PERSPECTIVES

PHYSICS

No vacancy in the Fermi sea

Optical transparency is increased by the Pauli principle in ultracold atom gases

By **Brian DeMarco**[1] *and* **Joseph H. Thywissen**[2]

Light scattering is one of the most effective scientific probes of matter. When light is used to investigate materials, the influence on a source, such as a laser beam, is measured. On pages 979, 972, and 976 of this issue, Sanner *et al.* (*1*), Deb and Kjaergaard (*2*), and Margalit *et al.* (*3*), respectively, report on the observation of a previously unobserved way in which the quantum exchange symmetry of neutral atoms is imprinted on the intensity and distribution of scattered photons.

The interaction of light with matter gives rise to a wide range of phenomena. For example, light can be scattered elastically from one direction into another. This effect is used in x-ray crystallography, which was used to identify the structure of DNA. Light can also scatter inelastically and change its wavelength through the Raman effect, which provides a fingerprint of the chemical composition of materials. Quantum states generate an even richer tapestry of scattering behavior that provides insights into the behavior of subatomic particles and electrons in materials.

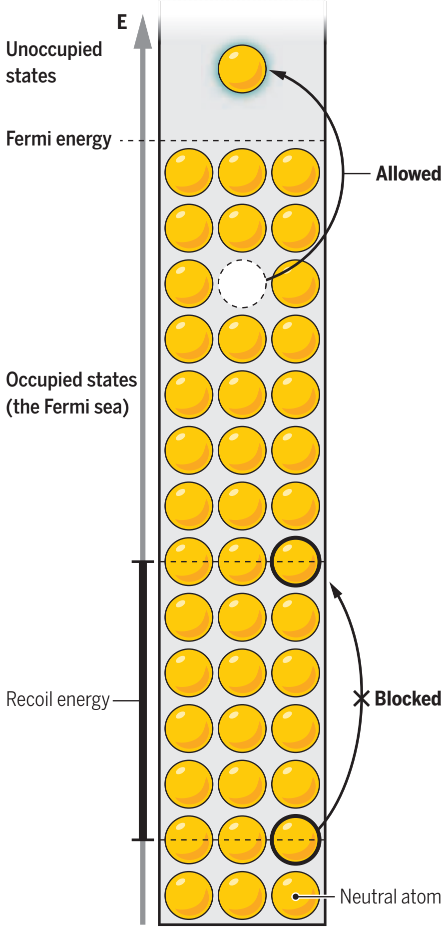
A previously unobserved quantum effect has been measured in these experiments—the Pauli exclusion principle suppressing light scattering in a gas of fermionic atoms cooled to ultralow temperatures. The Pauli principle is familiar as the rule that underlies the periodic table—no two bound electrons can occupy the same quantum state. This law is a consequence of exchange symmetry, which constrains the states of the two types of fundamental quantum particles found in the universe, bosons and fermions.

The exclusion principle applies to all collections of indistinguishable fermionic particles, including trapped gases of ultracold potassium, lithium, or strontium atoms. These atoms are composite fermions because the quantum number describing the combined spin of their neutrons, protons, and electrons is a half-integer. As in metals and neutron stars, when atomic gases are sufficiently cooled, a "Fermi sea" emerges. At absolute zero, all quantum states with an energy below the Fermi energy are occupied (see the figure).

The development of this collective quantum state changes the material properties.

Squashing light scattering

Light scattering can promote neutral atoms to a higher energy level. In a system of fermions, each quantum state can hold only one atom. This means that lower-energy atoms may not have an empty state to be excited into because all accessible states are already occupied. The net effect of this is to decrease the amount of light scattering.



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For neutron stars, this effect is drastic, and Fermi degeneracy stabilizes against gravitational collapse through quantum pressure. The impact is more subtle in ultracold atomic gases. One manifestation is the suppression of light scattering, which was proposed as a method to detect Fermi degeneracy more than 20 years ago. Light scattering is reduced in this regime because it involves recoil, or transfer of momentum and energy from the light to the atom. When the Fermi sea is full, this transfer cannot occur because the final states of the atoms are already occupied, except for a small band around the Fermi energy. The Pauli principle therefore forbids many light-scattering events.

Three research teams have now reported the observation of this effect. All three teams observed that the rate of light scattering was reduced when a trapped atomic cloud was cooled to ultracold temperatures.

Sanner *et al.*, at the JILA in Boulder, Colorado, measured the rate of light scattering from fermionic strontium (^{87}Sr). The authors observed that when a Fermi sea is formed, forward-scattered light is suppressed far more than side-scattered light. This behavior arises because atoms recoil more if they are kicked by larger-angle Rayleigh scattering and are therefore more easily able to find an empty final state outside the Fermi sea.

Deb and Kjaergaard at the University of Otago measured the extinction of light transmitted through fermionic potassium (^{40}K). The blocking effect manifests as an increased transparency of the cloud. By comparison, the transparency of a bosonic cloud of rubidium is not increased at low temperature. The exchange symmetry of bosons allows for multiple occupation of the same quantum state, so the Pauli principle should not apply. The authors also observe that the phase shift of a laser beam probe crossing the ^{40}K gas shows no signature of blocking, demonstrating that coherent processes are not Pauli suppressed.

Margalit *et al.*, at the Massachusetts Institute of Technology, studied a dense cloud of fermionic lithium (^{6}Li). The higher ratio of Fermi energy to photon recoil energy enabled them to observe stronger

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suppression of photons scattered at large angles. The authors also demonstrate the fragility of an ultracold Fermi sea, as only one photon can be detected per thousand atoms within the blocking regime. Beyond this, the phenomenon starts to fade because heating increases the number of unoccupied states, thereby increasing the available final states.

