Dual Confinement Of
Grand Unified Monopoles?

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Abstract

A simple formal computation, and a variation on an old thought experiment, both indicate that QCD with light quarks may confine fundamental color magnetic charges, giving an explicit as well as elegant resolution to the ‘global color’ paradox, strengthening Vachaspati’s SU(5) electric-magnetic duality, opening new lines of inquiry for monopoles in cosmology, and suggesting a class of geometrically large QCD excitations – loops of Z(3) color magnetic flux entwined with light-quark current. The proposal may be directly testable in lattice gauge theory or supersymmetric Yang-Mills theory. Recent results in deeply-inelastic electron scattering, and future experiments both there and in high-energy collisions of nuclei, could give evidence on the existence of Z(3) loops. If confirmed, they would represent a consistent realization of the bold concept underlying the Slansky-Goldman-Shaw ‘glow’ model – phenomena besides standard meson-baryon physics manifest at long distance scales – but without that model’s isolable fractional electric charges.
I. Introduction

A quarter century ago, the simultaneous and independent discoveries by Gross and Wilczek [1] and by Politzer [2] that quantum chromodynamics [QCD] is asymptotically free made this theory instantly what it still is – the unique candidate theory for describing the structure and interactions of baryons, as well as the mesons produced when baryons collide. For length scales below 0.1 fm and energy scales above 1 GeV, phenomena may be described accurately by perturbative techniques in terms of elementary quarks and gluons. At longer distances and lower energies, the most useful degrees of freedom become the baryons and mesons themselves, while the connection between these two regimes is less well determined because of the calculational difficulty associated with nonperturbative QCD. Nevertheless, a variety of experimental and theoretical approaches have produced so many successes that it would seem natural to assume there is little or no room for surprising new phenomena in QCD. That is especially plausible for the perturbative regime, so if there are surprises lurking they most likely will be found at long distance scales.

A rare if not unique proposal in this direction, which constitutes perhaps the boldest enterprise with Richard Slansky’s name on it, is the paper of Slansky, Goldman, and Shaw [SGS] [3] suggesting explicit departures from naive QCD expectations at long distance scales. Their work was stimulated by experimental indications of isolated electric charge with value 1/3 or 2/3 that of an electron charge. As Gordon Shaw explains [4], assuming that the manifest SU(3) gauge symmetry of QCD is reduced by a Higgs mechanism at very long distance scales to SO(3), one may envision isolated SO(3) singlets made of two quarks, and therefore carrying fractional electric charge. While seeking such objects in the laboratory remains a worthwhile challenge, there are serious grounds to be hesitant about the explicit SGS proposal. The reason is that a Higgs mechanism is easy to formulate in a regime where the gauge coupling of the theory is weak, as in the standard model of electroweak interactions, but becomes very hard to interpret if the coupling is strong, which inevitably would be true for QCD on the scale they had in mind. There was little choice about this for SGS, because any shorter distance scale or higher energy scale with such phenomena would have been prohibited by existing theoretical and experimental knowledge.

Even now there is no experimental confirmation of fractional electric charge, though searches continue [4], nor of any other long-range QCD effect. This paper presents a proposal which has significant features in common with SGS, namely, new long-range
phenomena beyond ordinary hadron dynamics (including confinement of fundamental magnetic monopoles), but does not imply fractional electric charge. If the proposal turns out to have merit, then it could well be viewed as a vindication of the essence of SGS. Certainly the intellectual structure they developed was an important influence on my thinking. The presentation involves both ‘push’ and ‘pull’ heuristic arguments, i.e., reasons to suspect the existence of new phenomena as well as appealing consequences which would follow if they occurred, but does not include a proof that they are inevitable. Because of the wide range of application, there likely will be a number of ways to test the proposal, including several outlined later. The focus begins with particles dual to quarks, namely, fundamental magnetic monopoles carrying both ordinary and color magnetic charge.

Before plunging into the proposal, we should review some long-range effects which already are expected, resulting from hybridization between different scales. If a region of space is sufficiently hot, then the temperature $T$ sets a scale which invokes asymptotic freedom, and thus allows one to describe the properties as if dealing with a gas of free quarks and gluons, commonly known as the ‘quark-gluon plasma’. Clearly long-distance correlations in this regime should look quite different from those at $T = 0$. Thus, long-distance phenomena are altered in a predictable way, but in a high-energy rather than low-energy regime. Something similar should happen if, for example, compression of cold nuclear matter, as in the interior of a neutron star, were to produce baryon density much greater than that in normal nuclei. This time the high density gives a short-distance and therefore high-energy scale which implies asymptotic freedom and a change in long-distance correlations.

