Cryogenic nano-electro-mechanical devices as model systems for classical issues in physics

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Nano-Electro-Mechanical Systems

Mesoscopic devices that can move, actuated/detected by electromagnetic means.

Quantum electronics context:
These are new components for hybrid superconducting quantum circuits

T.A. Palomaki et al., Nature Physics, 495, 210 (2013)

J. Bochmann et al., Nature Physics, 2748 (2013)

Optical photons to microwaves conversion

Microwaves state storage

Quantum memories,
Quantum interface optics/microwaves,
Quantum-enhanced sensing...

Nano-Electro-Mechanical Systems

Mesoscopic devices that can move, actuated/detected by electromagnetic means.

Quantum electronics context:
These are new components for hybrid superconducting quantum circuits

Requires mechanical object (here, top-down structures) to be:

Cooled to the quantum ground state,
To be driven and read-out at the quantum limit,
And interfaced with other systems.

Particularly demanding, ...
Nano-Electro-Mechanical Systems

Mesoscopic devices that can move, actuated/detected by electromagnetic means.

Quantum physics context:
These are unique systems dealing with the grounds of quantum mechanics.

Quantum coherence of position-states, Stochastic collapse models, Quantum gravity...

Single phonon control

Mass interferometry

Up to 6 910 amu!

C60F48
1632 amu

Stefan Gerlich et al., Nature Comm. 2, 263 (2011)


Nano-Electro-Mechanical Systems

Mesoscopic devices that can move, actuated/detected by electromagnetic means.

Quantum physics context:
These are unique systems dealing with the grounds of quantum mechanics

Proof of feasibility obtained.

Field starting today. Experimental proposals:

Addresses questions at the roots of quantum mechanics...

“The quanta of mechanics”,
See A.N. Cleland’s talk
Nano-Electro-Mechanical Systems

Mesoscopic devices that can move, actuated/detected by electromagnetic means.

Crossover quantum-to-classical context:
Besides the study of truly quantum devices, classical analogues of quantum effects

Model systems,
Pinpoint essential quantum features, ...

I. Mahboob et al., Nature Physics, 2277 (2012)
Classical sideband pumping

Classical two-level system
Nano-Electro-Mechanical Systems

Mesoscopic devices that can move, actuated/detected by electromagnetic means.

Crossover quantum-to-classical context:
Besides the study of truly quantum devices, classical analogues of quantum effects

High quality devices, high quality control demonstrated.

Can be applied to purely classical issues...

I. Mahboob et al., Nature Physics, 2277 (2012)
Nano-Electro-Mechanical Systems

Mesoscopic devices that can move, actuated/detected by electromagnetic means.

Classical context:
Mechanical nano-devices are model systems and mechanical mesoscopic probes

- Mesoscopic probes: moving mechanical objects at very small scales.

Dissipation in amorphous matter
Constitutive materials,
Surrounding fluids, ...

A. Venkatesan et al.,

C. Lissandrello et al.,
Nano-Electro-Mechanical Systems

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Classical context:
Mechanical nano-devices are **model systems** and **mechanical mesoscopic probes**

- **Mesoscopic probes**: moving mechanical objects at very small scales.

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**Importance of conduction electrons**

Constitutive materials,
Surrounding fluids, ...

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**Probing Knudsen layer**


Nano-Electro-Mechanical Systems

Mesoscopic devices that can move, actuated/detected by electromagnetic means.

Classical context:
Mechanical nano-devices are model systems and mechanical mesoscopic probes

• Model systems: simple, well-controlled devices.
  In cryogenic environment: low noise, high-Q, cryogenic vacuum.

Stochastic resonance

Mimic fundamental phenomena,

...
Nano-Electro-Mechanical Systems

Mesoscopic devices that can move, actuated/detected by electromagnetic means.

**Classical context:**
Mechanical nano-devices are *model systems* and *mechanical mesoscopic probes*.

**Application:**

- **Classical electronic components:** electro-mechanical functions. Especially with “new” materials: graphene, nanotubes, MoS$_2$

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Vincent Gouttenoire *et al.*, Small 6, 1060 (2010)

**The “nano-radio” mixing scheme**

I. Mahboob and H. Yamaguchi

**Bit storage and processing**
Nano-Electro-Mechanical Systems

Mesoscopic devices that can move, actuated/detected by electromagnetic means.

Classical context:
Mechanical nano-devices are **model systems** and **mechanical mesoscopic probes**.

