CAN WE DO FUNDAMENTAL PARTICLE PHYSICS WITHOUT THE SSC?

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Summary

A wide variety of physics issues which the proposed Superconducting Super Collider (SSC) can address also will benefit from lower-energy (particularly non-accelerator) studies, and vice versa. Here several topics are discussed with particular emphasis on the interplay between non-SSC and SSC experiments: (1) cosmic rays; (2) neutrino masses; (3) grand unification (including superstring models), leading to predictions for proton decay and monopoles; (4) dark matter candidates, including neutrinos, axions, and superpartners; (5) precision tests of QED and gravity; (6) CP violation.

I. Introduction

Experimental research on fundamental particle physics has traditionally been pursued on a broad front, making use of both high-energy and low-energy techniques. While the highest available energies are essential for uncovering new layers of matter and for clarifying our understanding of known structures, purely high-energy studies do not tell the whole story. The fundamental theory of the weak interactions was elaborated on the basis of low-energy beta-decay studies. Important support for electroweak unification came both from neutrino experiments (pursued in general, but not exclusively, at the highest available energies) and from the discovery of charm (at Brookhaven and SLAC, using energies substantially below the highest then attainable).

Conversely, the constant drive toward higher energies has provided a simplified picture of the structure of matter. The discovery of heavy hadrons has made the quark idea more palatable, leading to progress in our understanding of hadron physics. The W and Z, essential to the confirmation of the electroweak theory, were only found by extending the frontiers of available energies.

This review describes some low-energy studies which are complementary to ones possible at a large hadron collider. The topics to be discussed are: cosmic rays (sec. II), neutrino masses (sec. III), grand unification and superstrings (sec. IV), dark matter candidates (sec. V), precise tests of QED and gravity (sec. VI), and CP violation (sec. VII). In each of these topics we illustrate the complementarity of low- and high-energy studies (sec. VIII). We conclude in Sec. IX.

II. Cosmic Rays

A. Gamma Rays

In Fig. 1 we show some typical point γ-ray sources.[1] Most are in our own galaxy. One expects as many sources in the southern sky as in the northern. On the other hand, more of the large detectors for γ-ray showers at multi-TeV energies lie in the Northern Hemisphere, as shown in Fig. 2.[2]

High-energy cosmic ray emissions from astrophysical point sources seem to be intermittent, perhaps because matter falls now and then onto a compact object in a binary system. Thus one should observe such sources constantly: if not with one detector, then with a network of them, with uniform coverage in latitude and in longitude.

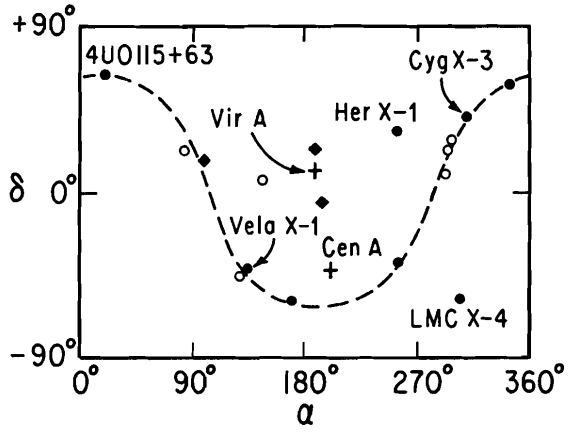

Fig. 1. Point γ-sources. Solid dots: x-ray binaries: open dots: radio pulsars; +: radio galaxies; diamonds: quasars; dashed line: galactic equator.

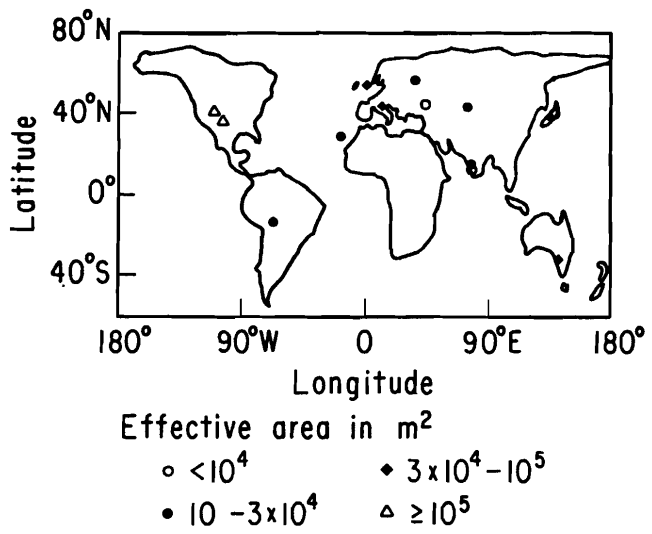

Fig. 2. Large detectors for γ-ray showers.

An interesting recent suggestion[3] has been to place a detector at the South Pole. Those sources which it can see will be visible constantly.

A "typical" point γ-ray sources is Cygnus X-3. Some data on the time-averaged fluxes from this source are collected in Fig. 3.[4] The integral intensity for photons of energy greater than E behaves as $I(>E) \sim E^{-1}$, corresponding to equal power per decade of energy. The size of an array needed to detect 250 photons per year ranges from 100 m^2 for $E > 10^{12}$ eV to 10^5 m^2 for $E > 10^{15}$ eV.

B. Muons

Have muons been detected from Cygnus X-3? Recent claims[5] are hard to understand in terms of conventional physics[6] for a number of reasons.

(1) The Soudan experiment[5] entails large fluxes: 7×10^{-11} $cm^{-2}s^{-1}$ for muons (which had to have at least

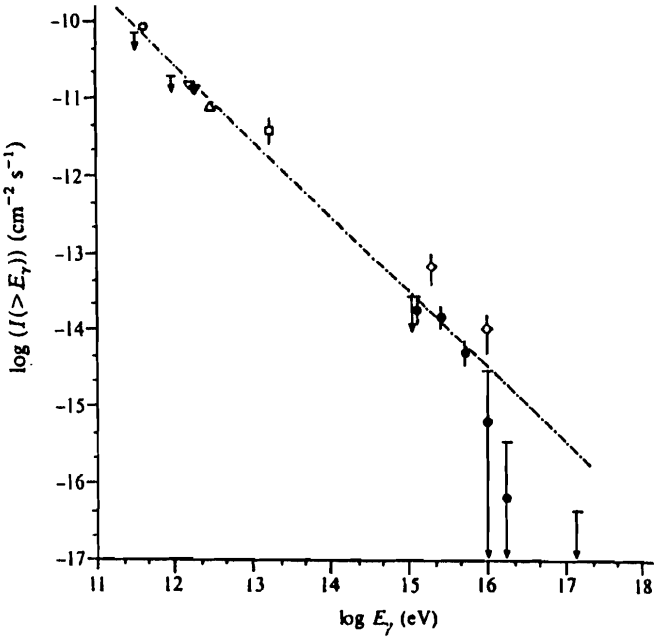

Fig. 3. Integral intensity of photons with energy >E from Cygnus X-3, for the source directly overhead. Fluxes averaged over 24 hours are about 1/4 of these.

several hundred GeV of energy initially if they came from the atmosphere) reaching the detector. This is to be compared with $I(E_\gamma > 1\ \text{TeV}) = 3 \times 10^{-11} \text{cm}^{-2}\text{s}^{-1}$ for the photons depicted in Fig. 3.

