(classical) force without any fundamental quantum limit.

The experiment by Mercier de Lépinay *et al.* explicitly demonstrated this idea using an optomechanical scheme first analyzed in (*9*). The unusual QMFS dynamics of the two mechanical membranes is realized by driving the circuit with four distinct microwave control tones, each at a different slightly detuned frequency. The net result is an effective single harmonic oscillator encoded in collective variables of the two physical vibrating membranes that can be measured without any degradation from quantum back action. Indeed, they achieved a measurement precision better than the SQL. Their technique allows for a complete measurement of the effective mechanical motion without a back action limit in both the sine and cosine quadratures of the motion. Previous work protected only one quadrature of the mechanical motion from back action (*10*–*12*), could not measure both protected collective quadratures (*13*), or coupled a mechanical resonator to an atomic ensemble (*14*).

Mercier de Lépinay *et al.* also show that their technique can be used to generate entanglement. By slightly breaking the conditions needed for a perfect QMFS measurement, the circuit realizes an effective autonomous measurement-plus-feedback operation that correlates and ultimately entangles the motions of the two vibrating drumheads. This approach can both generate and stabilize an entangled state as long as the circuit is energized. The method here is complementary to that of Kotler *et al.*, which does not stabilize an entangled state but has the advantage of being a true entangling quantum gate that preserves information in the initial mechanical state.

Beyond demonstrating direct evidence of quantum entanglement and measurement beyond the conventional limits imposed by the quantum back action for macroscopic objects, the advanced techniques developed by both groups could have a broader impact. The pulsed unitary entangling operation by Kotler *et al.* could be used as logic gates for quantum computation with continuous variables, and the collective measurement process by Mercier de Lépinay *et al.* could be combined with entanglement to enable new kinds of enhanced measurements. The refined microwave optomechanical devices of both groups could be used to faithfully convert quantum information between different physical platforms (*13*). Apart from practical applications, these experiments address how far into the macroscopic realm experiments can push quantum phenomena. ■

REFERENCES AND NOTES

1. S. Kotler *et al.*, *Science* **372**, xxx (2021).
2. L. Mercier de Lépinay, C. F. Ockelen-Korppi, M. J. Woolley, M. A. Sillanpää, *Science* **372**, yyy (2021).
3. M. Aspelmeyer, T. J. Kippenberg, F. Marquardt, *Rev. Mod. Phys.* **86**, 1391 (2014).
4. C. F. Ockeloen-Korppi *et al.*, *Nature* **556**, 478 (2018).
5. R. Riedinger *et al.*, *Nature* **556**, 473 (2018).
6. V. B. Braginsky, F. Ya Khalili, K. S. Thorne, *Quantum Measurement* (Cambridge Univ. Press, 1992).
7. M. Tsang, C. M. Caves, *Phys. Rev. X* **2**, 031016 (2012).
8. E. S. Polzik, K. Hammerer, *Ann. Phys*. **527**, A15 (2015).
9. M. J. Woolley, A. A. Clerk, *Phys. Rev*. A **87**, 063846 (2013).
10. J. Suh *et al.*, *Science* **344**, 1262 (2014).
11. F. Lecocq, J. B. Clark, R. W. Simmonds, J. Aumentado, J. D. Teufel, *Phys. Rev. X* **5**, 041037 (2015).
12. I. Shomroni, L. Qiu, D. Malz, A. Nunnenkamp, T. J. Kippenberg, *Nat. Commun*. **10**, 2086 (2019).
13. C. F. Ockeloen-Korppi *et al.*, *Phys. Rev. Lett*. **117**, 140401 (2016).
14. C. B. Møller *et al.*, *Nature* **547**, 191 (2017).
15. A. A. Clerk, K. W. Lehnert, P. Bertet, J. R. Petta, Y. Nakamura, *Nat. Phys*. **16**, 257 (2020).

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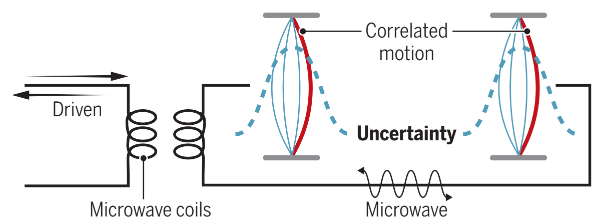
Quantum effects writ large

Two studies use microwave-drive membranes to demonstrate quantum-mechanical effects of macroscopic objects.

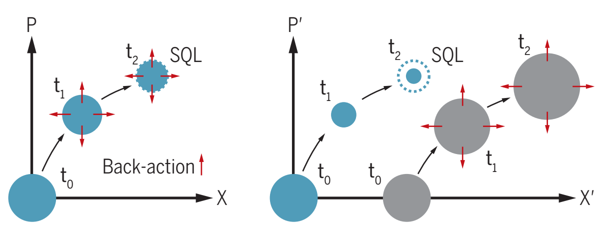
Entangled positions

Kotler et al. showed that unlike the position X and momentum P of unentangled oscillators (with fundamental uncertainty shown in blue), entangled oscillators had strongly correlated motion (red).