Margalit *et al.* present an alternative explanation for their observations, which can be applied to all three experimental results. Light scattering is the result of density fluctuations. For example, the white color of milk is the result of its heterogeneous density at the wavelength scale, created by a suspension of micelles. Similarly, the suppression of light scattering in these ultracold gases is the result of the sub-Poissonian density fluctuation because fermionic statistics suppress the probability that two fermions approach each other closer than their de Broglie wavelength. This "smooths out" the density of the gas. Taken to an extreme, a perfectly homogeneous material would be fully transparent.

All of the authors avoided resonant fluorescence by working with off-resonant laser light. This means that the laser wavelength was tuned far enough away from the atomic resonance so that the probability of scattering per photon was small. Using this strategy avoids the complications of multiple scattering, which is complex and has yielded its own recent surprises, such as the prediction of a maximum index of refraction through renormalization group theory ideas (*4*). However, the phenomenon as originally discussed (*5*), suppression of spontaneous emission, is yet to be observed.

The observation of a phenomenon that involves the collective quantum state of the Fermi sea is an important milestone for quantum-gas physics. Experiments can now leverage this effect as a tool to help cool, manipulate, and measure the properties of ultracold atoms in different ways. There is also the potential for using Pauli suppression of light scattering to improve the performance of atom-based quantum devices, such as optical lattice clocks and quantum network nodes. ■

REFERENCES AND NOTES

1. C. Sanner, L. Sonderhouse, R. B. Hutson, L. Yan, W. R. Milner, J. Ye, *Science* **374**, 979 (2021).
2. A. B. Deb, N. Kjærgaard, *Science* **374**, 972 (2021).
3. Y. Margalit, Y.-K. Lu, F. Ç. Top, W. Ketterle, *Science* **374**, 976 (2021).
4. F. Andreoli, M. J. Gullans, A. A. High, A. Browaeys, D. E. Chan, *Physical Review X* **11**, 011026 (2021).
5. T. Busch, J. Anglin, I. Cirac, P. Zoller, *Europhysical Letters* **44**, 1 (1998).

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NEUROSCIENCE

The head and the heart of fear

The insular cortex calibrates brain, body, and behavioral responses to danger

By **John P. Christianson**

Have you ever caught yourself speaking too loudly and quickly begin to whisper? This adjustment requires you to connect the volume of your voice, through brain commands to the vocal cords and diaphragm, with feedback through your own ears. Refinements like this occur for many behaviors and afford adaptation to a wide range of situations. On page 1010 of this issue, Klein *et al.* (*1*) investigated how and where this feedback integration occurs in response to threat. Akin to modulating our voice to be heard clearly, adjusting behavioral responses to environmental danger involves feedback integration. Insufficient reactions to danger may lead to risky behaviors, whereas overly strong reactions at times of safety would prevent exploration, feeding, or mating. The latter extreme is manifest in posttraumatic stress disorder, where feelings of dread and avoidance behaviors often prevail despite evidence of safety (*2*).

When expecting danger, animals display a combination of autonomic (e.g., changes in heart rate, breathing), behavioral (e.g., fight or flight), and cognitive (e.g., feelings of dread) responses for self-preservation. These are interrelated at the biological level such that a change in heart rate can modify behavioral and cognitive responses to danger, and vice versa. The emotional experience of fear emerges from the moment-to-moment interplay among mental appraisal and sensations from external and internal danger cues (*3*). Thus, the behavioral and mental aspects of emotion are subject to constant updating that is informed by incoming information and cognitive perceptions. The study of Klein *et al.* exposes some of the biological machinery through which the autonomic, behavioral, and mental aspects of the threat response are integrated (see the figure).

Laboratory mice were taught, or conditioned to, a danger signal through repeated presentation of a sound with a mild footshock. Subsequent presentations of the danger signal will evoke mental predictions that threat is imminent and evoke changes in heart rate and behavioral freezing. However, further presentation of the danger cue without shock violates the prediction of danger and leads to a normalization, or extinction, of cue-elicited autonomic and behavioral responses.

Searching for the neural loci wherein internal bodily states—such as heart rate, behavioral outputs (freezing), and cognition—merge, Klein *et al.* focused on the insular cortex. The insula is anatomically positioned to process visceral information (*4*), is interconnected with cortical and subcortical networks involved in executive function and behavioral control (*5*), and is implicated in the learning about danger and safety (*6*). Using optogenetics, a technology that provides temporally precise control of neural activity, the authors inhibited insula neurons during danger signals under conditions that led to either weak or strong danger learning. In mice exhibiting appropriately low freezing behavior after weak danger learning, insula inhibition increased freezing. However, in mice exhibiting appropriately high freezing after strong danger learning, insula inhibition reduced freezing. The interpretation is that the insular cortex contributes to the fine-tuning of behavioral responses to match the level of expected danger.

Cognitive and behavioral responses to danger cues are influenced by internal states, including heart rate. Central regulation and sensitivity to heartbeat is mediated by atrial baroreceptors (blood pressure sensors) that convey signals through the vagus nerve to the brainstem and, ultimately, to the insular cortex (*7*). Klein *et al.* hypothesized that in response to danger signals, information about heart rate and behavioral freezing might be integrated in the insula where it could be used to update or adjust danger responses. A key innovation in this study involved simultaneous recording of heart rate and insular cortex neuronal activity during danger learning and extinction. As with behavioral freezing and heart rate, insula neurons responding to the danger cue increased with sound-shock pairings, then reduced during extinction. Notably, the activity of insular neurons in response to the danger cue correlated closely with variations in heart rate. Synthetic stimulation of the vagus nerve to scramble in-

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