(2) The source seems to be larger in angular extent (± 5°) than the resolution of the detectors.

(3) The source seems to be intermittent. Early claims[5] were based on data up to 1985. In the period 1985-6, all observers agree the source is "off".[7]

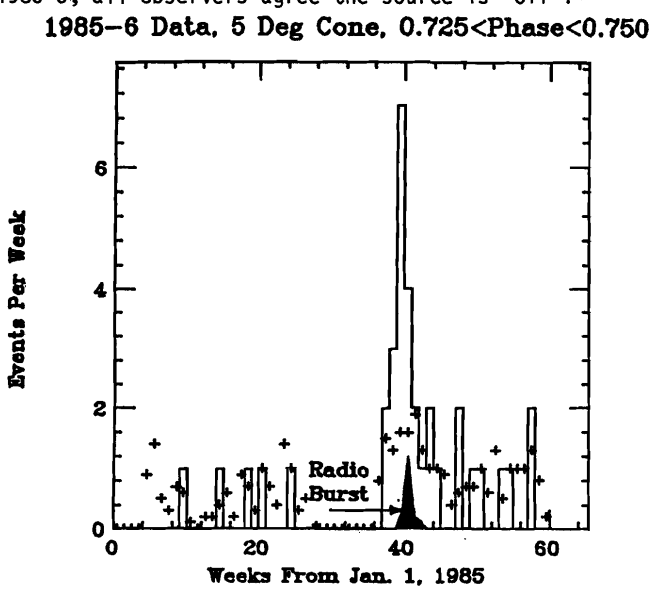

Fig. 4. Burst structure in muons detected from Cygnus X-3. The solid histogram is for events within 5° of the Cygnus X-3 direction, and the points are obtained from off-source directions.

(4) Recent evidence has been presented[7] (see Fig. 4) for a burst in muons from Cyg X-3 during a radio outburst in October of 1985. An experiment in the Homestake mine[8] did not see any activity during this period. One is now waiting for the next radio outburst (they appear to come about once a year) to see if it is correlated with muons. A new Los Alamos experiment,[9] among others, should be capable of monitoring the muons.

(5) One can't explain how any known particle could have reached us from Cyg X-3 with the observed fluxes.[6] We already think we know the photon fluxes, and photons are not expected to produce muons copiously. Neutrons would have decayed long before reaching us. Charged particles would have been bent away by the galactic magnetic field. This has prompted interesting (but premature) theoretical speculation on the possibility of new particles, such as ΛΛ bound states.[10]

C. Neutrinos

As protons are accelerated in a binary system, they may graze the companion object and produce pions which then can decay to neutrinos.[11] Estimated fluxes[12] are such that several large planned detectors (to be discussed) will be sensitive to such astrophysical objects.

D. Present and proposed detectors

High energy techniques that have been in use for many years in cosmic ray experiments, and that are just now bearing fruit at accelerators, include the use of transition radiation detectors.[13] Early indications of rising hadron-hadron total cross sections at high energies came from cosmic ray physics.[14] We can expect this fruitful two-way interchange of information to continue.

There are several forthcoming detectors that will address some of the questions we have mentioned above.

(1) The Homestake Large Area Scintillation Detector (LASD)[8] consists of 140 tons of liquid placed at a depth of 4200 m.w.e. (meters water equivalent). It has already reported surface-underground coincidences. The angular resolution of the detector is expected to be 3 mrad for coincidences.

(2) An existing extensive air shower array at Los Alamos has recently had a neutrino detector calorimeter placed in its center, for the purpose of detecting muons in the shower.[9] It is hoped that this detector may be able to see Cygnus X-3 without reference to the phase of the signal. This phase, with respect to the 4.8 hour orbital period of the binary system, has been a key feature up to now in the claims for signals in both photons and muons.

(3) A large array is planned in conjunction with the Fly's Eye detector in Utah. One group[15] is covering 1100 m^2 with muon detectors, buried 9 feet underground. Another[16] will build a surface array, with effective area 10^5 m^2, sensitive to air showers of energy at least 10^{14} eV. This last array will achieve angular resolution of better than half a degree by timing the arrival of the shower front. It should be able to establish conclusively the existence of a point source without any need to refer to the phase of the signal.

(4) The MACRO detector, planned for the Gran Sasso tunnel, will search for astrophysical neutrinos, among other signals. The masses of different species of neutrinos from supernovae may be measurable by comparing the times of arrival of these different species.

(5) Plans for the DUMAND detector[18] are proceeding apace. A muon-detector string is to be deployed soon.

III. Neutrino Masses

A. Direct measurements (^3H)

In experiments on the beta-decay of tritium, the ITEP group[19] has claimed evidence for a nonzero electron neutrino mass somewhere between 17 and 40 eV, with 30± 2 eV favored. The tritium is incorporated into the amino acid valine, leading to questions about molecular effects on the end-point of the spectrum.

The first results of other experiments sensitive at the same level have begun to appear this year. A Zurich group, using tritium deposited on a carbon foil, has claimed an upper limit of 18 eV for the electron neutrino mass.[20] The e^- spectrum is shown in Fig. 5, together with fits for neutrino masses of 35 eV (ruled out) and zero (compatible with the data). A Los Alamos experiment[21] has obtained an upper limit of 30 eV using an atomic beam, free of substrate effects. Other limits from Tokyo and Beijing groups are comparable.[22] It will take some time before there is a serious challenge to the ITEP value.

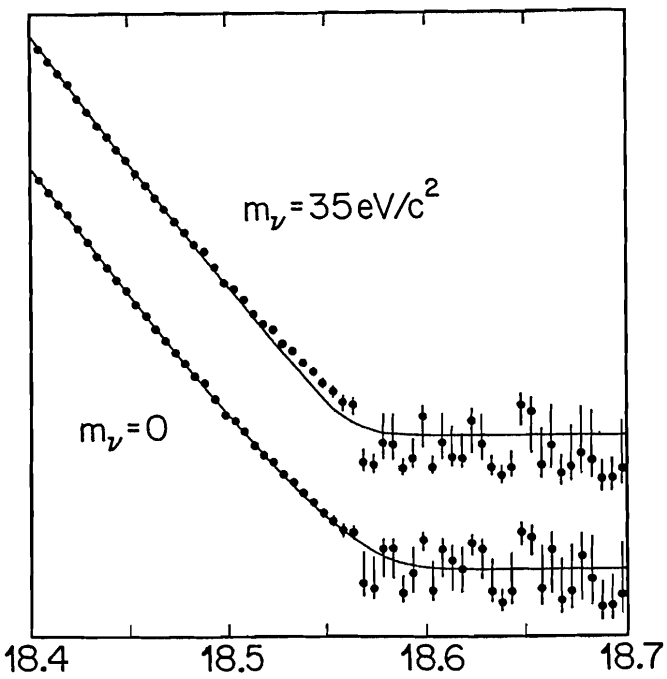

Fig. 5. Electron spectrum in tritium beta decay. The horizontal scale gives the energy in keV.

