JOSEPHSON PLASMONS

# The new wave

Electromagnetic waves below the plasma frequency usually reflect off a metal. A theory now suggests that a nonlinear Josephson plasma wave — an excitation in an anisotropic superconductor — can propagate below the plasma frequency.

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The Josephson effect, a strange visitor from the microscopic quantum world to our classical macroworld, has always had a particular attraction for physicists. It is at once esoteric — a manifestation of spontaneous breaking of a $U(1)$ gauge symmetry — and down to earth, observable by simply pressing together two pieces of rusty niobium. A proposal by Savel'ev *et al.,* on page 521 of this issue[1], that electromagnetic waves interacting with Josephson currents could open an unexpected realm of nonlinear optics resonates with both aspects of the Josephson effect.

Brian Josephson himself was intrigued by the broken symmetry viewpoint, introduced to him by Phil Anderson's lectures at Cambridge in 1961 (ref. 2). The symmetry that is broken is the phase of the wavefunction, which fluctuates wildly in a normal metal as electrons scatter from each other and from phonons. The normal metal becomes a superconductor when the wavefunction locks into a single phase throughout the entire chunk of metal, that is, the $U(1)$ symmetry is spontaneously broken. Fascinated by the intellectual appeal of this idea, Josephson considered how such an effect might actually be observed. He realized that although symmetry restrictions rule out the possibility to observe the absolute phase of an isolated piece of superconductor, the phase difference $\varphi$ between two superconductors could in principle be observed. The key is to establish a 'weak link' (or Josephson junction): two superconductors coupled strongly enough to allow Cooper pairs to tunnel between them, but sufficiently weakly such that a non-zero $\varphi$ can be created by external fields and currents. The coupling energy ($E_J$) will be periodic in $\varphi$, for example, $-E_J(1-\cos\varphi)$, because observables are invariant under the substitution $\varphi \rightarrow \varphi + 2\pi \times$ (integer).

The Josephson plasma resonance that is the basis of the proposal by Savel'ev and co-workers[1] comes into play when we consider the fluctuations of $\varphi$ about its equilibrium value of zero. The other key insight

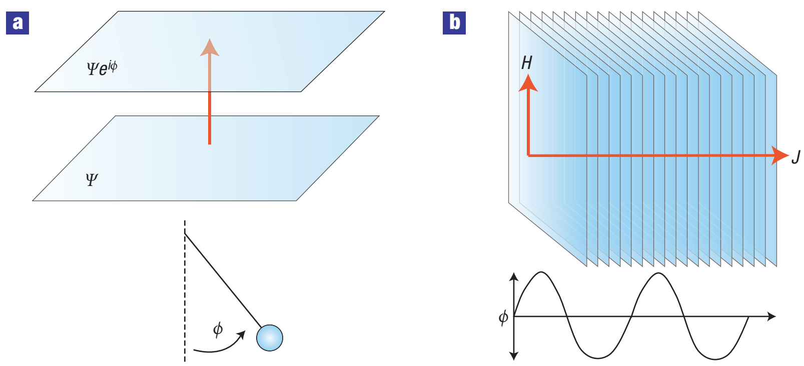


**Figure1** Stacked in our favour. **a**, A Josephson junction consists of two superconductors, coupled such that the Cooper-paired electrons can tunnel from one layer to the other. The dynamics of the relative phase $\varphi$ of the wavefunction $\Psi$ of the two superconductors obeys the same equations of motion as the angular displacement of the simple pendulum, pictured below the superconductors. For small departures from the equilibrium position, the phase oscillates at the Josephson frequency, the geometric mean of the charging energy and the coupling energy. (Adapted from http://www.princeton.edu/~npo/JosephsonPlasma.html.) **b**, A stack of superconducting layers makes a 'Josephson medium' that can support running waves of the superconducting phase. The pendulum-like restoring force causes the frequency of the waves to decrease as the amplitude increases, leading to a wide variety of nonlinear phenomena. *H* and *J* indicate the direction of magnetic field and current of a plane Josephson plasma wave propagating perpendicular to the sack.

