longer escape blithely from the superdense proto-neutron star but would instead become "trapped" and take several seconds to escape (see the box "Neutrino Trapping" on this page). Indeed, neutrino trapping can be used to "define" the proto-neutron star, in that inside the proto-neutron star, neutrinos are trapped. Outside the proto-neutron star, neutrinos no longer scatter strongly but free-stream through the star.

In many ways, neutrino trapping was remarkable. A neutrino is a particle that ordinarily passes through *half a light-year* of lead without scattering! But for a few seconds in the center of a dying star, neutrinos behave like any other particle. They scatter, are constantly absorbed and reemitted, and significantly, exert degeneracy pressure. It is the neutrino and electron degeneracy pressures (the dominant components of what is called the lepton degeneracy pressure) that support the shock front and prevent gravitational collapse.

However, even with neutrino trapping incorporated into the models, efforts to obtain explosions were frequently thwarted. Stellar fizzles were often the result of a detailed calculation. But a major shift in supernova models occurred in 1982, when James Wilson began running computer simulations that tracked events over very long periods of time. Partly because of computer limitations, researchers had tended to model only the core collapse and the events that occurred a few tens of milliseconds after the bounce. Wilson's simulations ran from the start of core collapse to about half a second after the bounce. In his simulations, apparent fizzles evolved into successful blowouts by what later was called the "delayed" (as opposed to prompt) mechanism.

In both the prompt and delayed models, the bounce shock moves out a few hundred kilometers beyond the proto-neutron star and stalls. A stagnant shock front would normally be a sign that all outward expansion has stopped, in which case no prompt explosion occurs and the star inevitably recollapses to a black hole.

But the bounce shock does play a crucial role in setting the stage for the success of the delayed mechanism. After the bounce shock stalls, the degenerate lepton pressure prevents material from recollapsing directly onto the proto-neutron star. By tracking the physics for long periods of time, the simulation showed that the shock front is able to withstand the initially large ram pressure of the infall and is still present when that pressure begins to subside. As a result, the quasi-static layer between the stalled shock and the surface of the proto-neutron star persists longer than the neutrino-diffusion time scale. Some of the energetic neutrinos slowly leaking out of the proto-neutron star can be absorbed in the dense material behind the shock front. Material is constantly heated

Neutrino Trapping

The neutrino is the particle that embodies the weak interactions. Up until 1973, neutrinos had been observed to participate only in charge-changing weak interactions, such as electron capture or the reactions making up the two-step Urca process. Two interacting particles exchange a W^+ or W^- boson, and so exchange one unit of electric charge. Charge-changing reactions occur so infrequently that, even at the high densities reached during core collapse, the neutrinos were thought to simply free-stream out of the core.

But in 1973 the neutral-current interaction, long predicted by theorists to be a necessary consequence of electroweak unification, was experimentally verified. This was a new type of weak interaction in which particles exchange a Z^0 boson. Thus, there is no change in the charge states of the participants. Instead, a neutrino could merely scatter from nucleons or electrons. In 1975, Tubbs and Schramm found neutral-current scattering to be favored under the conditions prevailing during core collapse. The neutrino could simultaneously scatter from all the nucleons in a heavy nucleus in a coherent process that boosted the scattering cross section by more than 1 order of magnitude over charged-current processes. At densities above 10^{11} g/cm^3, neutrinos began to scatter from nuclei so often that they became trapped within the core.

One profound consequence of the trapping is that the neutrino density increases enough to reverse the direction of the electron capture reaction:

$$p + e^- \leftrightarrow n + \nu_e \ .$$

Neutrons are transformed back into protons, thus allowing a proton/neutron equilibrium to be established. Neutron star formation is inhibited, and the proto-neutron star forms instead. A second consequence of the trapping is that the neutrino stays in the core long enough to form a degenerate gas. Together with electrons, the two light particles form a *degenerate lepton gas.* It is the lepton gas that stores most of the energy liberated by the gravitational collapse of the core, and it is also the lepton degeneracy pressure that expands the proto-neutron star and supports the bounce shock front long after core bounce has occurred.* Neutrinos of all flavors will scatter via neutral-current interactions, so that ν_μ and ν_τ neutrinos, produced as the core collapses, are also trapped.

*Note that the degenerate lepton pressure is unable to halt the initial collapse of the core. The response of the relativistic lepton gas to further compression is "mushy," and the pressure does not increase very fast when the gas is compressed. The strength of gravity, however, increases nonlinearly with decreasing radius, and the lepton degeneracy pressure alone is insufficient to overcome the increasing pull of gravity as the collapse proceeds.