B. Laboratory oscillations

A claim for neutrino oscillations observed at the Bugey reactor[23] is not borne out by data from Gösgen.[24] An extensive review of neutrino oscillation phenomena has been written by Flaminio and Saitta.[25]

C. Solar oscillations

The solar neutrino flux is predicted to give a capture rate in ^{37}Cl of 5.8±2.2 SNU,[26] where 1 SNU = 10^{-36} captures/atom/sec. This is larger than the observed rate of 2.1±0.3 SNU.[26,27] Recently it has been suggested that this may be due to the transition $\nu_e \rightarrow \nu_\mu$ in matter.[28] Now, various present and proposed solar neutrino experiments are sensitive to different energies:

Table 1. Solar neutrino experiments

Location	Medium	Size(t)	Threshold (MeV)	Ref.
Homestake	^{37}Cl	133	0.814	27
Homestake	^{81}Br	474	0.49	29
Baksan	^{71}Ga	60 (→80)	0.2332	30
Gran Sasso	^{71}Ga	30	0.2332	31
Kamioka	H_2O	680 (fid.)	6	32
Sudbury	D_2O	1000	2.2	33

The expected solar neutrino fluxes from various sources[26] are shown in Fig. 6. These would lead to the capture rates given in Table 2.

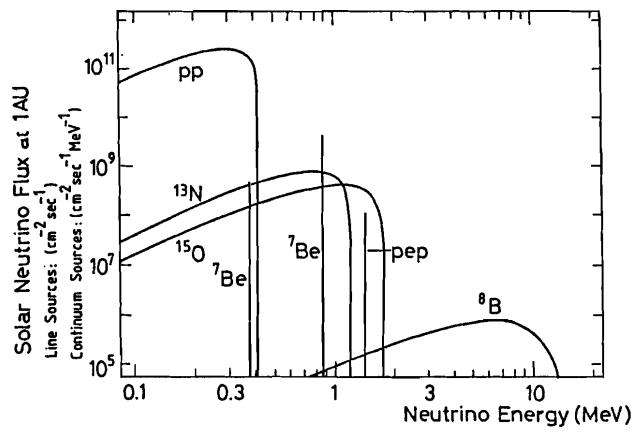

Fig. 6. Expected solar neutrino fluxes.

Table 2. Expected capture rates in SNU for solar neutrino detectors.[26,29] Underline indicates dominant process for each detector.

Source	Energy (MeV)	^{37}Cl rate[26]	^{71}Ga rate[26]	^{81}Br rate[29]
pp	0 - 0.42	0	70.2	0
pep	1.44	0.024	2.5	1.2
^{7}Be	0.384	0	0.9	
	0.862	0.95	26.1	10 - 11
^{8}B	0 - 15	4.3	1.2	1 - 2
^{13}N	0 - 1.2	0.08	2.6	1
^{15}O	0 - 1.73	0.24	3.5	1.5
Total		5.8	107	15

If the gallium experiments give the expected results, one may conclude either that the matter regeneration mechanism[28] is depleting the higher-energy neutrinos visible in the chlorine experiment, or that these neutrinos are less abundant because of a slightly lower solar core temperature. On the other hand, there is a substantial possibility that the matter-oscillation mechanism[28] can lead to fewer neutrinos in the gallium experiment than expected from Table 2. In that case, one has again at least two possibilities, since neutrino oscillations in vacuum can also lead to a depletion. The ^{81}Br experiment has a threshold intermediate to that of the low-threshold ^{71}Ga detector (sensitive to the main process in the Sun) and the high-threshold ^{37}Cl detector (sensitive to a subsidiary branch). It can provide useful complementary information. The H_2O and D_2O Cerenkov detectors noted in Table 1 will be sensitive to neutral- as well as charged-current inter-

actions of neutrinos, and hence will be able to check whether fluxes are lower because of oscillations or astrophysics. Other possible plans are discussed in Ref. 25.

IV. Grand Unification

A. Theories

The simplest unification of $SU(3)_{color} \times SU(2)_L \times U(1)$, into SU(5),[34] entails also interactions which change $SU(3)_{color}$ and $SU(2)_L$ simultaneously, and lead to proton decay. At the scale at which SU(5) breaks down, ultraheavy magnetic monopoles are generated.

Many unification schemes beyond SU(5) have been proposed. The simplest, SO(10),[35] which contains SU(5), unifies quarks and leptons into generations of 16-plet spinors. Recent attention to the group E_6,[36] which contains SO(10), has been generated by interest in superstrings.[37]

B. Nucleon decay

Several factors allow for less restrictive proton decay predictions in GUTs beyond SU(5). There can be more than one "low-energy" U(1). If low-energy supersymmetry holds, the rate at which coupling constants approach unification is slowed down, leading to higher unification mass scales. Superstring theories embody both extra U(1)'s and supersymmetry. If the proton does not decay in 1 sec (as a result of undesirable couplings which must be banned by hand), it can be made satisfactorily long-lived in such theories.

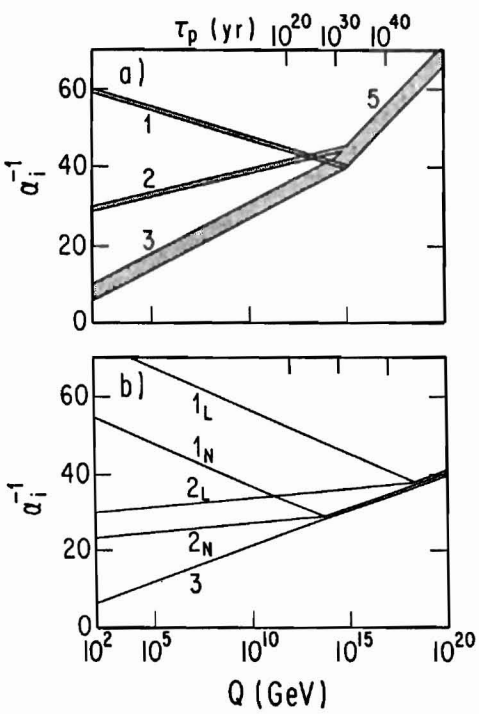

Fig. 7. Inverse coupling strengths vs. Q for color SU(3), $SU(2)_L$, and other gauge groups. a) Standard electroweak model; b) model with extra U(1) and other subgroups, based on $[SU(3)]^3$.

Consider, first, the SU(5) unification illustrated in Fig. 7a. $SU(3)_{color}$ and $SU(2)_L$ couplings come together somewhere between 10^{15} and 10^{18}GeV. If they are to be joined by a single U(1), the scale at which all three come together must be close to the lowest possible one in this interval. The requirement of unification below 10^{15} GeV leads to a predicted proton lifetime less than 10^{32} yr.[38]

If more than one "low-energy" U(1) contributes to the electric charge, the above constraints are relaxed. An extreme situation, motivated by superstrings, is shown in Fig. 7b. $SU(2)_L$ and a $U(1)_{"L"}$ come together at one energy into an $SU(3)_{"L"}$. Another $U(1)_{"N"}$ contributing to the electromagnetic charge is unified with an $SU(2)_{"N"}$, not contributing to charge, at some other energy. The result is an $[SU(3)]^3$ group which contains no gauge bosons that could cause proton decay.[39] Such a group can be incorporated into an E_6, which does not contain such bosons, but with only the Planck scale of 10^{19} GeV as an upper limit to the energy at which E_6 can break down to $[SU(3)]^3$, and hence only an upper limit of about 10^{50} years[40] to τ_p.