Neither of these effects would be a surprise. Something a bit closer was the proposal of Jaffe [5] that a six-quark system of strangeness $S = 2$ might be stable against decay to two Λ particles. This in turn raises a possibility discussed by Witten [6] that electrically neutral strange matter might be stable or metastable. However, even this effect if it occurred would be a consequence of relatively short-range interactions. Something still closer to what follows is the suggestion [7] that nuclei might have stable or metastable toroidal forms, where a quark-containing tube of color-magnetic flux is bent into a closed curve, a structure which might exhibit rigidity and incompressibility as well as tension.
II. Heuristic arguments for monopole confinement

Gauge invariance

Though the existence of a magnetic monopole has yet to be confirmed by experimental observation, even as a concept this object repeatedly has played the role of an intellectual aqua regia, exposing profound aspects of structure in physical systems. The most noted example is Dirac’s realization that the existence of isolable monopoles would require the quantization of electric charge $q$ and magnetic charge $g$, through the quantum condition that the product of $q$ with $g$ is proportional to an integer.

Dirac monopoles ‘inserted’ into QED give a model for confinement, because emanating from an elementary pole inside a Type II superconductor with its electron-pair condensate must be two strings of superconductor-quantized magnetic flux, each terminating only on an antipole. If one pair of pole and antipole were slowly separated, clearly the two strings coming out of the pole would terminate on the antipole, implying a confining string tension holding the two together. By analogy, if the vacuum of QCD without light quarks comprised a monopole condensate, this then would confine heavy quarks. However, if there are elementary quarks light on the scale of $\Lambda_{QCD}$, then there is no confinement of heavy quarks: Instead pair creation of light quarks allows heavy-quark-containing mesons to be separated with no further energy cost.

A general argument of ‘t Hooft for QCD without light quarks shows that either heavy elementary quarks or heavy fundamental monopoles should be confined, but not both. If this argument still applied in the presence of light quarks, then monopole confinement would be a triviality. In any case this makes it clear that there would be nothing obviously inconsistent about such confinement. To understand why it might be expected, let us examine in the more familiar superconductor case the issue of screening, and what charges can or cannot be screened. In electrodynamics it is useful to distinguish two different kinds of conserved charge, local or Gauss-law charge and Aharonov-Bohm [AB] or Lorentz-force charge. Although the local charge of an electron-quasiparticle is completely screened inside a superconductor, the AB charge cannot be screened, because of the reciprocity requirement that an AB phase of $\pi$ must occur whether a quasiparticle is diffracted around a fluxon (i.e., a superconductor quantum of flux) or a fluxon is diffracted around a quasiparticle. If the effect on the fluxon is to be described by a local interaction, evidently the AB charge is not screened.

Now let us look at the same issue for a fundamental monopole in QCD. The monopole
may be characterized as the source of a Dirac string carrying color magnetic flux which would produce an AB phase $2\pi/3$ for a fundamental quark diffracted around it. Of course, in addition to this color flux there must be an ordinary magnetic flux in the string yielding a phase $4\pi/3 \mod(2\pi)$. The fractional color flux in the string implies that there must be a net nonzero color magnetic flux coming out of the pole. A monopole whose Dirac string would carry full $2\pi$ color flux has no such consequence, because that could be exactly compensated by an ‘adjoint’ monopole made from a classical configuration of purely SU(3) gauge fields. Thus, in the sense just defined, adjoint monopoles can be screened but fundamental monopoles cannot (a suggestive analogue to what happens with adjoint gluons and fundamental quarks).

In the absence of dynamical quarks, this lack of screening may not matter, because vacuum fluctuations in the form of loops carrying flux $2\pi/3$ occur easily on arbitrarily large length scales, so that the magnetic charge is not definable as an eigenvalue. In this sense, it may be screened just like electric charge in a normal metal, i.e., with mean value zero but such large fluctuations that it is not defined as a sharp quantum observable. Thus the monopole charge, rather than being screened or compensated, may be hidden in much the same way a needle becomes invisible inside a haystack. Here is another perspective: In the theory with only adjoint fields, such as those of the gluons, the gauge symmetry is SU(3)/Z(3), so that an arbitrarily thin tube of Z(3) magnetic flux would be invisible even by the AB effect to all elementary excitations, hence could not excite the vacuum, and therefore need not carry an observable energy per unit length, as would have to be true for an observable string.

