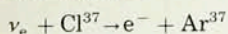


From neutrinos to quasiparticles

Leo P. Kadanoff

This column is about a particularly elegant idea for an experiment in neutrino physics. Of course any observation of neutrinos is a wonderful accomplishment. But the proposed experiment to be discussed here has the further charm that it makes essential use of the quantum mechanical properties of low-temperature matter. The matter, in this case, is liquid helium, and the experiment will rely on low-lying quantum excitations (called quasiparticles) as messengers to carry the energy transferred from the neutrinos to the helium.

A now classical experiment of Raymond Davis and coworkers sees solar neutrinos in a 600-ton vat of cleaning fluid via the reaction



Roughly one argon atom is produced every two days. The Ar^{37} , having a half-life of 35 days, is essentially not present in nature and hence the few atoms that are produced can be detected. These experiments have measured a solar neutrino flux a factor of three lower than predicted, thereby stimulating a considerable reexamination of solar and weak-interaction theories.

The next generation of neutrino experiments, now being planned and proposed, will measure the neutrino arrival time much more precisely. The observation of neutrinos produced by the recent supernova has pointed up the importance of good time resolution (see the article by David Helfand on page 24). (The end products of neutrino interaction were seen in Cerenkov radiation detectors originally designed to study proton decay.) Arrival time data from these observations were used to estimate the neutrino mass. Unfortunately the chlorine conversions are unsuitable for a time-resolved experiment simply because the argon atoms

produced cannot travel through the container rapidly enough. Their typical speed of about 300 meters per second would certainly be fast enough if they moved in a straight line. But they are in a liquid, so every few angstroms they bump into another molecule and change direction. The resulting tortuous path, called a random walk, then demands a very long time to achieve a reasonable displacement. For example, a time on the order of a month is required for the atom to move 1 meter away from its starting position. Given this time constant, the actual collection cannot utilize the natural motion of the argon atoms. Instead, at intervals, helium gas is bubbled through the fluid for 20 hours or so. The argon is caught in the helium and then detected. However, space and time resolution is lost in this collection process.

Several groups have been seeking a new approach to solar neutrino detection. One requirement is that the neutrinos produce an end product that will move directly and without substantial decay or delay to a detector. The proposal I'm writing about, by Robert Lanou, Humphrey Maris and George Seidel, is for a detection method based on the observation of rotons in liquid helium.¹ In a recent colloquium talk, I heard Blas Cabrera list eight different proposed detection schemes. I do not have any way of knowing which one is preferable. But I do wish to use this roton proposal as a device to discuss a fundamental idea from condensed matter physics, the idea of a quasiparticle.

Imagine any quantum system held at a temperature low enough that the energy of a typical excitation, kT , will be much lower than any characteristic interaction energy in the material. According to the ideas of Lev Landau and the theorists who followed him, such a system can be described in terms of elementary excitations called quasiparticles. In a material with a translational invariance, for example, a liquid

or an ordered solid, each such excitation can be described by a position vector \mathbf{q} , a momentum vector \mathbf{p} , and a quasiparticle energy that depends on \mathbf{p} and \mathbf{q} . The quasiparticles move in a straight line, like classical particles, until they collide with another excitation. Landau continued this mode of thinking by using statistical mechanics to estimate the number of quasiparticle excitations in the system at low temperatures. One finds, quite naturally, that the number of excitations becomes smaller and smaller as the temperature goes to zero. And now comes the major point for our present purposes: If the temperature is low enough that there are few excitations, there will be few collisions and the quasiparticles will move for a long distance in a straight line. This straight line, or ballistic, motion is to be contrasted with the result of many scatterings: random walk, or diffusive, motion.

Now let us come back to the problem of neutrino detection. Visualize the neutrinos as they move through a large vat, perhaps 1 meter on a side, of helium at a few tenths of a kelvin. Occasionally a neutrino will interact with an electron or nucleon in the vat, transferring a respectable amount of energy to this particle. This energy will in turn soon cascade into lots and lots of excitations with lower energy. In liquid He^4 , there are two kinds of excitations: phonons (which are the quanta of sound waves) and rotons. The latter are a kind of quasiparticle with a minimum energy of about 9 K. From one point of view, the roton is the quantum "ghost" of a vanishingly small vortex ring. A more mundane vision sees this excitation as an extra helium atom moving through the fluid, producing a swirling disturbance behind it.

Because the temperature is so low, the fluid is almost in its quantum mechanical ground state and contains very few thermally produced excitations. Hence according to the quasipar-

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ticle concept, once the quanta are set into motion, they will find nothing much to bump into. They will move in straight lines until they reach the walls of the container or the surface of the fluid. From the velocity of the excitation, we can construct an estimate of the typical transit time of an excitation through the helium. That time is 10 milliseconds. Wonder of wonders: By simply changing materials, going from argon in cleaning fluid to rotons in low-temperature liquid helium, we change the transit time by a factor of 10^9 or so. This change is a reflection of the transition from diffusive to ballistic motion.

Furthermore, the quasiparticles have an energy just larger than the 8-K binding energy of a helium atom to a free helium surface at that temperature. In fact, roughly 30% of the rotons that hit the surface will knock a helium out of the liquid. These knocked-off heliums are detectable and thus form the basis of the proposed roton-based neutrino detection scheme.

I find something rather satisfying about the conception of this experiment. We start from Landau's theoretically derived idea that quantum excitations are indivisible wholes (called "quanta") and that they have labels like position, energy and momentum that can be given real meanings. We might end with a piece of apparatus that works in a way that would be totally unexpected from classical thinking. If constructed, it will give us knowledge about phenomena that lie at the center of natural laws, both those involving the neutrino and those of bulk matter.

Notice that many features of the proposed experiment have never been tested. For example, the mean free path of rotons has not been measured at the temperatures at which the experiment will be performed. Moreover, relevant roton-phonon branching ratios are unknown, and hence the total number of rotons produced is uncertain. Another example: One cannot know about the effects of possible radioactive decay of contaminants in the helium or the containers. In fact, there will be no detector with sufficient sensitivity to measure these backgrounds until a reasonably large prototype of the neutrino detector is itself built. To an outsider like myself, it would appear that planning experiments like the ones mentioned here takes both vision and guts.

Reference

1. R. E. Lanou, H. J. Maris, G. M. Seidel, Phys. Rev. Lett. 58, 2498 (1987). ☐

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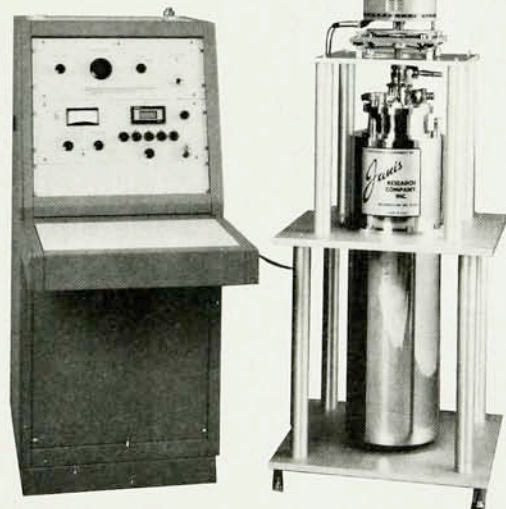
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