It has been suggested that the proton might decay to less accessible modes than the easily studied $e^+\pi^\circ$ channel. Considerable improvement has been reported recently in limits on many other channels.[41] The partial lifetimes generally exceed 10^{31} - 10^{32} yr.

Does an "ultimate" detector, capable of studying proton lifetimes in excess of 10^{34} yr, make sense? Of course it does, but now that the theorists' SU(5) milepost has been passed, the experimentalists are on their own.

C. Constraints on extra U(1)'s

Several low-energy tests of neutral current interactions may be used to constrain extra U(1)'s such as those appearing in superstring theories. These tests include:

1) Neutrino-quark deep inelastic scattering
2) Polarized electron-nucleon scattering
3) Atomic parity violation
4) Elastic (anti)neutrino-electron scattering
5) Forward-backward asymmetries in $e^+e^- \to \mu^+\mu^-$
6) Coherent neutrinoproduction of neutral pions.

Contributions to all these processes arise both from Z° exchange and from the exchange of any extra Z's. The typical extra contributions can be at most 10% those of the Z°. For equal couplings, this would imply $(m_{Z'}/m_Z)^2 > 10$. In fact the limits tend to be somewhat poorer, since the U(1) coupling strengths (involved in most Z' models) are smaller than that of $SU(2)_L$ (which contributes to the Z° interaction with matter).[42]

Recent studies of atomic parity violation in cesium,[43] at the 10-15% level, are the major constraint on certain models of extra U(1)'s, particularly the one that arises in an SO(10) GUT.[42,44]

D. Monopoles

1) Flux limits are pushing down toward the Parker bound[45] of less than $10^{-15}cm^{-2}sr^{-1}s^{-1}$.

2) New large detectors are coming into operation, such as the Large Area Scintillation Detector[8] at Homestake, and MACRO[17] at Gran Sasso (see Fig. 8). MACRO will improve present scintillator-based bounds (Fig. 9).[46]

3) Nucleon decay catalysis is an expected property of GUT monopoles.[47] If the cross section for catalysis is a typical strong one, observed neutron star luminosities limit the flux to be less than $10^{-21}cm^{-2}sr^{-1}s^{-1}$.[48,49]

4) Monopoles that don't catalyze nucleon decay aren't constrained by the above estimate, but may be able to gobble up magnetic fields in neutron stars too

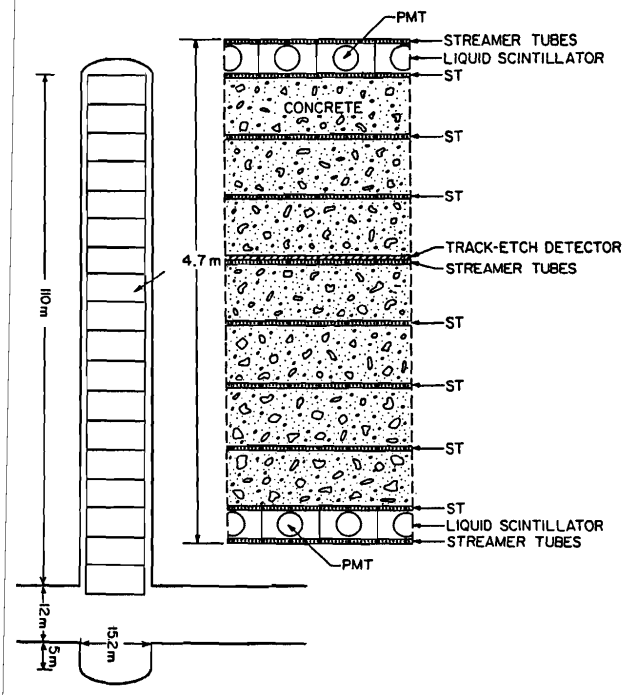

Fig. 8. Experimental hall and detail of one module for the MACRO detector in the Gran Sasso tunnel.

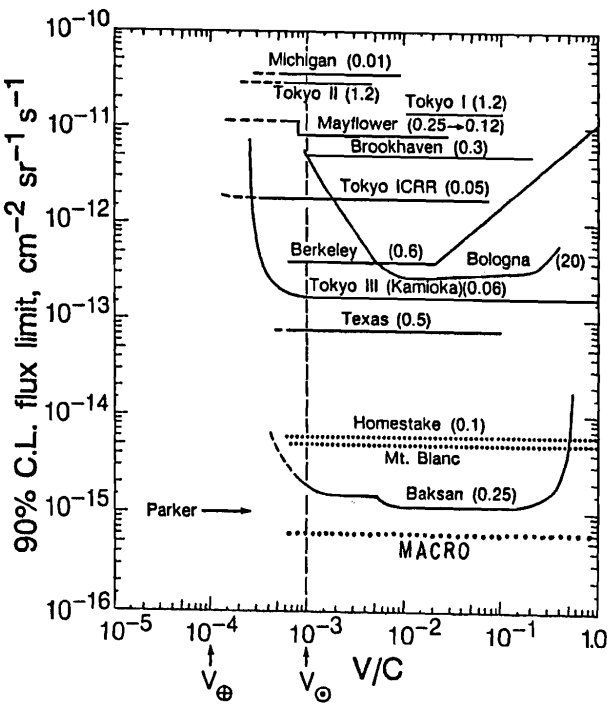

Fig. 9. Bounds on monopole fluxes obtained from scintillation detectors. Dotted lines indicate one-year limits for planned experiments.

rapidly unless their fluxes at those stars are very low.[49] Such monopoles can emerge at lower mass scales than the GUT scale in theories beyond SU(5). They can have larger charges than ordinary GUT monopoles, which makes the Parker limit on them somewhat more stringent.[50]

V. Dark Matter Candidates

A. Why is there a problem?

Current ideas on the inflationary universe favor the notion that the universe is just on the boundary between being open and closed.[51] The amount of luminous matter in galaxies, on the other hand, seems to be a small fraction of that needed to close the universe.[52] The dynamics of galaxies and clusters indicates that some matter isn't shining.[53] What could this matter be?

B. Candidates for dark matter

1) Subluminous stars (Jupiters) are very hard to see, even at close range.

2) Neutral leptons such as neutrinos of 30 electron volts[54] could close the Universe.

3) Superpartners of observed particles, such as GeV photinos,[55] could be present in galactic halos.

4) Axions associated with the spontaneous breakdown at energies of 10^9 - 10^{12}GeV of global symmetries are acceptable candidates for dark matter in the Universe.[56] Such particles are expected to be ultralight, typically of masses 10^{-5} - 10^{-2}eV.