On the other hand, once quarks are present, there could be a nonvanishing string tension for loops of Z(3) color magnetic flux, so that geometrically large quantum fluctuations of these loops should be suppressed. A reason for suspecting this is that now the AB effect would make even the thinnest tube visible for those quark trajectories which surround the tube. Thus, the fractional color magnetic charge could become sharp, meaning that an observable color magnetic field, confined to a tube of fixed radius, emanates from the monopole out to infinity. More formally, because now there are particles in the fundamental representation of SU(3), the full gauge symmetry applies, and so a nonzero Z(3) color magnetic flux out of a fundamental monopole is at least potentially observable.  

Ideal experiment

Here is a thought experiment suggesting the same conclusion. Imagine a hadron such
as a proton at rest near an SU(5) monopole, with its ordinary as well as color magnetic charge. If a deeply-inelastic electron scattering sends a quark out of the proton with very high momentum parallel to that of the incident electron, then the quark’s evolution in the beam direction can be described perturbatively for a time proportional to that momentum, which means the ordinary magnetic field of the monopole will deflect it in such a way that only a fraction of a quantum of angular momentum will be transferred to the quark. This is inconsistent with conservation and quantization of angular momentum [14]. The analysis also can be carried out in the rest frame of the fastest final hadron. In this frame a perturbative computation is accurate for a fixed time of order 1 fm/c. However, the magnetic field of the monopole flashes by the quark in a much shorter time because of the Lorentz contraction of the field configuration, and therefore again there is a definite, but fractional transfer to the quark of angular momentum projected along the beam direction.

One way to restore consistency is to assume that there is also a spherically symmetric color magnetic field, so that the combined fields always transfer an integer number of angular momentum units to the quark. However, that assumption directly contradicts the most basic understanding of QCD, which requires a mass gap for color-carrying excitations, so that a long-range, ‘classical’, isotropic, color-magnetic field is impossible. How can these two requirements, of nonscreening and yet no isotropic long-range field, be reconciled? An obvious if not unique way to avoid the dilemma is by ‘escape into asymptotic freedom’: Color fields make sense in the high-energy, short-distance, perturbative regime, so if the magnetic flux comes out in a tube with radius of scale \( \leq \Lambda_{QCD}^{-1} \) it is consistent with knowledge about the low-energy behavior of the theory, and at the same time satisfies the requirement of nonscreening. Evidently such a tube must have a finite tension, so that the energy of a pole-antipole pair connected by the tube must rise linearly with separation, and this implies confinement of fundamental monopoles.

From the viewpoint of the deeply-inelastic ‘thought experiment’, why shouldn’t the monopole confinement argument apply even if there are no dynamical quarks? In that case heavy ‘external’ quark sources certainly are confined, and the failure of angular momentum quantization for a single pole-quark pair is acceptable, as there is never a single isolated quark moving in the field of the monopole.

While the above arguments might be appealing, they surely do not constitute a proof of monopole confinement. The reason is that even with light quarks it may be that large
loops of magnetic flux, at least of a certain cross sectional radius, still have arbitrarily low energy, in which case they would be part of the vacuum structure rather than physical excitations. Then the net flux out of a monopole again would be hidden by vacuum fluctuations. However, because the quarks would be sensitive to arbitrarily thin tubes even with $Z(3)$ flux, there is now a much stronger constraint, from below as well as above, on the acceptable radii for flux tubes with very low energy.

Both because the thought experiment was the germinating element in my own thinking on this subject, and because more careful examination could tend either to strengthen or to weaken the argument, it seems worthwhile to focus more explicitly on the wave function evolution entailed by this process. In the presence of gauge fields, the conventional (non-gauge-invariant) momentum of an object whose charges couple to these fields becomes undefined. Thus, in the directions transverse to the very high momentum of the struck quark, it makes no sense to think about the momentum of the quark by itself. However, the correlated wavefunction of the quark and the associated slower remnants might have a well-defined wave function in transverse momentum $p_T$, a wave function which initially would be strongly peaked at $p_T \approx 0$ and azimuthal angular momentum about the beam direction also zero. Then the essential idea is that, absent any contribution from color magnetic fields, the only effect feeding some change in this azimuthal angular momentum would be coming from the scattering of the fast quark on the ordinary magnetic field of the monopole. A fractional value for this angular momentum transfer gives the conclusion that something is inconsistent about this picture, and leads by elimination of alternatives to the inference that an observable string of color magnetic flux emanates from the monopole.

