microscope (MFM) image of Co nanorods in a PMMA matrix:

MFM scan along the line shown at the left. Different signs correspond to different directions of the vertical film component of the magnetic field;

Scanning Hall Probe Microscope

Scan of the alternating magnetic field distribution of the magnetic nanostructure.
Fabrication of Magnetic Nanorods-Superconductor Array
Resistance vs Magnetic Field for SC film

R vs H for PbBi film with an array of Ni nanorods (blue) and for control film (red)

R vs H for PbBi film with an array of Ni nanorods
Nanoscale Magnetic Fields via Hybrids: Arrays of Magnetic Nanorods

- Magnetic field inside array
- Template: $-4\pi M (\pi R^2 / A)$
- Nanowire: $\vec{B} = 4\pi \vec{M} + \vec{H} = 4\pi \vec{M} (1 - (\pi R^2 / A))$
Nanoscale Magnetic Fields via Hybrids: Arrays of Magnetic Nanorods in External Field
Phase diagram for PbBi film with an array of Co nanorods

Phase diagram for PbBi film with an array of Ni nanorods

Simulated phase diagram for PbBi film with an array of Ni nanorods
Resistance vs Magnetic Field for SC film above Transition

R vs H in PbBi film with an array of Ni nanorods near transition temperature

R vs H in PbBi film with an array of Co nanorods near transition temperature
Critical Current in Hybrids with Ni and Co Nanorods

Critical current in PbBi film with an array of Ni nanorods

Critical current in PbBi film with an array of Co nanorods
Critical Current for Magnetic Nanorods Array

Critical current in PbBi film with an array of Ni nanorods
Dark-field cross-section image of a film showing α-Fe nanocolumns embedded in a LaSrFeO₄ matrix

Self-assembled single-crystal ferromagnetic iron nanowires
(α-Fe nanocolumns embedded in a LaSrFeO₄ matrix)

Room-temperature magnetic properties of α-Fe nanocolumns embedded in a LaSrFeO₄ matrix. Out-of-plane (wide loop) and in-plane (narrow loop) magnetic hysteresis loops correspond to α-Fe nanocolumns and indicate strong anisotropy

L. Mohaddes-Ardabili et al,
Magnetic Rails for Vortices in a Superconducting Film

Magnetic Stripe Structures (Magnetic Rails for Vortices)
- 275µm period alternating Iron-Brass laminate structure.
- 9µm period array of high aspect ratio (2-3) Co stripes.
- 500nm period array of 120nmx120nm cross section Ni stripes.
Magnetic force microscope (MFM) phase angle image taken at room temperature along the surface of Ni nanowires array, and the phase angle profile along the white line in the image.
Figure 1. (a) The production of cold and ultracold molecules in different regions of spatial density \((n)\) and temperature \((T)\). Some technical approaches that are yet to be demonstrated in experiments can potentially address the important region of \(n \sim 10^7 - 10^{10} \, \text{cm}^{-3}\) and \(T \sim 1 \, \text{mK} - 1 \, \mu\text{K}\) (the panel in the middle). (b) Applications of cold and ultracold molecules to various scientific explorations are shown with the required values of \(n\) and \(T\). The various bounds shown here are not meant to be strictly applied, but rather they serve as general guidelines for the technical requirements necessary for specific scientific topics.
Figure 5. a) The principle of supersonic expansion to generate pulsed molecular beams. A gas is expanded under high pressure from a container through a small hole into a region with significantly lower pressure ($P = 10^{-5} - 10^{-6}$ mbar). Particles with transverse velocity components that are too high are separated with a skimmer, so that the resulting pulsed molecular beam is highly directed. As is apparent from the velocity distribution for ammonia molecules in a container at room temperature and in the supersonic beam, the molecules in the molecular beam have a narrow velocity distribution (i.e., relative to an accompanying coordinate system they are already very cold), but the absolute velocity of the molecules relative to the laboratory coordinate system is still very high (see text). If a heavy noble gas (e.g., xenon) is used as carrier gas, the absolute velocity is reduced significantly, and the velocity distribution of molecules in the packet is narrower.
Anonymous NSF reviewer opinion:

Most work on slowing molecular beams has been using time varying electric fields (Stark deceleration) practiced by Gerard Meijer’s group and more recently Jun Ye’s group and others.