Application:

• **Classical electronic components**: electro-mechanical functions. Especially with “new” materials: graphene, nanotubes, MoS₂.

Focus of the talk: fundamental aspects, not applications:

Cryogenic NEMS as **model systems**,

*In classical physics.*

Concluding remarks back on the **quantum aspects** and **mesoscopic probes**.
Nano-Electro-Mechanical Systems

Mesoscopic devices that can move, actuated/detected by electromagnetic means.

**Model systems,**
Dynamic bifurcation

Simple beam-based top-down structures.
A **mechanical material** (amorphous, crystalline) covered by **metal** (normal, superconducting) “Easy” to make, “easy” to model (almost fully analytically).
Nano-Electro-Mechanical Systems

Mesoscopic devices that can move, actuated/detected by electromagnetic means.

Model systems,
Dynamic bifurcation
Nano-Electro-Mechanical Systems

Mesoscopic devices that can move, actuated/detected by electromagnetic means.

Model systems,
Linear drive and detection
Dynamic bifurcation

Doubly-clamped

Cantilever
Nano-Electro-Mechanical Systems

Mesoscopic devices that can move, actuated/detected by electromagnetic means.

Model systems,

Linear drive and detection

Doubly-clamped

Magnetomotive scheme: applied force

\[ F_n(t) \propto I(t) \| \times B \]

Nano-Electro-Mechanical Systems

Mesoscopic devices that can move, actuated/detected by electromagnetic means.

Model systems,

Linear drive and detection

Doubly-clamped

Doubly-clamped

Cantilever

Magnetomotive scheme: detected voltage

\[ V_n(t) \propto v_n(t) \times B \]

Nano-Electro-Mechanical Systems

Mesoscopic devices that can move, actuated/detected by electromagnetic means.

**Model systems**,

- Linear drive and detection
- Dynamic bifurcation
- Non-linear tuning

Doubly-clamped

Cantilever
Nano-Electro-Mechanical Systems

Mesoscopic devices that can move, actuated/detected by electromagnetic means.

Model systems,
- Linear drive and detection
- Non-linear tuning
- Dynamic bifurcation

Capacitive scheme: D.C. tuning of frequency & nonlinearity $\delta k(t) \propto V_g^2$

Nano-Electro-Mechanical Systems

Mesoscopic devices that can move, actuated/detected by electromagnetic means.

Model systems,

Linear drive and detection

Doubly-clamped

Capacitive scheme: D.C. tuning of frequency & nonlinearity $\delta k(t) \alpha V_g^2$


Non-linear tuning

Extremely broad dynamic range can be explored.

From linear to highly non-linear regime,
Dynamics can be quantitatively characterized,

Nano-Electro-Mechanical Systems

Mesoscopic devices that can move, actuated/detected by electromagnetic means.

Model systems,

Dynamic bifurcation
Modeling bifurcation phenomena

Bifurcation: switching from a metastable state to a stable one is of ubiquitous interest.

H. A. Kramers, Physica (Utrecht) 7, 284 (1940)

Chemical reactions

\[ e^{-\frac{E_A}{k_BT}} \]

First order phase transitions:

e.g. nucleation of bubbles in water


Thermal escape of a Josephson junction
Modeling bifurcation phenomena

Similarly, in **dynamic systems**: Equivalent situation in the “rotating frame”. **Universal features** depending on type of bifurcation. Here, saddle-node.

R-f driven Josephson junction


**Mechanical bistable nonlinear oscillators**

**Complex nonlinear dynamics and chaos**

Modeling bifurcation phenomena

Similarly, in **dynamic systems**: Equivalent situation in the “rotating frame”. **Universal features** depending on type of bifurcation. Here, saddle-node.


Mechanical bistable nonlinear oscillators

For Nano-mechanics, **simple** artificial devices with:

\[ \text{Bifurcation rate } \Gamma \ll \text{Decay rate } \Delta f \ll \text{Resonance frequency } f_0 \]

\[ \text{Hz} \ll \text{kHz} \ll \text{MHz} \]

Here, **unique tunable** goalpost structure:

3 decades in excitation force \( F(t) \)

Tunable nonlinearity through gate voltage term in \( \delta k(t) \)
Modeling bifurcation phenomena

Dynamic bifurcation with a **Duffing nonlinear resonator**.