If we accept that inference, how do we find consistency restored? As an example, imagine that the observable string comes out of the monopole in the direction parallel to the fast quark momentum. We still may use gauge invariance to place the Dirac string of ordinary plus color flux anywhere we like, and thus may choose it along the observable color string. In this case, for all except those trajectories which penetrate the observable, finite-thickness string, the effective field is just that of a pole which is one end of a solenoid with ordinary magnetic flux such that a quark going around it acquires a fractional phase $2\pi/3 \mod 2\pi$. Evidently mesons or baryons generated by fragmentation of the fast quark will always have integer azimuthal angular momentum, but nevertheless the initial effect of fast passage of the quark by the monopole will be to generate a fractional change in the net angular momentum of the entire system interacting with the pole, something now
allowed because an observable string with fractional magnetic flux is present.

III. Consequences and applications

Now let us look at how fundamental monopole confinement would reorient perspectives on a variety of issues.

1. Paradox of ‘global color’

A number of authors addressed the problem of generalizing a collective-coordinate quantization technique, accepted as describing the electric or ‘dyon’ charge of an SU(2) monopole, to the case of the SU(5) monopole \[15, 16, 17, 18\]. They found that for the unbroken SU(3) of color the dyon charge of an isolated pole is not defined – an effect reminiscent of spontaneous symmetry breaking as in ferromagnetism. Evidently if monopoles with fundamental color charge are confined, this problem simply disappears. A more general and straightforward comment is that, with or without monopole confinement, the paradox is ill-posed, because the collective-coordinate method has been used to quantize zero modes of the monopole placed in a perturbative QCD vacuum, which definitely is an incorrect description of the lowest-energy degrees of freedom on length scales large compared to \(\Lambda_{QCD}^{-1}\). Thus, while monopole confinement eliminates the problem at the very beginning, the significance of that resolution perhaps is diminished because there might well not be such a problem if the right vacuum were understood well enough to be implemented for the analysis.

2. Electric-magnetic duality in a grand unified model

Recently Vachaspati \[19\] has described a remarkable duality of SU(5), clearly relevant for any grand unified theory. The fundamental monopole is part of a family of tightly bound states, with magnetic charges 1,2,3,4, and 6 times the fundamental charge. These five states can be identified as dual partners of the five fundamental fermions in SU(5), three quarks, a lepton, and a neutrino. There is a possibly deep or possibly just technical issue, that the charge-2 state should be identified with an antiquark. There are two other difficulties. First, the monopoles appear to be spinless, while the fermions of course have spin-1/2. This problem arose already with the original Montonen-Olive proposal of duality between monopoles and gauge bosons \[20\], and eventually found two resolutions. One is to introduce supersymmetry, so that both monopoles and the dual elementary particles come in families with the same range of spins \[21, 22, 23, 24, 25\]. The other, acknowledging the possibility in principle of making a perfect correspondence through supersymmetry,
is to be satisfied with what might be called ‘virtual duality’ – a symmetry applied to all properties except spin. Whichever approach one prefers, with respect to this issue Vachaspati’s system is in the same category as the older examples.

The other difficulty \[19\] is that the effective long-range couplings of the monopoles and their dual partners are identical, except that quarks are confined, whereas previous discussions suggested that the colored monopoles are not. For this reason Vachaspati considered introducing the confinement essentially by hand. The argument above that the monopoles which nominally carry nontrivial $Z(3)$ color magnetic charge are automatically confined gives a way to perfect Vachaspati’s duality, lending additional interest to pursuing it further. One side note: Confinement could lead to loosely bound ‘baryons’, but these then could collapse to the tightly bound ‘leptons’ already identified in Vachaspati’s scheme. Clearly this is different from the separate baryon and lepton conservation laws which apply at low energy scales, but as one expects those laws not to hold for particles on energy scales approaching the monopole masses this may well be a consistent result.

**Monopole evolution in cosmology**

Monopoles formed on a mass scale significantly higher than the mass scale for inflation would have disappeared during inflation \[26\]: indeed, that is one of the attractive features of inflationary models. However, lighter monopoles would need some other mechanism to explain why we don’t see abundant evidence of their existence today. Many such mechanisms have been proposed, up to quite recent times. One possibility is that the dynamics at some intermediate era between monopole formation and the present would make the poles unstable, allowing them to disappear, even though any remnant which did survive would be stable now \[27, 28\].

