gued that neither a homogeneous charge distribution nor a deformed Fermi distribution correctly describes the situation in this region. There are, in fact, some experimental data to support the latter proposition.[18] Such local variations in charge density could have a profound influence on the analysis of sub-Coulomb scattering data.

It thus seems appropriate that further research on the problem be concentrated on reconsidering the origins and implications of the large measured $E4$ transition moments in the W and Os region of the nuclear chart.

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[1]C. E. Bemis *et al.*, Phys. Rev. C 8, 1934 (1973).

[2]F. T. Baker, T. H. Kruse, and W. Hartwig, Bull. Amer. Phys. Soc. 19, 577 (1974); F. T. Baker, private communication.

[3]J. P. Davidson, D. A. Close, and J. J. Malanify, Phys. Rev. Lett. 32, 337 (1974).

[4]D. L. Hendrie, Phys. Rev. Lett. 31, 478 (1973).

[5]R. F. Casten, Phys. Lett. 49B, 258 (1974).

[6]S. G. Nilsson *et al.*, Nucl. Phys. A131, 1 (1969).

[7]G. Sletten and P. Knudsen, Nucl. Instrum. Methods 102, 459 (1972).

[8]P. J. Daly, K. Ahlgren, K. J. Hofstetter, and R. Hochel, Nucl. Phys. A161, 177 (1971).

[9]K. Ahlgren and P. J. Daly, Nucl. Phys. A189, 368 (1972).

[10]P. Kleinheinz, R. F. Casten, and B. Nilsson, Nucl. Phys. A203, 539 (1973).

[11]P. Morgen, B. S. Nielsen, J. Onsgaard, and C. Søndergaard, Nucl. Phys. A204, 81 (1973).

[12]Th. Lindblad, H. Ryde, and P. Kleinheinz, Nucl. Phys. A210, 253 (1973).

[13]Th. Lindblad, H. Ryde, and D. Barneoud, Nucl. Phys. A193, 155 (1972).

[14]W. Ogle, S. Wahlborn, R. Piepenbring, and S. Fredriksson, Rev. Mod. Phys. 43, 424 (1971).

[15]J. X. Saladin, private communication; cf. also I. Y. Lee *et al.*, Phys. Rev. Lett. 33, 383 (1974).

[16]F. M. Bernthal and R. A. Warner, to be published.

[17]P. Kleinheinz, P. J. Daly, and R. F. Casten, Nucl. Phys. A208, 93 (1973).

[18]J. Heisenberg *et al.*, in *Proceedings of the International Conference on Nuclear Physics, Munich, Germany, 1973,* edited by J. de Boer and H. J. Mang (North-Holland, Amsterdam, 1973), Vol. 1, p. 629.

Experimental Test for the Charge Superselection Rule*

D. Kershaw and C. H. Woo
University of Maryland, College Park, Maryland 20742
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An experiment is suggested to test the existence of a phase correlation for two space-separated superconductors. The phase in question is that of the eigenvalue of the operator S that creates a pair in one superconductor and removes a pair from the other. This will also provide a clear-cut test for the charge and lepton number superselection rules.

It has been argued[1,2] that, from *a priori* theoretical grounds, there is no sharp distinction between charge conservation and the conservation of other Abelian quantum numbers, such as momentum conservation. Gauge invariance renders the relative phases between different charge states arbitrary, but fixing the phase of a single suitable reference system removes this arbitrariness. In the same way, translation invariance renders the relative phases between different momentum components arbitrary, but the fixed position of a reference system removes the arbitrariness.