After ten years and nearly unlimited resources, many cute and clever technical experiments have been performed but there have been few quantitative measurements.
Zeeman Decelerator

Sketch of magnetic decelerator. Green dots represent cross-sectional view of wires of the electromagnet coil. The magnetic field is “on” for part (a), “off” for part (b). Red dots indicate molecules, lines show magnetic field lines. Red arrows represent velocity vectors.

FIG. 4. Full range time-of-flight measurement recorded with the QMS detector for 114 m/s final velocity. This figure shows the perturbed initial beam along with the slowed peak. The curve is an average of 200 individual measurements.
Counter rotating source

Beam density (cm$^{-3}$) $10^{12} < n < 10^{14}$
Old and New Iron

Question: why he need towel?
General outlook:

A) Main chamber;
B) main diffusion pump;
C) detector chamber,
D) diffusion pump for detector chamber;
E) Rack with controllers;
F) Gas feeding station.
Rotor in Color
Top left: Upper curve shows typical dependence of the RGA signal (arb units) vs time (in seconds) with set of oxygen gas pulses corresponding to the periodic return of the rotor to the shooting position. Lower curve shows single pulse obtained with shutter, which is open during only one shot; Bottom left: Single shot with fitting curve for oxygen V= 119 m/s, velocity spread 29m/s. Top right: Data for Zeeman decelerator (Raizen group).

FIG. 4. Full range time-of-flight measurement recorded with the QMS detector for 114 m/s final velocity. This figure shows the perturbed initial beam along with the slowed peak. The curve is an average of 200 individual measurements.
Top left: Upper curve shows typical dependence of the RGA signal (arb units) vs time (in seconds) with set of krypton gas pulses corresponding to the periodic return of the rotor to the shooting position. Lower curve shows single pulse obtained with shutter, which is open during only one shot;

Bottom left: Single shot with fitting curve for krypton with \( V = 88 \text{ m/s} \), velocity spread 16 m/s.

Top right: Single shot with fitting curve for krypton with \( V = 37 \text{ m/s} \), velocity spread 7 m/s.
Time of flight data for krypton vs rotor velocity minus theoretical supersonic krypton beam speed (385 m/s).

Pulse profile for krypton with fit (in red) for speed 37 m/s.

Pulse profile for oxygen seeded in xenon with fit (in red) for speed 119 m/s.

Pulse profile for nitrogen dioxide seeded in xenon with fit (in red) for speed 97 m/s.
Current Focus: Matterwave Chemistry

We have: $10^{12} < n < 10^{14}$

Pulse profile for nitrogen dioxide seeded in xenon with fit (in red) for speed 97 m/s. Velocity spread 16 m/s
Comparison of schematic field profiles from typical coil in a multistage magnetic decelerator (black dots), with two options for a single-stage magnetic slower: the extended solenoid (blue line) and the isochronous parabolic profile.

Comparison of simulation results for velocity distributions of oxygen molecules emerging from magnetic slower with different field profiles:
Left: for isochronous, parabolic case with 35 mm path length.
Right: for extended solenoid case.
Synergy:

Magnetic Micro / Nanotraps:

Magnetic field lines for the magnetic trap on a chip

Schematic showing an array of perpendicularly magnetized parallel slabs with a period of 10 µm. A magnetic lattice of elongated microtraps with non-zero potential minima is formed by applying a bias field along the y-direction and an additional bias field along the x-direction.

Magnetic field from the magnetic film edge is equivalent to the field from the linear current.

Left: SEM image of the Co stripes embedded into photoresist [24] with a period of 9 micron; Right: Magnetic field profile across the Co stripes in adjacent image measured with (SHPM) at 5 kOe applied field.
Future Applications

- **Rotor**
  - V = 400 m/s
  - Source speed
  - Counter rotating source
  - Compensate the speed of molecules exiting to the right with supersonic speed (500 m/s) from the rotating nozzle

- **Helmholtz coils**
  - V = 100 m/s

- **Magnetic decelerator**
  - V = 5 m/s
  - Pulsed magnet

- **Nanostructured magnetic trap**

- **MCP**
  - Microchannel plate detector

- **Nanostructure**
  - Diffraction grating
Research Plans for the Future

Emergent Behavior in Magnet-Superconductor Hybrids

Project will continue for the next three years

Funding by DOE is available for 2010-2013

Cold Molecules

Project will expand from the current focus on building apparatus and chemistry to applications in physics

Funding is available for the next 1.5 years

The effect of a concept-driven revolution is to explain old things in new ways. The effect of a tool-driven revolution is to discover new things that have to be explained.

Freeman Dyson In his book Imagined Worlds
Thank you for coming