

the same media as before: gas and dust with only the modification that the regions far from the axis have to be held relatively free of dust. Under this condition, with help of the potential of the moving particles in the focusing-lens system, the energy of the oscillations will be damped.

At high energies the gas and dust strippers become equal in stripping efficiency. The result is that the dust and gas strippers produce equilibrium charges that are about the same. Under these circumstances, no further acceleration is possible. Upon extrapolation of the curves of charge equilibrium as functions of energy, it has been estimated that the maximum

energy is about 50 MeV/nucleon.

Peter Rose of High Voltage Engineering Corporation is interested in developing such a heavy-ion accelerator. He feels that stripper design is the most crucial problem. Foil strippers would work except that they have very short lifetimes in energetic heavy-ion beams, so he looks upon dust strippers as a hopeful approach. HVEC has built a couple of such strippers. (Van de Graaff was working on this problem before his death.) The first design was crude and was basically a Ferris wheel that rotated in the beam with dust falling from one cup of the wheel to the next one below. A second model used a vibrator with a spoonful of dust on it. These models lasted only an hour or so before the dust dispersed. Nevertheless, they

showed that dust strippers are possible and effective.

Rose is proposing capturing a cigar shape of charged dust in an rf field. This procedure would have the advantage of localizing the dust near the beam axis, thereby satisfying the condition necessary for damping transverse components of momentum. The Hortig accelerator design works in favor of dust strippers because they could be located outside the acceleration region. Consequently, bad effects from dispersed dust would be reduced. Rose feels that the problem of designing a good stripper definitely is solvable and that once this obstacle is overcome the accelerator can contend seriously with the Omnitron (PHYSICS TODAY, May, page 64) as a heavy-ion accelerator.

Helium-3 Dilution Makes Millidegree Temperatures

A new kind of refrigerator for cooling below 0.1°K holds great promise for cryogenics. Over the past year several groups have built He³-dilution refrigerators that can cool samples continuously below 0.2°. Although adiabatic-demagnetization methods have traditionally been used to cool below 0.3°, the new refrigerator is much simpler to use. At the April American Physical Society meeting John Wheatley (formerly of the University of Illinois and now at the University of California, San Diego) reported that his continuously operating He³-dilution refrigerator had reached 0.020° and his single-cycle device had reached 0.0044°.

Heinz London of Harwell, England, first proposed a He³ cooling cycle in 1951. He suggested that He³ atoms dissolved in He⁴ behave in many ways like a gas. Introduction of more He⁴ into the system would cause cooling in analogy to adiabatic gas expansion.

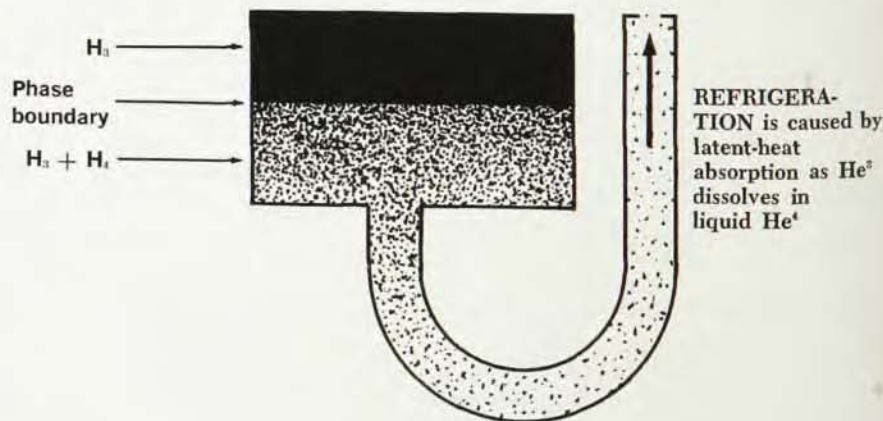
Then in 1956 G. K. Walters and William Fairbank found that below 0.087° He³-He⁴ mixtures separate into two distinct phases. Pure He³ floats on top of a dilute solution of He³ in He⁴. It became apparent that one could devise continuous and more powerful cooling cycles in which He³ atoms would move across the phase boundary; the process is analogous to evaporation of a liquid into a gas.

Refrigeration occurs when He³ dissolves out of the pure He³ phase into the liquid He⁴. The latent heat absorbed as the He³ goes into solution does the cooling; the He⁴ acts only as a carrier. This procedure is a marked advance over a conventional evaporation refrigerator, which can not be operated effectively below about 0.25°K because the He³ vapor pressure decreases exponentially with decreasing temperature.