Thus the relevant consideration[3] in assessing the significance of the charge superselection rule is an empirical one. One has to ask whether there exists in nature any system which is already a coherent superposition of different charge states, and can therefore act as a reference system for the phase. In their derivation of charge superselection, Wick, Wightman, and Wigner state,[3] "It may be well, however, to reemphasize the critical assumption on which our analysis is based: that we have no states naturally given which are superpositions (rather than mixtures) of states with different charges." Recently Kibble[2] argued that a local region of a superfluid or a superconductor, or each side of a Josephson junction, is just such a system. However, it seems to us that the existence of a Josephson current, or the interference between Josephson currents, does not resolve the question in a definitive way. While the presence of phase coherence between the two sides of a Josephson junction seems well established, in the usual experimental situation the two sides are connected together, and pairs are continuously transferred between them. If a phase relation can be established only for such continuously interacting parts, it becomes doubtful whether each part alone has enough identity, in the sense of space-time separation, to be regarded as an isolated system distinct from the reference sink. As a matter of fact, it seems to be generally believed that the phase relation relevant for the two sides of a Josephson junction will get lost as soon as the two sides become separated. The phase is a delicate thing which accommodates itself to the magnitude of the supercurrent, and reverses its sign with a reversal of the voltage bias. Thus the reality of a phase relation between isolated superconductors, without a current flowing between them, seems never to have been experimentally established.

The analog for position correlations would be as though the relative position of an electron had been reasonably well established as a meaningful concept only for electrons inside a crystal, but never for unbound electrons. It is as if there had never been a two-slit interference experiment.

In view of this, it seems highly desirable to have an experimental test of the existence of phase relations for space-separated superconductors. It is to be emphasized that we do not disagree with Kibble's statement that exchange of particles should be allowed during measurements of relative phases. What we are saying is that in between measurements there should be at least a time interval during which a subsystem is isolated from the sink, except for electromagnetic influences, and does not exchange particles with it. If, during this interval, the subsystem retains some phase coherence relative to the sink, then the charge superselection rule is clearly not valid. Explicitly, we seek a system of two superconductors in a quantum state $|\psi\rangle = \sum_n e^{inU}|Q_1 - 2ne, Q_2 + 2ne\rangle$, where $Q_1 - 2ne$ in each component refers to the charge of the sink, $Q_2 + 2ne$ to the charge of the subsystem, U is the relative phase, and the sink and the subsystem are macroscopically separated in space. From an examination of the mechanisms usually given for the absence of a phase correlation between separated superconductors, we come to believe that (1) the difficulty of maintaining a phase relation for disjoint superconductors is only a matter of degree and not one of principle, and that (2) with some moderate extensions of even present day techniques, an experimental test may be on the borderline of feasibility.

An example of such an experiment is schematically shown in Fig. 1. A superconducting ring carrying a persistent current has three arms coming out. The middle arm BB' is connected by contact to a second superconductor $F'F$. If the contact is reasonably good, the two sides would be weakly coupled, and in this configuration $F'F$ has essentially the same phase as the point B on the ring. The relative phase between the points D' and B is given by the sum

$$(2m/\hbar\rho)\int_B^D \vec{j}_{\text{surface}}\cdot d\vec{s} + (2e/\hbar)\int_B^{D} \vec{A}\cdot d\vec{s}.$$

So, if during the time when F' is switched from B' to D' the phase information is not totally lost, then with $\pi > (2m/\hbar\rho)\int_B^D \vec{j}_{\text{surface}}\cdot d\vec{s} > 0$ the initial current flow upon contact will be from F' to D'. In contrast, if F' is switched to A', an initial current will be from A' to F'. (To lessen the magnetic field in the path of switching, one may consider using a long cylinder instead of a ring.) The experiment needs to establish only such a qualitative difference to show that during the time the second superconductor is not in contact with the ring, it retains some information about its phase relative to the ring, and hence is a coherent superposition of many different charge states.

A positive result is not incompatible with the theorem in Ref. 3 that if a density matrix describing a big system obeys a superselection

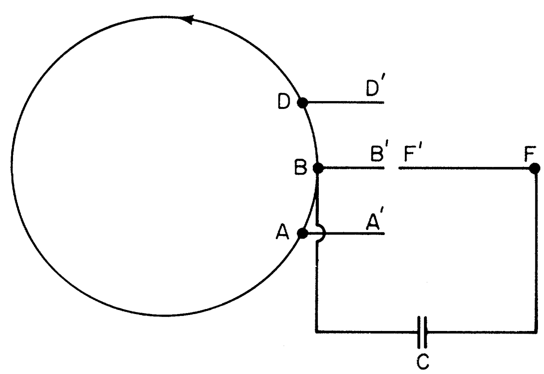

FIG. 1. Schematic diagram of the experiment.