C. Detection schemes

Many techniques are under discussion for observing dark matter candidates.[57] A few of these include thermal and acoustic phonon detection,[58] the Primakoff effect,[59] the axionic analogue of the photoelectric effect,[60] and the search for neutrinos produced by the annihilation of such candidates in the sun.[61]

VI. Precision Tests

A. QED

It is instructive to discuss the mass scales attainable by a beautiful series of non-accelerator experiments: the study of single electrons in a Penning trap.[62] The corresponding experimental and theoretical[63] values,

$$a_e \equiv (g-2)_e/2 = 1\ 159\ 652\ 193\ \ (4) \times 10^{-12}(\text{exp}),$$

$$1\ 159\ 652\ 460\ (147) \times 10^{-12}(\text{th}),$$

imply that if [64] $|\delta a_e| = m_e/m^* \equiv m_e R_e$, then $m^* > 1000$ TeV or $R_e < 2 \times 10^{-20}$cm; similar limits exist for muons. However, for chirally invariant models, $|\delta a_e| \sim (m_e/m^*)^2$, and since this is $<5 \times 10^{-10}$, the limit only implies $m^* > 20$ GeV. The impact of low-energy experiments depends on the theory being tested.

B. Gravity

1) Reports of a "fifth force" stemmed from a reanalysis of the Eötvös experiments which seemed to show a dependence of the gravitational attraction on the ratio of baryon number to atomic mass number.[65] The evidence is controversial.[66] However, it has stimulated more precise experiments.[67,68] Imagine the correction to the gravitational potential to be of the form

$$V = -(GM/R)\ (1 + \alpha e^{-R/\lambda}) \quad .$$

Satellite observations constrain the product $\alpha\lambda$ to be less than 10 m,[68] while observations[68,69] for $R \ll \lambda$ constrain $\alpha/\lambda^2 < 3 \times 10^{-3} m^{-2}$. These regions are shown in Fig. 10, together with a dashed line showing possible deviations from an inverse-square force based

on geophysical experiments.[70] There is clearly a large gap in our present knowledge at intermediate distances.

2) Gravitational radiation experiments have had a long and difficult history, since Weber's original proposal[71] in 1960. The most recent published experiments[72] set limits on a strain parameter $h <$ (few x 10^{-18}), only a couple of orders of magnitude below Weber's original sensitivity. An accuracy of $h < 10^{-20}$ is envisioned for the near future.[73] Other groups engaged in such studies include those in Rochester,[74] Caltech/Glasgow,[75] and MPI-Munich.[76] These are not "table-top" experiments. They involve much effort and cost.

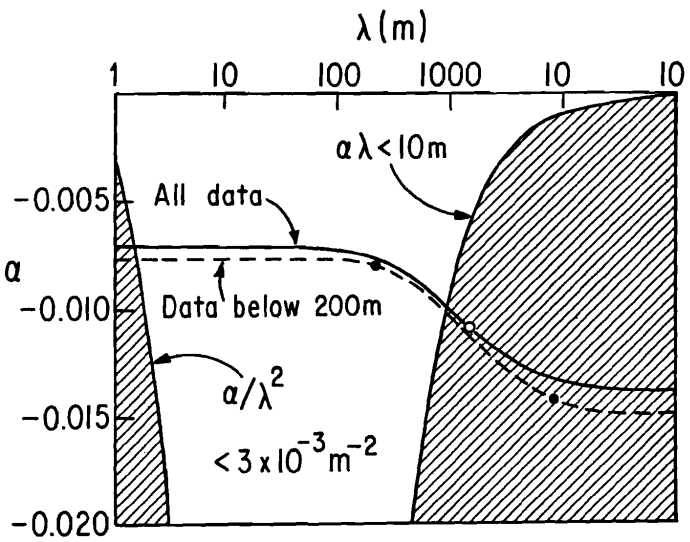

Fig. 10. Parameters α (strength) and λ (range) allowed for a fifth force.

VII. CP Violation

High-energy studies of the K_S - K_L system have been the mainstay of CP violation investigations so far. However, low-energy production of kaons under controlled circumstances (as in proton-antiproton annihilations[77]) may be a major source of future information. Limits on the electric dipole moment of the neutron, obtained without high energy accelerators, keep improving.[78] Recently it has been proposed to study such T-violating observables by applying an electric field to a paramagnetic sample and observing the induced magnetization with a SQUID.[79]

VIII. Interrelations

We shall discuss several examples of the two-way information flow between "Non-Accelerator" and "Accelerator-based" physics.

A. Cosmic rays

1) "Non-Accelerator" → "Accelerator": New particles can make their first appearance in cosmic sources. Optimists believe this has already happened in the case of Cygnus X-3. Astrophysical sources could provide ideas for new acceleration techniques, for example through the intense magnetic fields in neutron stars.[11]

2) "Accelerator" → "Non-Accelerator": Conventional accelerator-based experiments are an excellent way to find the exotic particles invoked to explain unusual cosmic ray events. For example, the hypothetical ΛΛ bound state discussed earlier[10] is accessible at the Brookhaven AGS, and plans exist to look for it there.[80] Accelerator beams, despite all the whims of directors, scheduling committees, and machine tinkerers, are still more reliable than intermittent astrophysical sources.

B. Neutrino masses

1) "Non-Accelerator" → "Accelerator": The electron-volt neutrino masses m_ν accessible in beta-decay experiments provide indirect information on very large mass scales M, possibly higher than can be probed by present accelerators. (In many theories, the product $m_\nu M$ is of the same order as a typical charged fermion mass.)

2) "Accelerator" → "Non-Accelerator": The Z° width will enable us to learn more about the number of light neutrino species, thus providing a check of nucleosynthesis models.[81] Fixed target experiments involving neutrinos continue to be of use in studying oscillations, and in the search for rare neutral leptons. Accelerators are a prime tool for massive neutrino searches (especially in rare Z decays). Finally, at accelerators, one can learn by looking at the signs of charged leptons in the decay products about the nature of any new heavy neutral leptons that may be discovered. Are they Majorana or Dirac? Answering this question is crucial to the interpretation of the non-accelerator-based beta decay experiments discussed just above.

C. Grand unified theories and strings

1) "Non-Accelerator" → "Accelerator": Experiments on nucleon decay and monopoles probe GUT scales far higher than those accessible in direct accelerator studies. "Table-top" experiments on atomic parity violation test for unusual neutral currents, shedding indirect light on extra Z's as heavy as a couple of hundred GeV.

2) "Accelerator" → "Non-Accelerator": The discovery of exotic fermions and new gauge bosons predicted by extended GUTs will lead to new nucleon decay and monopole predictions.

D. Dark matter

1) "Non-Accelerator" → "Accelerator": The dynamics of galaxies and clusters suggests that we need some form of dark matter, whether new or more familiar. Numerous constraints on this matter exist, coming from the isotropy of the 3K background radiation and from neutrino detectors.[82]

2) "Accelerator" → "Non-Accelerator": Laboratory searches for such objects as photinos and heavy leptons are straightforward (though they have been negative, so far). These searches are essential in finding out what the dark matter candidates are.

E. How can the SSC help?

1) Cosmic rays: The SSC can verify crude initial results, as for the hadron-hadron total cross-section.[14] Recall that a 20 + 20 TeV collider is like having 10^{18} eV cosmic ray protons strike a fixed target!