Harmonic (driven) oscillator:

\[ m \ddot{x}(t) + 2\Lambda_1 \dot{x}(t) + (k_0) x = F_{mag} \cos(\omega t) \]

Flexural mode state: \( x = x_0 \cos(\omega t + \phi) \)

- **Voltage (V)**
  - X, Y the two quadratures (lock-in)
  - \( X = x_0 \cos(\phi) \)
  - \( Y = -x_0 \sin(\phi) \)

3 µm feet
150 nm thick

Cantilever-type very linear.

Here, 100 nm deflection
Modeling bifurcation phenomena

Dynamic bifurcation with a Duffing nonlinear resonator.

Duffing oscillator with gate voltage:

\[
m \ddot{x}(t) + 2 \Lambda_1 \dot{x}(t) + (k_0 + \delta k_0) x + \delta k_2 x^3 = F_{\text{mag}} \cos(\omega t)
\]

Flexural mode state: \( x = x_0 \cos(\omega t + \phi) \)
Modeling bifurcation phenomena

Dynamic bifurcation with a **Duffing nonlinear resonator**.

Tune the “Duffing” non-linearity: 
Freq. shift & Duffing, $\alpha V_g^2$

$$m \ddot{x}(t) + 2\Lambda_1 \dot{x}(t) + (k_0 + \delta k_0) x + \delta k_2 x^3 = F_{mag} \cos(\omega t)$$

Flexural mode state: $x = x_0 \cos(\omega t + \phi)$

In the hysteretic region, two (dynamic) states coexist.
Modeling bifurcation phenomena

Dynamic bifurcation with a **Duffing nonlinear resonator**.

Tune the “Duffing” non-linearity:

\[ m \ddot{x}(t) + 2 \Lambda_1 \dot{x}(t) + (k_0 + \delta k_0) x + \delta k_2 x^3 = F_{mag} \cos(\omega t) \]

Flex. mode state: \( x = x_0 \cos(\omega t + \phi) \)

Stochastic, exponential decay

\[ \delta \omega = \frac{\Gamma_0}{2\pi} \]

\[ E_a = \eta \delta \omega \xi \]

\[ \Gamma = \Gamma_0 e^{-\frac{E_a}{I_N}} \]
Modeling bifurcation phenomena

Dynamic bifurcation with a **Duffing nonlinear resonator**.

Tune the “Duffing” non-linearity:

\[ m \ddot{x}(t) + 2 \Lambda_1 \dot{x}(t) + \left( k_0 + \delta k_0 \right) x + \delta k_2 x^3 = F_{mag} \cos(\omega t) + f(t) \]

Flex. mode state: \( x = x_0 \cos(\omega t + \phi) \)

Residence time experiment:

After 1000 switches

\[ N = N_0 e^{-\Gamma t} \]

\[ \Gamma_0 = \lambda \delta \omega^\zeta \]

\[ E_a = \eta \delta \omega^\xi \]

\[ \Gamma = \Gamma_0 e^{-\frac{E_a}{I_N}} \]
Modeling bifurcation phenomena

Dynamic bifurcation with a **Duffing nonlinear resonator**.

Tune the “Duffing” non-linearity:

\[
m \ddot{x}(t) + 2 \Lambda_1 \dot{x}(t) + (k_0 + \delta k_0) x + \delta k_2 x^3 = F_{\text{mag}} \cos(\omega t) + f(t)
\]

Flex. mode state: \( x = x_0 \cos(\omega t + \phi) \)

**White noise** \( I_N \propto f(\omega) \)

\[
\Gamma_0 = \lambda \delta \omega^\zeta
\]

\[
E_a = \eta \delta \omega^\xi
\]

\[
\Gamma = \Gamma_0 e^{-\frac{E_a}{I_N}}
\]

Extract \( \Gamma \) as a function of noise: obtain \( \Gamma_0 \) and \( E_a \)
Modeling bifurcation phenomena

Dynamic bifurcation with a **Duffing nonlinear resonator**.