rule, then the subdensity matrix obtained by taking partial trace describes a subsystem also obeying the superselection rule. In the above experiment the system taken as a whole is in a definite charge state, but the second superconductor when separated from the first is not described by taking a partial trace of the total density matrix. Again one can compare with the analogous situation of an ordinary two-slit interference experiment done in a laboratory that is nearly in an eigenstate of total momentum: The position of the total system has no well-defined value, but the relative positions of the interfering beams, of the slits, and of the diffraction patterns are well defined. The system as a whole has sharp momentum, but the subsystem of each beam is a coherent superposition of different momentum states. Just as in that experiment where a measurement of which slit the photon went through destroys the interference pattern, in our experiment any attempt to measure the charge of the second superconductor in isolation will destroy its phase memory.

We next consider whether, even in principle, the second superconductor $F'F$ will necessarily lose its phase memory anyway as it becomes separated from the arm BB'. According to Anderson[4] the Josephson junction linking $B'F'$ may be described by a model Hamiltonian

$$H=e^2n^2/2C+E(1-\cos U).$$

Here $n/2$ is the number of pairs transferred, and U the phase difference, between the two sides; $[n,U]=1$. C is the relative capacitance of the two sides of the junction, and $eE/\hbar=J$ is the maximum current that can flow through the junction with zero voltage drop. Consider first the junction at absolute zero temperature. The system is then in the ground state, with $\langle U^2\rangle_0 =e(2CE)^{-1/2}$. When one separates FF' from BB', E goes to 0 and H becomes $e^2n^2/2C$. Thus the Gaussian wave packet begins to spread and the time it takes before $\langle U^2\rangle=1$ is given by

$$t_c=\hbar Ce^{-2}(\langle U^2\rangle_0)^{1/2}=\hbar(e^2/C)^{-3/4}E^{-1/4}.$$

In order to make t_c large we need a large capacitance and this is the purpose of the superconducting capacitor in Fig. 1. The capacitance C in this problem plays the same role as the mass plays in ordinary wave-packet spreading in position space. Just as the large mass of macroscopic bodies makes possible approximate localization over long periods of time, a large capacitance in this problem makes phase stability possible.

Although a measurement of the radiation emitted during switching is tantamount to charge measurement, one can not only reduce the amount of radiation by increasing the switching time, but also refrain from measuring the emitted photons. Again, one may consider the usual electron-beam interference experiment where a measurement of the emitted radiation would indicate which way the electron has been bent. But the presence of radiation, without any attempt to detect it, does not destroy the interference patterns.

Therefore, with sufficiently large capacitance C and low enough temperature, phase coherence between space-separated superconductors can be maintained over a long period, and in principle the violation of charge superselection rule is subject to observation.

We now come to the question of the practical feasibility of such an experiment. Since no large voltage will be put on the capacitor, it does not seem exceedingly difficult to construct a capacitor of reasonable size with a $C\simeq 10^{-2}$ F. If the junction has $J\simeq 10^{-3}$ A, one finds $t_c\simeq 10^{-3}$ sec. (To get a large capacitance the condenser will, of course, be constructed with closely stacked sheets, so that the two superconductors in Fig. 1 will not be physically disjoint. But if the experiment gives a positive result with such an arrangement, it should be clear that one can get the same C from two large superconductors more clearly separated in space from each other.[5] One must also consider the effect of a finite temperature. There will be a thermal excitation of large n values, such that $e^2\langle n^2\rangle_0/C=kT$. When $F'F$ is separated from BB', n becomes a constant of motion, and $\dot{U}=e^2n(\hbar C)^{-1}$. Since $\langle n^2\rangle_0 =CkTe^{-2}$, the time it takes before $\langle U^2\rangle=1$ is given by

$$t_c=\hbar Ce^{-2}\langle n^2\rangle_0^{-1/2}=\hbar(kT)^{-1/2}(e^2/C)^{-1/2}.$$

With $T\simeq 1$°K, t_c is of the order of magnitude of 10^{-4} sec. Thus, if the switching can be done in less than 10^{-4} sec, some phase information will be retained.