If monopoles were created at some early epoch and not swept away meanwhile, then the only way to explain their scarcity today would be by confinement, exactly the phenomenon discussed here. How would that work? If monopoles were formed above the QCD phase transition expected at a temperature of order $\Lambda_{QCD}$, then confinement below that transition would result in attachment of $Z(3)$ strings to each pole, either a single outgoing $2\pi/3$ string, or two outgoing $-2\pi/3$ strings, with the opposite arrangement for antipoles. A pair connected by a single string likely would have disappeared by now, thanks to dissipative forces leading to gradual collapse and annihilation. On the other hand, a large loop with alternating negative and positive flux connecting alternating pole and antipole could be much more durable. This kind of ‘cosmic necklace’, with the poles
as ‘beads’, was suggested by Berezinskii and Vilenkin [29] as a possible source of the highest-energy component of the cosmic ray spectrum, through occasional annihilations of poles and antipoles, which might for example slowly drift together by sliding along the string. The evolution of networks of such strings is an interesting and nontrivial problem, which could be studied once the basic couplings associated with string crossings were determined. In particular, in principle a ‘fusion’ of three strings converging together should be possible, which would allow three monopoles to be connected to each other in a dual version of a baryon. However, if this could happen easily then the problem of too many monopoles would be restored, so a crucial question is whether there is a substantial inhibition of such fusion.

IV. New phenomena in QCD at accessible scales

Theoretical aspects

Even though it is consideration of heavy, fundamental monopoles and their interactions which has led here to the suggestion that they would be held together by $Z(3)$ color flux strings, that statement clearly has a consequence for phenomena at much lower scales than the monopole mass. It means that even in the absence of such poles QCD must support excitations consisting of loops of color magnetic flux, with the mass of a loop being proportional to its circumference. The loops would be unstable against shrinkage, but would give an interesting and nontrivial structure of QCD excitations on a length scale large compared to $1/\Lambda_{QCD}$. This is reminiscent of the Slansky-Goldman-Shaw proposal to explain experimental reports of fractional electric charge [3]. As mentioned earlier, they noted that if a Higgs mechanism at energy scales below, or length scales above, the scale associated with $\Lambda_{QCD}$ could operate to reduce SU(3) of color to SO(3) of ‘glow’, then diquarks could exist in isolation, and of course would carry fractional electric charge. Shortly after, Lazarides, Shafi, and Trower [LST] [30] observed that such a Higgs effect automatically would imply confinement of fundamental monopoles exactly like that argued above.

As was also mentioned earlier, there is no natural starting point from which the phenomena of this particular Higgs mechanism could be deduced in a perturbative framework, the only recognized way to do it. This criticism applies equally to the deduction by LST. Of course, the fact that a conceivable route to a particular result turns out to be rocky and uncertain does not mean the result itself is necessarily wrong, only one still lacks
evidence that it is right. Here the issue has been approached from the other end, and fundamental monopole confinement derived. This does not necessarily imply the isolability of fractional electric charge or the screening of some QCD color-electric fields, but it certainly does say there must be a new feature of QCD at large length scales, namely, loops of color-magnetic flux, just as indicated by LST. Without light quarks, heavy quark confinement implies loops of color-electric flux, so familiar pictures would not be changed so enormously, just ‘dualized’. This means that the change in structure of QCD as the mass of light quarks passes from above to below $\Lambda_{QCD}$ would be quite subtle: Above there would be at least metastable color-electric but substantial suppression of color-magnetic strings (more accurately, very low magnetic string tension), and below something more like the opposite would be true.

The meaning of confinement or non-confinement needs a bit more attention. In terms of a four-dimensional euclidean path integral, confinement is associated with exponential suppression, with the area of an appropriate loop appearing in the exponent, as opposed to effects associated with widely separated finite-mass excitations, in which case only the length (perimeter) of the loop appears. For QCD with dynamical quarks, sufficiently large loops must exhibit a perimeter law, but the coefficient of the perimeter term itself falls exponentially with quark mass because the tunneling leading to quark pair creation is exponentially suppressed. Thus a visible transition on a finite lattice from area to perimeter law occurs at some finite mass, presumably of order $\Lambda_{QCD}$, and should be rather smooth. For the proposed monopole confinement, with monopoles expected to be extraordinarily massive, the breaking of strings by monopole pair creation should be impossibly rare for observation on any finite lattice. If the magnetic strings only exist for finite quark mass, it becomes a delicate question exactly how the string tension depends on that mass. However, again one would expect a smooth transition, with the maximum tension approached for quark mass below $\Lambda_{QCD}$. This leads to the amusing conclusion that fundamental dyons carrying both monopole and quark charges might exhibit an effective confinement with very weak dependence on quark mass.