2) Neutrinos: The SSC can produce massive neutral leptons, which are related to light neutrino masses in some schemes. Fixed-target physics at the SSC can play an important role in neutral-lepton studies.

3) GUTS and superstrings: The SSC will be ideal for searching beyond the standard electroweak gauge group and for uncovering new Z's, W's, and fermions. It can find the hypothetical superpartners at the root of most modern GUT and superstring theories, and, at an even more elementary level, the Higgs bosons whose masses are to be protected from divergences by supersymmetry.

4) Dark matter: Light pseudoscalar mesons (axion-like objects) are harbingers of new (spontaneously broken) global symmetries, such as arise in technicolor

schemes. The SSC[83] (and, indeed, lower-energy machines[84]) will study such schemes in detail. Other candidates for dark matter accessible at the SSC include heavy neutral leptons and superpartners.

5) Precision tests: Using the SSC, one will be able to directly dissociate quarks and leptons into components if the compositeness scale is several TeV or less. Thus the SSC can be competitive with precise experiments testing for substructure, as noted earlier. The SSC, by producing new gauge bosons, also can uncover aspects of new forces which may have implications for gravity tests.

6) CP tests: It was concluded in 1984 that the SSC was a possible source of B mesons for CP violation studies, but that experiments would not be easy.[85] Recent projections are more optimistic, and a specific detector of heavy flavors at the SSC is being designed.[86]

IX. Conclusions

Accelerator-based and non-accelerator (or low- and high-energy) experiments are complementary to one another.

One must choose forthcoming high-energy experiments carefully, as some physics is best addressed on the "table top". (Here we must include "tables" of up to $10^5 m^2$ in area!)

However, some "table-top" experiments, when looked at more closely, require substantial time, manpower, and funds in order to have an impact.

One must also choose non-accelerator experiments carefully. Some questions are answered most directly at high energies, and/or via accelerator experiments.

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References

1. G. Cocconi, presented at Capri Meeting on Ultra-high-energy Gamma Ray Astronomy, April, 1984; T. Matano et al., in *Techniques in Ultra High Energy Gamma Ray Astronomy* (Proc. of workshop at La Jolla during 19th ICRC, Aug. 23, 1985), edited by R. J. Protheroe and S. A. Stephens, Dept. of Physics, Univ. of Adelaide, October, 1985, p. 54; M. Cherry *et al.* and M. Samorski, presentations at International School of Cosmic Ray Physics, Erice, Sicily, June 5, 1986; E. Peterson, private communication; J. Cronin, private communication; K. Gibbs, private communication.
2. M. Samorski (Ref. 1).
3. A. M. Hillas, Univ. of Leeds preprint, April, 1986.
4. J. Lloyd-Evans *et al.*, Nature 305, 784 (1983), and references therein.
5. M. L. Marshak *et al.*, Phys. Rev. Lett. 54, 2079 (1985); 55, 1965 (1985); J. Bartelt *et al.*, Phys. Rev. D32, 1630 (1985); C. Battistoni *et al.*, Phys. Lett. 155B, 465 (1985).
6. V. S. Berezinsky, J. Ellis, and B. L. Ioffe, Phys. Lett. 172B, 423 (1986); K. Ruddick, Phys. Rev. Lett. 57, 531 (1986); T. Gaisser and F. Halzen, Univ. of Wisconsin preprint MAD/PH/287, May, 1986, presented at Joint-Physics-Astrophysics Session, 21st Rencontre de Moriond, Les Arcs, France, Mar. 9-16, 1986; J. Collins and F. Olness, Illinois Institute of Technology preprint IIT-TH-86-29, May, 1986, contributed to the 23rd Int. Conf. on High Energy Physics, Berkeley, CA, July 16-23, 1986.
7. D. S. Ayres, Argonne Natl. Lab. report ANL-HEP-CP-86-39, June 5, 1986, presented to the 2nd Conference on the Intersections between Particle and Nuclear Physics, Lake Louise, Canada, May, 1986, proceedings edited by Donald F. Geesaman (AIP, New York, 1986).
8. M. Cherry, *et al.* (Ref. 1).
9. D.E. Nagle *et al.*, 19th ICRC, La Jolla, 1985, Proc. Gamma Ray Workshop (see Ref. 1), p. 66.
10. G. Baym *et al.*, Phys. Lett. 160B, 181 (1985).
11. For discussion of proposed acceleration mechanisms, see Gaisser and Halzen (Ref. 6).
12. T. Gaisser, Bartol Research Foundation preprint BA-86-31, 1986, presented at Joint Physics-Astrophysics Session, 21st Rencontre de Moriond, Les Arcs, France, Mar. 9-16, 1986, and at Vulcano Workshop, Vulcano, Sicily, May, 1986.
13. S. Y. Hsueh *et al.*, Phys. Rev. Lett. 54, 2399 (1985).
14. G. B. Yodh, Y. Pal, and J. S. Trefil, Phys. Rev. Lett. 28, 1005 (1972); Phys. Rev. D8, 3233 (1973); D.E. Groom, report no. SSC-N-154, Lawrence Berkeley Laboratory, June 25, 1986.
15. J. W. Chapman *et al.*, "Proposal to complement the Fly's Eye with subsurface muon detectors," July, 1985 (D. Sinclair and J. C. van der Velde, spokesmen).
16. J. W. Cronin, "A proposal for a large surface array at Fly's Eye II," preliminary version, June, 1986.
17. Bari-Bologna-Caltech-CERN-Drexel-Frascati-Indiana-Michigan-Pisa-Roma-Texas A&M-Torino-Virginia Tech Colaboration, "Proposal for a Large Area Detector Dedicated to Monopole Search, Astrophysics, and Cosmic Ray Physics at the Gran Sasso Laboratory," November, 1984 (unpublished).
18. V. Peterson, in "Proceedings of the Sixth Workshop on Grand Unification, Minneapolis, MN, Apr. 18-20, 1985, edited by S. Rudaz and T. Walsh (World Scientific, Singapore, 1985), p. 543.
19. S. D. Boris *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. 42, 107 (1985) [Sov. Phys. - JETP Lett. 42, 130 (1985)]; Phys. Lett. 159B, 217 (1985); V. A. Lyubimov, to be published in *Proceedings of the 6th Moriond Workshop on Massive Neutrinos in Particle Physics and Astrophysics*, Tignes, France, Jan. 25-Feb. 1, 1986.
20. M. Fritschi *et al.*, presented at Lake Louise Conference (Ref. 7); Phys. Lett. 173B, 485 (1986).
21. D.A. Knapp *et al.*, presented at Lake Louise Conference (see Ref. 7.)
22. R.G.H. Robertson, Los Alamos report LA-UR-86-1956, 1986, presented at Lake Louise Conference (see Ref. 7).
23. J. F. Cavaignac *et al.*, Phys. Lett. 148B, 387 (1984).
24. V. Zacek *et al.*, Phys. Lett. 164B, 193 (1985), and 6th Moriond Workshop (see Ref. 6). Possible resolutions of the conflict between Ref. 23 and this work, and a claimed signal for oscillations at the CERN PS, are reviewed in Ref. 22.
25. V. Flaminio and B. Saitta, report no. INFN PI/AE

85/6, submitted to Rivista del Nuovo Cimento. See also S.M. Bilenky and S.T. Petcov, submitted to Rev. Mod. Phys., 1986.