Both single-cycle and continuously operating refrigerators have been built. In single-cycle operation one just allows the He³ to diffuse through the He⁴ column and boil out into a vacuum at a higher temperature until the He³ reservoir is depleted. In this way temperatures as low as 0.0044°K have been reached. Continuous

refrigeration is achieved by returning the He³ atoms to the reservoir after they evaporate from the He⁴. The recirculated He³ carries heat and also some He⁴ back into the reservoir. The heat and the effects of the He⁴ have so far limited cooling by continuous refrigeration to approximately 0.020°K.

Several possible cooling cycles were suggested in 1962 by London, G. R. Clarke, E. Mendoza and H. E. Hall. Two years later a group at Leiden (P. Das, R. de Bruyn Ouboter and K. W. Taconis) reported the first attempt to build such a refrigerator. In 1965 groups at Manchester and Dubna independently succeeded in building the new device. Hall, P. J. Ford and K. Thompson at Manchester built one that reached as low as 0.065° and re-



moved heat at 40 ergs/sec at 0.1° . In Dubna B. S. Neganov, N. S. Borisov and M. Yu. Liburg built a much larger refrigerator that could extract 1300 ergs/sec at 0.1° and got down to 0.025° with no heat load.

Besides the Illinois refrigerator, built by Wheatley and O. E. Vilches, and the ones at Dubna and Manchester, such devices are being built by many other groups and some are already finished. Wheatley's and Vilches's has been used for experiments on helium properties. W. A. Steyert and his collaborators at Los Alamos have used theirs to measure resistivity and susceptibility of a copper-iron alloy. At Brookhaven two large machines, each expected to remove 1300 ergs/sec at 0.01° or better (Los Alamos and Illinois machines are about a tenth as large) will probably be working this summer. Oxford (England) Instrument Co. Ltd., headed by Martin Wood, is already shipping commercial He^3 -dilution refrigerators that go down to $0.03\text{--}0.06^\circ$.

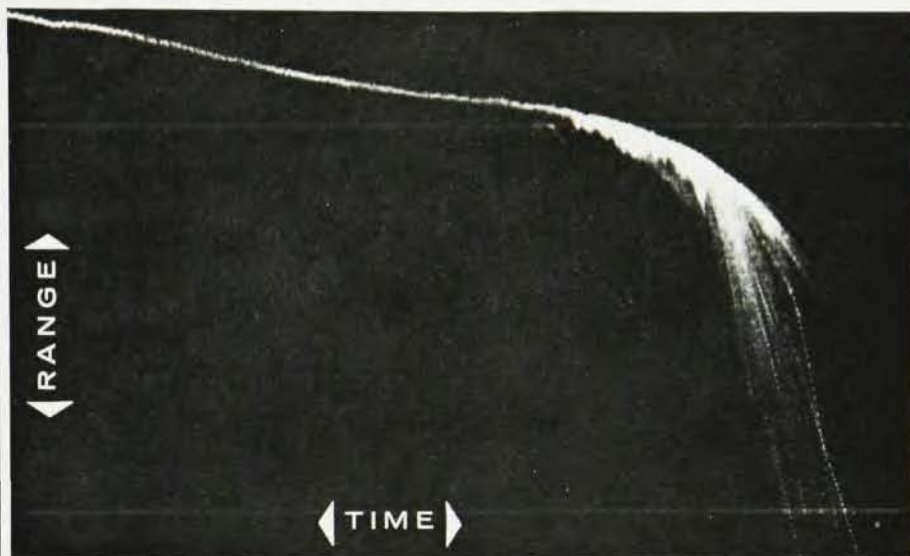
In principle the only lower limit for the He^3 -dilution refrigerator is absolute zero. D. O. Edwards and his coworkers at Ohio State suggested that about 6% He^3 in He^4 is in equilibrium with a pure He^3 phase down to $T = 0$, and Wheatley has confirmed the prediction experimentally.

In practice, however, the refrigerator may not be effective below about a millidegree. Wood feels that the practical limit is set by unavoidable heat leaks into the system and the inefficiency of the heat exchangers. Problems associated with the heat exchangers are particularly intransigent at the low end of the temperature scale where a mismatch of phonon frequencies produces a serious thermal impedance, first reported by Peter Kapitza, between the liquids involved and the tubes in which they flow.

Wheatley is somewhat less definite about the low temperature limit. He feels that actual limits will be set by He^3 viscosity (which increases as temperature decreases) and thermal conduction. You can beat the viscosity effect by using a larger-diameter "pumping" tube, but then heat conduction increases. It is not clear what the useful limit is but he feels it might be better than a millidegree. $\square$

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