In order that the difference in work functions for the two conductors will not induce a current masking the supercurrent, the two superconductors have to be made of the same material with a good alignment of the crystal faces. Finally, the characteristic time of oscillations in the circuit after F' is switched to D' and the junction $F'D'$ is established is mainly controlled by $(LC)^{1/2}$, where L is the inductance of the circuit. If L can be made as small as 10^{-7} H, this time constant $\simeq 10^{-4.5}$ sec; so the detection system should be designed to measure the direction of the initial current in that time interval.

Clearly the experiment is a difficult one, involving the making and breaking of contacts that serve as weak couples.[6] But the difficulties do not seem insurmountable. It should be worth doing not only from the viewpoint of superselection rules, but also from the viewpoint of getting a clearer understanding of the reality of the phase of a disjoint superconductor, not just relative phases between coupled local regions.

If "phase retention" by a superconductor in space-time isolation from the sink can be experimentally established, not only the charge superselection rule loses fundamental significance, but the lepton number superselection rule does also. It is then difficult to conceive that the baryon number superselection rule is more fundamental (even though experimentally it would be harder to test the proposition). One may ask in that case whether there is any superselection rule in nature at all. In this connection we wish to note that the univalence superselection rule seems to be in a different category. Although in Ref. 1 *gedanken* experiments were discussed as to how the change in phase of a fermion under a 360° rotation may be "measured," it seems to us that as long as the connection between spin and statistics remains valid, operators connecting different univalent sectors cannot be local observables without violating causality. Since the electron field ψ smeared with test functions localized in spacelike separated regions do not commute, ψ cannot be an observable, whereas $\psi\psi$ can be if the experiment proposed here has a positive result.

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[1]Y. Aharonov and L. Susskind, Phys. Rev. 155, 1428 (1967); R. Mirman, Phys. Rev. 186, 1380 (1969), and Phys. Rev. D 1, 3349 (1970).

[2]T. W. B. Kibble, unpublished.

[3]G. C. Wick, A. S. Wightman, and E. P. Wigner, Phys. Rev. D 1, 3267 (1970).

[4]P. W. Anderson, in *Lectures on the Many Body Problem*, edited by E. R. Caianiello (Academic, New York, 1964), Vol. 2.

[5]In fact, for large separation $C \simeq C_1C_2/(C_1+C_2)$, where C_1 and C_2 are the self-capacitances. Therefore the two superconductors may be arbitrarily far apart and still retain the relative phase if their self-capacitances are both large enough.

[6]Point contact junctions have been extensively studied since they were first applied to Josephson effect experiments [J. E. Zimmerman and A. H. Silver, Phys. Lett. 10, 47 (1964)]; we thank T. Bedard and N. Walker for a discussion of some experimental aspects of such junctions. Other ways of switching should also be explored; the arrangement proposed here is illustrative and may not be the most effective one.

Vacuum Polarization in Heavy-Ion Collisions*

Miklos Gyulassy
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720
(Received 5 August 1974)

The results of a study on vacuum polarization, orders $\alpha(Z\alpha)^n$, $n \geq 3$, for large-Z systems encountered in heavy-ion collisions are presented. It is shown that the higher-order vacuum polarization cannot prevent the $1S_{1/2}$ state from reaching the lower continuum, $E = -m_ec^2$, for some critical charge $Z_{\rm cr} \sim 170$. In addition, the stability and localization of a heliumlike system for $Z > Z_{\rm cr}$ is demonstrated.

An interesting application of heavy-ion collisions is to the study of quantum electrodynamics of strong fields. For short times, at least, systems with large effective charge Z will be formed with $Z\alpha > 1$. In the strong fields of such systems, highly relativistic electronic bound states are expected to occur with binding energies B exceeding the electron rest mass m_e, and for some critical charge, $Z_{\rm cr} \sim 170$, the $1S_{1/2}$ state is expected to reach the lower continuum with $B = 2m_e$.[1] For $Z > Z_{\rm cr}$, it has been predicted[2,3] that spontaneous e^+e^- pair production will occur with the subse-