26. J. Bahcall, B.T. Cleveland, R. Davis, Jr., and J. K. Rowley, Astrophys. J. 292, L79 (1985).

27. J.K. Rowley, B.T. Cleveland, and R. Davis, Jr., in *Solar Neutrinos and Neutrino Astronomy* (Homestake, 1984), AIP Conference Proceedings No. 126, ed. by M. L. Cherry *et al.* (AIP, New York, 1985), p. 1.

28. L. Wolfenstein, Phys. Rev. D17, 2369 (1978); D20, 2634 (2979), V. Barger *et al.*, *ibid.*, D22, 2718 (1980); S.P. Mikheyev and A. Yu. Smirnov, Nuovo Cim. 9C, 17 (1986); H. A. Bethe, Phys. Rev. Lett. 56, 1305 (1986); P. Langacker *et al.*, CERN report Th.-4421/86, April, 1986; S.P. Rosen and J. M. Gelb, Phys. Rev. D34, 969 (1986); E.W. Kolb, M. S. Turner, and T.P. Walker, Phys. Lett. 175B, 478 (1986); V. Barger, R.J.N. Phillips, and K. Whisnant, Phys. Rev. D34, 980 (1986); A. Dar and A. Mann, Technion preprint PH-86-29, 1986; G. Steigman, Bartol Research Foundation report BA-86-22, 1986, to be published in *Proceedings of the 6th Moriond Workshop on Massive Neutrinos in Particle Physics and Astrophysics*, Tignes, France, Jan. 25-Feb. 1, 1986; W.C. Haxton, Phys. Rev. Lett. 57, 1271 (1986); S. Parke, Phys. Rev. Lett. 57, 1275 (1986); S. Parke and T. Walker, Fermilab-Pub-86/107-TA, July, 1986.

29. G.S. Hurst *et al.*, in *Solar Neutrinos and Neutrino Astronomy* (see Ref. 27), p. 152. For an early discussion see R.D. Scott, Nature 264, 729 (1976). The ^{81}Br numbers in Table 2 are preliminary values from M. Cherry (private communication). For more recent estimates and a discussion of uncertainties in the ^{81}Br and ^{71}Ga rates, see M. Cherry, these proceedings.

30. R. Davis, M.L. Cherry, and K. Lande, "Proposal for a US-USSR Collaborative Search for Solar p-p Fusion Neutrinos Using a Gallium Detector," Univ. of Pennsylvania preprint, 1986.

31. D. Vignaud *et al.*, Saclay preprint DPhPE 85/02, June, 1985, presented at 5th Moriond Astrophysics Meeting on Nucleosynthesis and Its Implications on Nuclear and Particle Physics, Les Arcs, France, Mar. 17-23, 1985.

32. M. Koshiba *et al.*, Univ. of Tokyo UT-ICEPP-85-04, 1985, to be published in Prog. Theor. Phys. Suppl., 1986 (volume dedicated to Prof. Y. Nambu); E. Beier, private communication and these proceedings. For the parameters of the proposed "Super Kamiokande" experiment, see Y. Totsuka, Univ. of Tokyo report UT-ICEPP-86-06, presented at 7th Workshop on Grand Unification, Toyama, Japan, April, 1986.

33. G.T. Ewan *et al.*, Sudbury Neutrino Observatory report SNO-85-3, July, 1985 (unpublished); E.D. Earle *et al.*, in *Weak and Electromagnetic interactions in Nuclei* (Heidelberg, 1986), edited by H.V. Klapdor and J. Metzinger (Univ. of Heidelberg, 1986), Abstracts, p. 62.

34. H. Georgi and S.L. Glashow, Phys. Rev. Lett. 32, 438 (1973).

35. H. Georgi, in *Particles and Fields - 1974*, proceedings of the meeting of the Division of Particles and Fields of the American Physical Society, Williamsburg, Virginia, edited by C.E. Carlson (AIP, New York, 1974), p. 575; H. Fritzsch and P. Minkowski, Ann. Phys. (N.Y.) 93, 193 (1975).

36. F. Gürsey, P. Ramond, and P. Sikivie, Phys. Lett. 60B, 177 (1976); R. Barbieri, D.V. Nanopoulos, and A. Masiero, Phys. Lett. 104B, 194 (1981), and references therein.

37. J. Rosner, Comments on Nuclear and Particle Physics 15, 195 (1986), and references therein.

38. For a recent summary see P. Langacker, in *Proceedings of the 1985 International Symposium on Lepton and Photon Interactions at High Energies*, Kyoto, Aug. 19-24, 1985, edited by M. Konuma and K. Takahashi (Research Institute for Fundamental Physics, Kyoto, 1986), p. 186. W. Marciano (these proceedings) has recently cited the slight mismatch of unification scales, evident in Fig. 7a, as further evidence against SU(5).

39. R.W. Robinett and J.L. Rosner, Phys. Rev. D26, 2396 (1982); S.L. Glashow, in *Proceedings of the 5th Workshop on Grand Unification*, Providence, R.I., Apr. 12-14, 1984, edited by K. Kang, H. Fried, and P. Frampton (World Scientific, Singapore, 1984), p. 88.

40. A.D. Sakharov, Zh. Eksp. Teor. Fiz. Pis'ma 5, 32 (1967) [Sov. Phys. - JETP Letters 5, 24 (1967)].

41. G. Blewett *et al.*, Phys. Rev. Lett. 55, 2114 (1985); J. M. LoSecco *et al.*, Univ. of Notre Dame report UND-PDK-86-8, presented at Neutrino '86, Sendai, Japan, June, 1986; S. Seidel, these proceedings; M. Koshiba, *et al.*, presented at 7th Workshop on Grand Unification, Toyama, Japan, April, 1986.

42. D. London and J. Rosner, Phys. Rev. D34, 1530 (1986); V. Barger *et al.*, Univ. of Wisconsin preprint MAD/PH/299, July, 1986, submitted to Phys. Rev. Letters.

43. S.L. Gilbert *et al.*, Phys. Rev. Lett. 55, 2680 (1985); S.L. Gilbert and C.E. Wieman, Univ. of Colo. preprint, 1986, subm. to Phys. Rev. D.

44. R.W. Robinett and J.L. Rosner, Phys. Rev. D25, 3036 (1982), and references therein.

45. E.N. Parker, Astrophys. J. 160, 383 (1970); M.S. Turner, E.N. Parker, and T.J. Bogdan, Phys. Rev. D26, 1296 (1982); E.E. Salpeter, S.L. Shapiro, and I. Wasserman, Phys. Rev. Lett. 49, 1114 (1982).

46. D. Groom, Univ. of Utah report UUHEP-85/8, October, 1985, to be published in Phys. Reports.

47. V.A. Rubakov, Pis'ma v Zh.Eksp. Teor. Fiz. 33, 658 (1981) [Sov. Phys. - JETP Letters 33, 644 (1981)]; Nucl. Phys. B203, 311 (1982); N.S. Craigie, W. Nahm, and V.A. Rubakov, Nucl. Phys. B241, 274 (1984), and references therein; C. G. Callan, Jr., Phys. Rev. D25, 2141 (1982); D26, 2058 (1982); Nucl. Phys. B212, 391 (1983).