If all this were confirmed, it would be a vindication of the essential claim of SGS for nontrivial manifestations of fundamental QCD degrees of freedom at large length scales. These color-magnetic-flux-loop excitations presumably should be an important class of what have been called ‘glueballs’, which likely would be drastically different in character from what one would find in QCD without light quarks, and would NOT be pure glue,
as the light quarks must be an essential part of their structure.

As already stated, the fact that confinement of fundamental monopoles would be equivalent to the existence of $Z(3)$ magnetic flux strings means that there is a way to test this proposal in familiar energy regimes of QCD. In particular, as lattice calculations grow steadily better at taking account of light quark degrees of freedom, it should become possible to study this issue on the lattice and obtain credible results. The best way to formulate the problem might be to insist à la Wu and Yang [31] that along a straight line between monopole and antimonopole there is a gauge-matching between vector potentials outside and inside the smallest plaquettes surrounding that line, involving one unit of $Z(3)$ color flux, and one Aharonov-Bohm unit of ordinary magnetic flux. This means a phase of $2\pi$ associated with those plaquettes for $u$ quarks encircling them, but 0 for $d$ quarks. Of course in all other respects there is a standard Dirac electromagnetic monopole vector potential for the pole-antipole system. All this implies, as stated earlier, that there must be a net $Z(3)$ color magnetic flux between monopole and antimonopole. If that flux were observable and not hidden, then monopole confinement would follow, and would be signaled by an area law for exponential suppression of monopole loops in the path integral, associated with the product of the separation between pole and antipole and the Euclidean time duration of that separation.

There might be an analytic approach to determining whether or not confinement occurs, afforded by recent progress in studying supersymmetric nonabelian gauge theories [24, 25, 32, 33]. In these theories it is often possible to make precise conjectures about the particle spectrum, and to verify the conjectures not by a direct proof but rather by subjecting the proposed forms to many different consistency checks, and finding that all are passed. To do this for our problem would require starting with at least an SU(5) theory (including a hypermultiplet containing quarks and leptons), and following an elaborate sequence of Higgs mechanisms to break the manifest symmetry down to $SU(3)_{color} \times U(1)_{electromagnetic}$. This is surely much more complicated than anything which has been done so far with such systems, but might nevertheless be manageable.

**Experimental aspects**

As physics is an experimental science, it surely is worth considering how the new kind of structure proposed here might be accessible to experimental observation. Up to this point in the paper, the main speculation has been the unproved proposal that $Z(3)$ flux loops may exist. To connect that with experiment entails more speculation.
Conventional hadron collisions are not promising. First of all, any frequently occurring peculiar phenomena in such processes would have been noted already. Secondly, because $Z(3)$ strings cannot break by creation of light-quark pairs, their coupling to conventional hadrons should be weak. This implies that they would not be generated easily in typical collisions. What couplings would be possible? Because $u$ and $d$ quark vacuum currents would circulate oppositely around the string, there should be a $\rho_0$-meson magnetic coupling ‘contact term’ – i.e., only acting on sources which themselves overlap geometrically with the string. Thus a contracting string could release energy through emission of $\rho_0$ mesons, but as these are rather massive there would be a poor match, between the likely small energy release in the contraction from one loop energy eigenstate to a lower one and the large mass of the emitted particle. All this implies a quite substantial lifetime for a large loop before collapse. Slow decay almost invariably goes together with low production rates, and helps to explain why even if they can exist $Z(3)$ loops would not have leapt to our attention.

Recently, experiments on deeply-inelastic electron-proton scattering [34] have been interpreted as indicating a ‘hard-pomeron’ contribution to the reaction [35, 36, 37]. By familiar reasoning of Regge duality, such an effect should be associated with a new class of glueball excitations [35]. Could these new glueballs be the magnetic loops proposed here? If so, then it would not be strange if processes described by the hard pomeron also produced the loops. Perhaps detailed exclusive or semi-inclusive studies of such events would reveal structure related to the loops, formed as geometrically large and therefore high-energy excitations.