in Anderson's lectures was that the number of Cooper pairs, $n$, is the conjugate variable to $\varphi$. Hamilton's equations of motion for $n$ and $\varphi$ then lead directly to the celebrated Josephson relations: $\hbar\dot{n} = \partial E/\partial\varphi$ and $\hbar\dot{\varphi} = -\partial E/\partial n$, where $E$ is the junction energy. According to the second of these relations, if $E$ is independent of $n$, $\varphi$ has no intrinsic dynamics. However, superconductors are charged condensates, and this property makes all the difference. Changing $n$ means exchanging charge $-(2e)n$, raising the energy by $(2en)^2/2C$, where $C$ is the junction capacitance. Suddenly the hamiltonian for a simple pendulum comes into view (Fig. 1a), with $\varphi$ as the angular displacement, and $E_J$ and $C^{-1}$ in the roles of gravitational potential and mass, respectively. For small $\varphi$ we have a simple harmonic oscillator (SHO), and a pretty result is that the natural oscillation frequency is the geometric mean of the charging energy $(2en)^2/2C$ and $E_J$.

A simple Josephson junction geometry is represented by two parallel sheets of a superconductor (Fig. 1a) separated by a distance $d$. In their paper, Savel'ev *et al.*[1] ask us to consider a Josephson medium, an infinite array of such sheets (Fig. 1b). The degrees of freedom of the Josephson medium are the phases on each superconducting sheet, or $\varphi_n$, and the normal modes are waves of phase oscillation that run up and down the stack. When the wavelengths are much longer than $d$, the frequency of the Josephson waves, $\Omega_J$, is very nearly the same as the frequency of a simple bilayer junction. Most importantly, there are no modes below $\Omega_J$; light with frequency $\omega < \Omega_J$ can't get inside the Josephson medium, as there are no propagating modes to excite. With the benefit of far-infrared vision we would see perfect metallic reflection setting in for frequencies less than $\Omega_J$.

Savel'ev *et al.*[1] point out that for frequencies near $\Omega_J$, wave propagation in the Josephson medium is exquisitely sensitive to amplitude. To see why, consider the pendulum analogy. As the pendulum swings with greater amplitude it explores more fully the difference between its $\cos\varphi$ potential and the parabolic potential well of the SHO. The larger the amplitude, the softer the effective restoring force, leading to a reduction in $\Omega_J$. If we tune a source to $\omega$ just below $\Omega_J$ and crank up the amplitude, Savel'ev *et al.* predict that we can turn a reflected wave into a transmitted one — a massive optical nonlinearity. They further predict that a host of other nonlinear optical effects, such as self-focusing, slowing down of light and optical bistability, will all occur under similar conditions of excitation.

In providing a test bed for these ideas, nature has been kind in providing high-$T_c$ copper oxide superconductors, the crystal structure of which happens to be a realization of the Josephson medium. Sharp features in the far-infrared[3,4] and microwave[5] regions of the spectrum were observed in the early days of high-$T_c$ research, and identified as Josephson resonances[6–8] soon after. Nature being kinder still, a quirk of their electronic band-structure forbids normal electrons (quasiparticle excitations) from propagating between planes. Ohmic dissipation from normal electrons would dampen the Josephson plasmon, broaden its linewidth and prevent us from tuning close to resonance. Thus it is possible that the effects predicted by Savel'ev and co-workers could actually be observed. However, the technological application of these effects will probably await nature's ultimate beneficence, in the form of a room-temperature superconductor.

**REFERENCES**

1. Savel'ev, S., Rakhmanov, A. L., Yampol'skii, V. A. & Nori, F. *Nature Phys.* **2,** 521–525 (2006).
2. Josephson, B. D. *The Discovery of Tunnelling Supercurrents* (Nobel Lecture, 1973).
3. Noh, T. W., Kaplan, S. G. & Sievers, A. J. *Phys. Rev. Lett.* **62,** 599–602 (1989).
4. Collins, R. T., Schlesinger, Z., Holtzberg, F. & Feild, C. *Phys. Rev. Lett.* **63,** 422–425 (1989).
5. Tsui, Ophelia K. C., Ong, N. P., Matsuda, Y., Yan, Y. F. & Peterson, J. B. *Phys. Rev. Lett.* **73,** 724–727 (1994).
6. Shibauchi, T., Kitano, H., Uchinokura, K., Maeda, A., Kimura, T. & Kishio, K. *Phys. Rev. Lett.* **72,** 2263–2266 (1994).
7. Basov, D. N., Timusk, T., Dobrowski, B. & Jorgensen J. D. *Phys. Rev. B* **50,** 3511–3514 (1994).
8. Ophelia, K. C., Tsui, N. P., Ong, Y. & peterson, J. P. *Phys. Rev. Lett.* **76,** 819–822 (1996).