Beating back-action limits

(Right) Uncertainty in the oscillator's motion (shaded area) is reduced by measurement over times *t* but could not beat the standard quantum limit (SQL, dashed circle). (Left) Mercier de Lepinay *et al.* moved quantum backaction into a second, unmeasured effective oscillator whose uncertainty grows (gray shaded area) so that X' and P' (blue) beat the SQL.



CORONAVIRUS

Rapid antigen testing in COVID-19 responses

SARS-CoV-2 transmission was reduced with measures centered on rapid antigen testing

By **Marta García-Fiñana** *and* **Iain E. Buchan**

The value of rapid antigen testing of people (with or without COVID-19 symptoms) to reduce transmission of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) has been discussed extensively (*1*–*5*) but remains a topic of policy debates (*6*, *7*). Lateral flow devices (LFDs) to test for SARS-CoV-2 antigen are inexpensive, provide results in minutes, and are highly specific (*2*–*4*), and although less sensitive than reverse transcriptase polymerase chain reaction (RT-PCR) tests to detect viral RNA, they detect most cases with high viral load (*2*, *3*, *8*), which are likely the most infectious (*8*, *9*). Successful mass testing relies on public trust, the social and organizational factors that support uptake, contact tracing, and adherence to quarantine. On page XXX of this issue, Pavelka *et al.* (*10*) report the substantial reduction in transmission that population-wide rapid antigen testing had, in combination with other measures, in Slovakia.

Slovakia ran mass testing interventions from the last week of October to the second week of November 2020, with 65% of the target populations taking rapid antigen tests. Testing started in the four counties with the highest rates of infection, continued with national mass testing, then was followed up with more testing in high-prevalence areas. Nasopharyngeal swabs for the LFDs were taken by clinical staff, not self-administered. Sample quality and test accuracy are higher with tests taken by health professionals (*3*). Although the specific impact of Slovakia's mass testing could not be disentangled from

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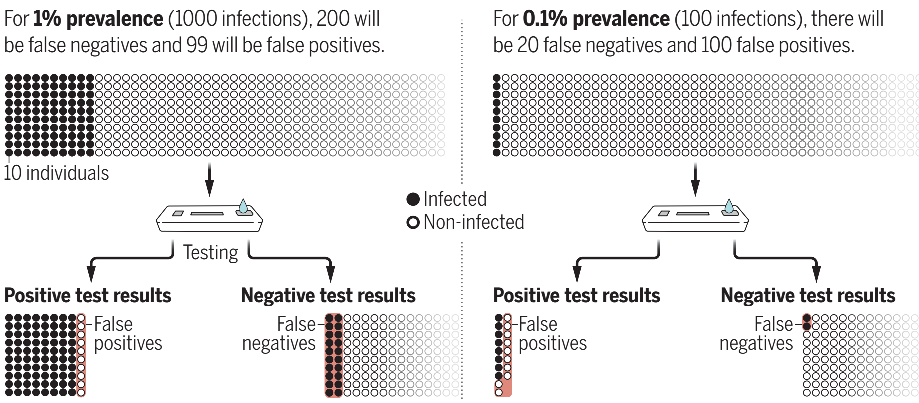
the contribution of other concurrent control measures (including closure of secondary schools and restrictions on hospitality and indoor leisure activities), statistical modelling by Pavelka *et al.* estimated a 70% reduction in the prevalence of COVID-19 cases compared with unmitigated growth.

The UK piloted mass testing in Liverpool in November 2020 after the city experienced the highest COVID-19 prevalence in the country. Slovakia applied more pressure on its citizens to get tested than did Liverpool, by requiring anyone not participating in mass testing to quarantine. The Liverpool testing uptake was consequently lower than Slovakia's, involving 25% of the population in 4 weeks. Liverpool's public health service valued the testing as an additional control measure, but impacts were limited by lack of support for those in socioeconomically deprived areas facing income loss from quarantine after a positive test (*2*): in 100 positive test results are false). In absolute terms, however, if testing 100,000 people, these scenarios would result in 99 false positives (out of 899 positive results) and 100 false positives (out of 180 positive results) for 1% and 0.1% prevalence, respectively (see the figure). Confirmatory RT-PCR tests after a positive LFD test result was recently reintroduced by Public Health England because of both the low positive predictive values of testing at low prevalence and the utility of reusing PCR samples for viral genetic sequencing in variant surveillance (*13*).

The pilot in Slovakia was conducted while the prevalence was still high (3.9%). Rapid antigen testing was used as an additional tool to identify a substantial proportion of asymptomatic SARS-CoV-2–infected individuals, who were required to quarantine. Additionally, those who did not agree to take part in testing were required to quarantine,

Predictive value of testing changes with prevalence

Based on tests of 100,000 individuals with a lateral flow device with 80% sensitivity and 99.9% specificity, the proportion of false positive and false negative test results will vary according to the prevalence of COVID-19 cases.