Scalings of parameters:

\[ \Gamma_0 = \lambda \delta \omega^\zeta \]
\[ E_a = \eta \delta \omega^\xi \]

But also as a function of \( \delta k_2 \):

\[ \lambda \propto \delta k_2^\gamma \]
\[ \eta \propto \delta k_2^\mu \]

Slow amplitude \( z(t) \), two components:

\[ x(t) = z(t)e^{i\omega t} + z(t)^*e^{-i\omega t} \]

\[ z = \sqrt{3}\frac{\delta k_2/m}{\Delta \omega} (u + i \nu) \]

Normalized bias parameters:

\[ \Omega = 2|\omega - \omega_0| / \Delta \omega, \quad \Omega_b = 3\frac{\delta k_2}{m}\left(\frac{F_{mag}}{m}\right)^2 / (4\omega^2 \Delta \omega^2) \]

Theoretically, universal scaling \( \xi = 3/2, \zeta = 1/2 \)

Predicted \( \gamma = +1/2, \mu = -5/2 \)

- M.I. Dykman et al., PRE 49, 1198 (1994)

Exponential law valid for \( E_a/I_N >> 1 \),

"Dykman" == simple 1D theory of escape

Fokker-Planck problem is 2D
with real and imaginary parts \( u(t) \) and \( v(t) \).

1D valid only very close (but away to be exponential) from bifurcation point!

O. Kogan, arXiv:0805.0972v2
Modeling bifurcation phenomena

Dynamic bifurcation with a **Duffing nonlinear resonator**.

Scalings of parameters:

\[ \Gamma_0 = \lambda \delta \omega^\zeta \quad E_a = \eta \delta \omega^\xi \]
\[ \lambda \alpha \delta k_2^\gamma \quad \eta \alpha \delta k_2^\mu \]

Theoretically, universal scaling \( \xi=3/2, \zeta=1/2 \)
Predicted \( \gamma=+1/2, \mu=-5/2 \)

Measurements for 5 different \( \delta k_2 \), each with about 3 detunings and 3 noise levels, from within to far outside 1D “Dykman” range!

Modeling bifurcation phenomena

Dynamic bifurcation with a **Duffing nonlinear resonator**.

Scalings:

\[
\Gamma_0 = \lambda \delta \omega \zeta
\]

\[
\lambda \alpha \delta \omega \zeta
\]

**First quantitative agreement** theory/experiment extracting pseudo-potential parameters (10 % on noise calibration)

Modeling bifurcation phenomena

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First measurement with respect to \( \delta k^2 \)

First measurement of \( \Gamma_0 \)

Modeling bifurcation phenomena

Dynamic bifurcation with a **Duffing nonlinear resonator**.

Scalings of parameters:

\[ \Gamma_0 = \lambda \delta \omega \zeta \]
\[ E_a = \eta \delta \omega \xi \]

**Theoretically, universal scaling**

\[ \xi = \frac{3}{2}, \quad \zeta = \frac{1}{2} \]

**Predicted**

\[ \gamma = \frac{1}{2}, \quad \mu = -\frac{5}{2} \]

Measurements for 5 different \( \delta k^2 \), each with about 3 detunings and 3 noise levels, from within to far outside 1D “Dykman” range!

Dynamic bifurcation with a Duffing nonlinear resonator. First quantitative agreement theory/experiment extracting pseudo-potential parameters (10 % on noise calibration)

First measurement with respect to \( \delta k^2 \)

First measurement of \( \Gamma_0 \)

Amazingly, scalings of \( E_a \) far beyond the validity range!

Some property of Duffing oscillator, or more universal?

O. Kogan, arXiv:0805.0972v2
Modeling bifurcation phenomena

Dynamic bifurcation with a **Duffing nonlinear resonator**.

Scalings:

\[ \Gamma_0 = \lambda \delta \omega \zeta \]
\[ \lambda \alpha \delta \kappa^2 \gamma \eta \alpha \delta \kappa^2 \mu \]

First quantitative agreement theory/experiment extracting pseudo-potential parameters (10% on noise calibration)

First measurement with respect to \( \delta k_2 \)

First measurement of \( \Gamma_0 \)

Amazingly, scalings of \( E_a \) far beyond the validity range!

**Some property of Duffing oscillator, or more universal?**

O. Kogan, arXiv:0805.0972v2

**Intrinsic frequency-noise...**

e.g. Y. Zhang et al., PRL 113, 255502 (2014)

Classical decoherence and \( T_1, T_2 \) measurements

B.H. Schneider et al., Nature Com. 5, 5819 (2014)
Outcomes

An example of NEMS results on fundamental **classical issues**.

**Model systems**,  
Dynamic bifurcation  
**Quantitative match – extended validity range scalings**

M. Defoort *et al.*, PRB Rapid Com. accepted (2015)
Perspectives

Pushing to the lowest achievable temperatures. Beyond the classical aspects...