It then becomes interesting to consider what kind of signal such an object would generate, but that is not easy to determine. All features of closed-string dynamics, many still obscure despite all the years of string studies, would appear to be relevant for the behavior of these $Z(3)$ loops. Thus some caution is needed in guessing what should happen in these scattering processes. This time of course the coupling leading to production would be electromagnetic, but again would involve a contact interaction which at lowest order in momentum transfer would be to the anapole or toroidal moment of the flux loop. This suggests that at the moment of appearance the loop would be quite small in size, but then could expand. If such primitive thinking covers the main features, then it becomes possible to suppose that in a suitable frame boosted along the beam direction there would be a fairly large isotropic ensemble of pions. Because of the decay energy mismatch mentioned
earlier, the pions might be quite limited in their range of momenta. Such an effect could be quite striking, and very different from typical results of deeply-inelastic scattering.

A different picture, analogous to bremsstrahlung of photons, would be that with small probability virtual $Z(3)$ loops exist in the neighborhood of the incident proton, and these are made real by the absorption of the highly virtual photon. To avoid enormous form-factor suppression, in a suitable Breit frame the initial and final momenta of the loop would both have to be large, implying Lorentz contraction which compensates for spatial oscillation of the phase factor in position space, an effect discussed some time ago for elastic scattering on deuterons [38].

If deeply-inelastic electron-proton scattering gives an indirect hint of new long-distance dynamics in QCD, plus the potential to provide more direct evidence, then very high-energy nucleus-nucleus collisions at least have the possibility of generating such evidence in processes with large rate. By heating substantial volumes above the QCD phase-transition temperature, such collisions could permit formation of $Z(3)$ loops, and if so their slow decay during the cooling process would give a characteristic signal, providing important evidence that quark-gluon plasma had formed. If the idea of slow decay is right, this would allow a loop to escape from the dense, highly excited formation region, and then to populate a small volume in pion momentum space with a large number of particles.

While these thoughts about experimental signals are vague and sketchy, it may well be possible with further study to make more precise statements. What seems likely to be unchanged is the fact that a geometrically large object of high coherence, which decays slowly in small energy steps, will produce a signal different from any more familiar system, including a large nucleus. [Of course, if the objects turned out to be at least stable against small perturbations, the signal would be even more striking.]

V. Conclusions

In the title the phenomenon proposed here is referred to as ‘dual confinement’. Of course this makes sense because familiar color-electric confinement of heavy quarks is replaced by color-magnetic confinement of heavy monopoles, but if the proposal is correct as stated then something deeper is at work. Usual discussions posit a duality between superconducting screening of one kind of charge and confinement of the other. Here, however, the screening of color-electric charge is more powerful even than that by a su-
perconductor, because for every heavy quark there is an attached light antiquark, exactly screening not only the local charge but also the Aharonov-Bohm charge. Total screening of the color electric charge carried by heavy quarks is the remnant of the heavy-quark confinement which exists without light quarks. Thus the duality would be one between confinement of fundamental color-magnetic monopoles and total screening of heavy quark color charge, not inconsistent with the familiar version but nevertheless clearly different. If found, such a duality therefore would be something new.

It is enticing to think that physics research is now at a stage where within a short time there might be direct evidence from a variety of directions on whether $Z(3)$ strings occur in nature. Lattice gauge theory or supersymmetric gauge theory could give information, as could deeply-inelastic electron scattering or high-energy nucleus-nucleus scattering. A positive answer would provide a firm foundation for the theoretical and cosmological applications explored above. Perhaps even more satisfying if this happened would be the realization of a remarkable new consequence of QCD. This suggests a further challenge: Are there any other possible ways in which QCD could really give us a surprise? Not easy or obvious, but surely worth looking!

This study was supported in part by the National Science Foundation. I have benefited over a period of time from conversations with Martin Bucher, Georgi Dvali, Edward Shuryak, Mikhail Stephanov, and Tanmay Vachaspati. Richard Slansky was a valued friend and colleague from student days on – about forty years. Although we never collaborated on a paper, it was always a pleasure to discuss with him, and to experience his intelligent and discriminating enthusiasm for physics. His courage in facing physical challenges (in all senses!) was inspiring. Truly the word “glow” was as descriptive of his luminous personality as of the beautiful SGS idea.

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