Test positivity rates were highest and testing uptake lowest in the most deprived areas (*2*, *11*). Similar socioeconomic barriers were reported for test uptake among care home staff (*12*). This highlights the importance of addressing public perceptions of testing and support for low-income workers to quarantine when implementing mass testing.

The predictive value of testing varies with the population prevalence of infection and phase of the epidemic curve (*7*). As the prevalence of SARS-CoV-2 infections decreases, the proportion of false-positive test results increases, whereas the number of false-negative test results decreases. For example, with 99.9% specificity (proportion of noninfections that the test rejects) and 80% sensitivity (proportion of infections that the test detects), the positive predictive value (proportion of people with a true-positive result) is 89% when the prevalence is 1%, and it drops to 45% at 0.1% prevalence (55

thus reducing the chance of transmission among those who were permitted to mix. At higher prevalence of COVID-19, more infections can be identified, but the proportion of false-negative tests is also higher, so the reliance on other control measures is greater. No matter what the prevalence, mass testing regimes can only properly be considered amid other health protection measures.

By the end of the mass testing program in Slovakia, rapid antigen tests had identified more than 50,000 people without COVID-19 symptoms who were likely contagious with SARS-CoV-2. UK mass testing pilots in Liverpool and also in Wales that started at a similar time as the pilot in Slovakia, but with fewer pressures to take part, identified more than 4000 asymptomatic cases in the Cheshire and Merseyside region around Liverpool (*14*) and more than 700 in Wales (*15*). Although the testing technology was equivalent across Slovakia, England, and Wales, the interventions were different, spanning a variety of population prevalence, phases of the epidemic curve, surges of new variants, periods of lockdown, periods of reopening of large-scale social mixing, and targeting of testing. For example, the Liverpool project shifted in public messaging from "Let's All Get Tested" to "Test Before You Go" to "Testing Our Front Line" (for anyone having to leave home to go to work in lockdown).

In places with low SARS-CoV-2 prevalence, mindful of the cumulative harms from COVID-19 restrictions, the emphasis is on restarting social and economic activities while minimizing infections. As research continues to clarify the impact of vaccines on SARS-CoV-2 transmission, there is a need to use rapid antigen testing as a part of comprehensive public health measures that reduce the risk of the virus escaping vaccine or natural immunity through avoidable transmission—for example, testing to secure workplaces and large events as societies reopen after lockdowns. Successful implementation, however, depends on public participation in testing and adequate support to quarantine. ■

REFERENCES AND NOTES

1. Z. Kmietowicz, *BMJ* **372**, n81 (2021). 10.1136/bmj.n81
2. I. Buchan *et al.*, Liverpool COVID-19 community testing pilot. Interim evaluation report. 2020 (University of Liverpool, 2020); www.gov.uk/government/publications/liverpool-covid-19-community-testing-pilot-interim-evaluation-report-summary.
3. T. Peto *et al.*, *medRxiv* 10.1101/2021.01.13.21249563 (2021).
4. A. Crozier, S. Rajan, I. Buchan, M. McKee, *BMJ* **372**, 208 (2021).
5. M. J. Mina, T. E. Peto, M. García-Fiñana, M. G. Semple, I. E. Buchan, *Lancet* **397**, 1425 (2021).
6. L. Y. W. Lee *et al.*, *medRxiv* 10.1101/2021.03.31.21254687 (2021).
7. R. W. Peeling, P. Olliaro, *Lancet* 10.1016/S1473-3099(21)00152-3 (2021).
8. L. Y. W. Lee *et al.*, An observational study of SARS-CoV-1 2 infectivity by viral load and demographic factors and the utility lateral flow devices to prevent transmission (Modernising Medical Microbiology, 2021); http://modmedmicro.nsms.ox.ac.uk/wp-content/uploads/2021/01/infectivity_manuscript_20210119_merged.pdf.
9. M. Marks *et al.*, *Lancet Infect. Dis.* (2021). 10.1016/S1473-3099(20)30985-3
10. M. Pavelka *et al.*, *Science* 372, XXX (2021).
11. M. A. Green *et al.*, medRxiv 10.1101/2021.02.10.21251256 (2021).
12. J. Tulloch *et al.*, *SSRN* 10.2139/ssrn.3822257 (2021).
13. S. Hopkins, Gov.UK 30 March 2021); https://publichealthmatters.blog.gov.uk/2021/03/30/covid-19-reintroducing-confirmatory-pcr-testing.
14. NHS Cheshire and Merseyside, Combined Intelligence for Population Health Action (2021): www.cipha.nhs.uk.
15. K. Nnoaham, Evaluation of the lateral flow device testing pilot for COVID-19 in Merthyr Tydfil and the lower Cynon Valley (2021); https://cwmtafmorgannwg.wales/Docs/Publications/FINAL_V2_Whole%20Area%20Testing%20Evaluation%20Full%20Report%2020210325.pdf.

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