- **Ground-state cooling**,
  “Brute force” cooling of “big” structures, state-of-the-art cryogenics

  Today \( T \approx 15 \text{ mK} \); tomorrow \( T \leq 1 \text{ mK} \)

  European Microkelvin Platform

- **Quantum Fluids & Solids probes**,
  Mesoscopic lengthscale at reach

  New quantum states, topological matter

  Edge states, well defined order parameter

  \( ^3\text{He-B} \) (almost) ideal medium


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Happy birthday Quantronics!
30, that’s young!!

& the Microkelvin collaboration
Nano-Electro-Mechanical Systems

Mesoscopic devices that can move, actuated/detected by electromagnetic means.

- **Model systems**,  
  Dynamic bifurcation
- **Mesoscopic probes**,  
  Boundary layer in fluid
Mesoscopic mechanical probes

Micro and nano-flows. **Boundary layer problem.**

**Bulk, laminar**

Maxwellian distribution velocities, Newtonian fluid viscosity

**Boundary, laminar**

Knudsen layer:
Non-Maxwellian distribution velocities, Non-Newtonian fluid viscosity, Slippage, reduced effective viscosity
Mesoscopic mechanical probes

Micro and nano-flows. **Boundary layer problem.**

A growing literature on **micro/nano fluidics.**


Technological implications, and **fundamental questions:**

Structure of boundary layer?


... and (few) experiments.

Mesoscopic mechanical probes

Micro and nano-flows. **Boundary layer problem.**

Local nano-probes: **oscillatory flows from nano-resonators.**

Bulk, laminar

![Graph showing quality factor vs. N, gas pressure (ton)].

Boundary, laminar

![Diagram illustrating boundary layer problem with labels: velocity (v), radius (R), gap (z), gas pressure (F), dither, optical fiber, goldened sphere, Au plane].


Cross-over between Navier-Stokes and molecular regimes observed.

Efficient probes, but: pressures not low enough ($l_{mfp}$ too small), too big structures, too complex setup (room T, Air)…
Mesoscopic mechanical probes

Micro and nano-flows. **Boundary layer problem.**

Local nano-probes: **oscillatory flows from nano-resonators.**

**String nano-mechanical resonator**
in $^4$He gas at 4.2 K. Aspect ratio 1 000.

“Very simple” setup.
Paradigm of the (almost) **ideal gas.**
Properties tabulated (NIST,...)

Out-of-plane motion,
Width & thickness & displacement **small**

100 nm x 100 μm SiN beam
Mesoscopic mechanical probes

Micro and nano-flows. **Boundary layer problem.**

Local nano-probes: oscillatory flows from nano-resonators.

**String nano-mechanical resonator**
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“Very simple” setup.
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Properties tabulated (NIST, ...)

- **Width (Hz)**
- **P (Torr)**

Cross-over viscous to ballistic

Modes:
- **mode #1**
- **mode #3**
- **mode #5**
- **intrinsic #1**
- **radiative #1 (est.)**

$\ell_{\text{mfp}} = 4 \mu m$


100 nm x 100 µm SiN beam

$10^{-3}$ $10^{-2}$ $10^{-1}$ $10^{0}$ $10^{1}$ $10^{2}$

$10^{0}$ $10^{1}$ $10^{2}$ $10^{3}$ $10^{4}$ $10^{5}$
Mesoscopic mechanical probes

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Local nano-probes: oscillatory flows from nano-resonators.

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“Very simple” setup. Paradigm of the (almost) ideal gas. Properties tabulated (NIST,...)

![Image](image.png)

100 nm x 100 μm SiN beam

Cross-over viscous to ballistic

**Power law disappearance:** Signature of Knudsen layer

Mesoscopic mechanical probes

Micro and nano-flows. **Boundary layer problem.**

Local nano-probes: **oscillatory flows from nano-resonators.**

**String nano-mechanical resonator** in $^4$He gas at 4.2 K. Aspect ratio 1 000.

“Very simple” setup. Paradigm of the (almost) ideal gas.

Properties tabulated (NIST, …)

First **NEMS** local measurement in boundary layer of an almost ideal gas.

Present theories are not sufficient to fit data...

Cross-over viscous to ballistic

$\text{P (Torr)}$

$10^{-2}$ $10^{-1}$ $10^{0}$ $10^{1}$

$100 \text{ nm x 100 } \mu \text{m SiN beam}$