48. K. Freese, M.S. Turner, and D.N. Schramm, Phys. Rev. Lett. 51, 1625 (1983).

49. J. Harvey, M. Ruderman, and J. Shaham, Phys. Rev. D33, 2084 (1986).

50. H. Hodges, E.W. Kolb, and M. Turner, Fermilab-Pub-86/63-A, April, 1986.

51. A. Guth, Phys. Rev. D23, 347 (1981).

52. S. Faber and J.S. Gallagher, Ann. Rev. Astron. and Astrophys. 17, 135 (1979).

53. D. Burstein and V.C. Rubin, Ap. J. 297, 423 (1985).

54. R. Cowsik and J. McLelland, Phys. Rev. Lett. 29, 669 (1972).

55. J. Silk and M. Srednicki, Phys. Rev. Lett. 53, 624 (1984); J. Silk, K. Olive, and M. Srednicki, *ibid.*, 55, 257 (1985).

56. J. Ipser and P. Sikivie, Phys. Rev. Lett. 50, 925 (1983); F. Stecker and Q. Shafi, *ibid.*, 928 (1983); M. Turner, F. Wilczek, and A. Zee, Phys. Lett. 125B, 35 (1983).

57. *Workshop on Cryogenic Detectors for Neutrinos and Dark Matter Candidates*, Santa Barbara, Calif., Jan. 17-19, 1986.

58. B. Cabrera, L. Krauss, and F. Wilczek, Phys. Rev. D32, 2988 (1985); A. Zehnder, Ref. 57; S.P. Ahlen *et al*., Harvard Center for Astrophysics preprint no. 2292, 1986, submitted to Phys. Rev. Lett.

59. P. Sikivie, Phys. Rev. Lett. 51, 1415 (1983); Phys. Rev. D32, 1988 (1985); P. Sikivie, N. Sullivan, and D. Tanner, proposal, 1986 (unpublished); L. Krauss, J. Moody, F. Wilczek, and D. E. Morris, Phys. Rev. Lett. 55, 1797 (1985).

60. S. Dimopoulos, G. Starkman, and B.W. Lynn, Phys. Lett. 168B, 145 (1986); F. T. Avignone *et al.*, report SLAC-PUB-3872, Jan., 1986, subm. to Phys. Rev. D.

61. M. Srednicki, K.A. Olive, and J. Silk, Univ. of Minn. preprint UMN-TH-553/86, March, 1986; T. K. Gaisser, G. Steigman, and T. Tilav, Bartol Research Foundation report BA-86-42, 1986, and references therein.

62. H. Dehmelt, Ann. Phys. Fr. 10, 777 (1985); R. S. van Dyck, Jr., P.B. Schwinberg, and H. Dehmelt, Phys. Rev. D34, 722 (1986).

63. T. Kinoshita and J. Sapirstein, in *Atomic Physics 9* (Proceedings of the 9th Int. Conf. on Atomic Physics, Seattle, Wash., July 23-27, 1984), edited by R.S. van Dyck and E.N. Fortson (World Scientific, New York, 1985).

64. S. J. Brodsky and S.D. Drell, Phys. Rev. D22, 2236 (1980).

65. E. Fischbach *et al*, Phys. Rev. Lett. 56, 3, 1427(E), 2424(C), 2426(C) (1986); S. Aronson *et al.*, *ibid.*, 1342, 2334(E) (1986).

66. H.H. Thodberg, Phys. Rev. Lett. 56, 2423(C) (1986); P.T. Keyser, T. Niebauer, and J.E. Faller, *ibid.*, 2425(C) (1986).

67. See, e.g., I. Marson and J.E. Faller, J. Phys. E19, 22 (1986); U. Cavasinni *et al.*, CERN preprint EP/86-41, March, 1986, subm. to Phys. Lett. A; C.C. Speaker and T.J. Quinn, Nature 321, 567 (1986); U. Amaldi, INFN int. note #8-6 (1986); L. Holloway, 1986 (unpubl.).

68. For reviews and theoretical perspectives see S.L. Glashow, Harvard Univ. Preprint HUTP/A-012, presented at Rencontre de Moriond, March, 1986, and report presented at Seventh Workshop on Grand Unification, Toyama, Japan, April, 1986; A. De Rújula, CERN report TH-4466/86, June, 1986, presented at symposium in honor of V.F. Weisskopf, Erice, Sicily, July, 1986.

69. Y.T. Chen, A.H. Cook, and A.J.F. Metherell, Proc Roy. Soc. London A394, 47 (1984); J.K. Hoskins, R.D. Newman, R. Spero, and J. Schultz, Phys. Rev D32, 3084 (1985).

70. S.C. Holding, F.D. Stacey, and G.J. Tuck, Phys. Rev. D33, 3487 (1986).

71. J. Weber, Phys. Rev. 117, 306 (1960).

72. S. P. Boughn, *et al.*, Astrophys. J. 261, L19 (1982).

73. H.J. Paik, Phys. Rev. D33, 309 (1986).

74. M. Karim, Phys. Rev. D30, 2031 (1984), and earlier references therein.

75. J. Hough *et al.*, in *Gravitation, Geometry, and Relativistic Physics* (Aussois, 1984), p. 212.

76. A. Rüdiger *et al.*, Max Planck Institute (Munich) Quantenoptik report MPQ-101, 1985 (unpublished).

77. See, e.g., N.W. Tanner and R. H. Dalitz, Oxford University report OXFORD-TP-2/86, May, 1986.

78. N. Ramsey, Ann. Rev. Nucl. Part. Sci. 32, 211 (1982).

79. W. Bialek, J. Moody and F. Wilczek, Phys. Rev. Lett. 56, 1623 (1986).

80. G.B. Franklin and P.D. Barnes, Brookhaven Natl. Lab. proposal P-815, 1985; V. Fitch, private communication. For an earlier (negative) search see A.S. Carroll *et al.*, Phys. Rev. Lett. 41, 777, 1002(E) (1978).

81. G. Steigman, K. Olive, D. Schramm, and M. Turner, Phys. Lett. 176B, 33 (1986).

82. See, e.g., G. Steigman, Bartol Research Foundation preprint BA-86-20, 1986, to be published in *Proceedings of the 6th Moriond Workshop on Massive Neutrinos in Particle Physics and Astrophysics*, Tignes, France, Jan. 25-Feb. 1, 1986.

83. E. Eichten, I. Hinchliffe, K. Lane, and C. Quigg, Rev. Mod. Phys. 56, 579 (1984).

84. E. Eichten, I. Hinchliffe, K. Lane, and C. Quigg, Phys. Rev. D34, 1547 (1986).

85. J. W. Cronin, in *Design and Untilization of the SSC* (Snowmass, 1984), edited by R. Donaldson and J.G. Morfin (Fermilab, Batavia, Ill., 1984), p. 170.

86. B. Cox, F. Gilman, and T. Gottschalk, these proceedings.