Proposal to Fermilab, Batavia, Illinois

A Search for Low Mass Monopoles

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ABSTRACT

A magnetic induction search for monopoles trapped in the CDF and D0 beam pipes is proposed. Significant improvements on the limits for low mass monopoles (up to several hundred GeV) can be attained.

INTRODUCTION

Although the present experimental emphasis has concentrated on thinking about and looking for super-heavy GUT monopoles via cosmic ray bombardment of the earth, expanding the search for accelerator created monopoles to the highest masses and lowest cross-sections available should also be continued [1, 2].

Since the Price, et al [3,4], exposures at the Tevatron in 1990 at some initial low luminosity, CDF and D0 have amassed more than 200 pb^{-1}. This suggests extending the cross-section limits some 4-5 orders of magnitude smaller. The current limits on cross-sections are given in Fig. 1 (Fig. 1 of Price [3]); the shaded region shows the area exporable in this proposal.

As shown in Eberhard, et al [5] and Ross, et al [6], all searches for monopoles have various differing (implicit or explicit) assumptions that modify the interpretation or validity of the limits quoted. This is true for this proposed search as well: we will discuss these below and indicate how much of the shaded area of Fig. 1 can be accessed with some suitable assumptions. We believe that this extension warrants approval of this modest search.

In addition, the next collider runs of the Tevatron with the Main Injector in a few years will lead to a luminosity increase of a factor of ten or more, and with suitable improvements (including possibly a dedicated intersection region) a search with less restrictive assumptions.

FIG. 1

FROM PRICE, GUIRI, KINOSHITA

PRL 65, 149 (1990) [ref. 3]

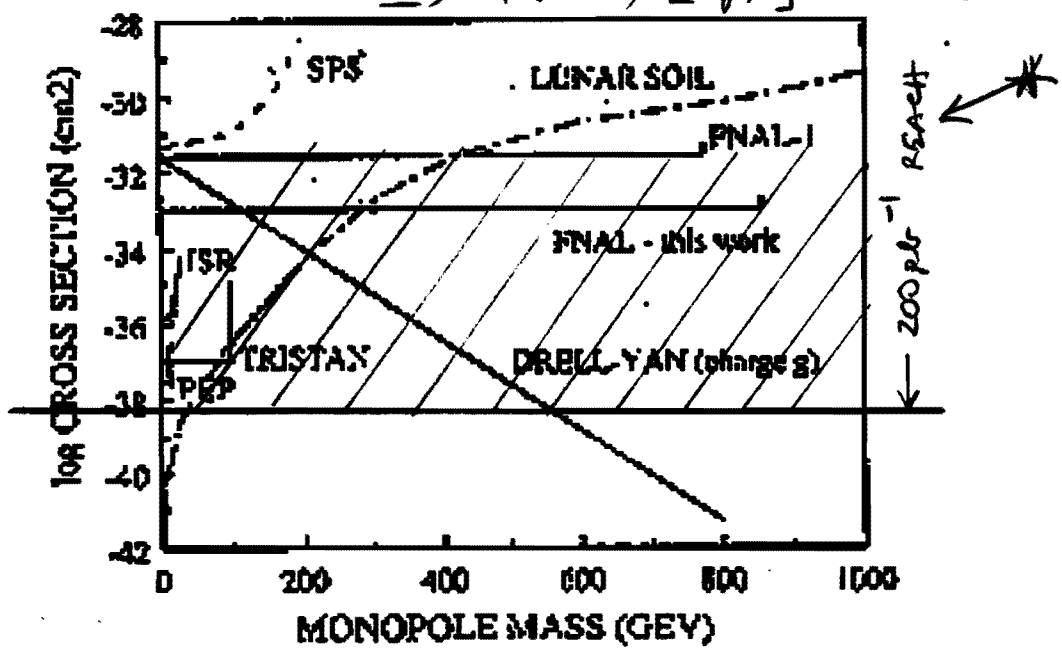

FIG. 1. Upper limits on monopole production cross section. References are as follows: PEP, Ref. 9; ISR, Ref. 11; TRISTAN, Ref. 10; SPS, Ref. 7; lunar soil, Ref. 8; FNAL-1, Ref. 5.

EXPERIMENTAL TECHNIQUES

The CDF and D0 experiments have been exposed to a high integrated luminosity for several years now. The beryllium beam pipes of these experiments are presumed to be replaced in future running, but in any case are expendable/replaceable elements (other parts of the detectors are not so considered). Although the total amount of material in these beam pipes is not massive, the very large energy loss rate of monopoles in matter allows for the expectation of a reasonable trapping fraction for such monopoles under suitable assumptions.

The techniques to be used can encompass ALL previous ones, if done in a suitable order. The techniques previously used are 1) multiple (Alvarez induction method [5]) or single (Cabrerra induction method) traversals of a superconductiong loop, 2) extraction with a (pulsed) high magnetic field (Carrigan method [7]), and 3) acceleration by magnetic fields into suitable etchable plastics such as Lexan or CR39, etc (Price method [4]).

In addition, one can contemplate a chemical method whereby one "dissociates" the material in a 4) magnetic field-free environment and looks for the "annihilation" of the pole-antipole pairs that are attracted to each other during diffusion through the "liquid" medium or 5) in a configured field environment to concentrate the monopoles for additional testing via the other four methods. Apart from the annihilation method, any candidate samples found can obviously be rerun "ad nauseum" to verify the observations. Measurement of the total annihilation energy [8] for any verified monopole candidates will measure its mass. Note that the rate of dissociation, and the fractions to be dissociated, of the samples can also be controlled. Redundancy will be practiced.

The detectors of Alvarez and Carrigan are either obsolete or have been "cannibalized," so that new ones must be found or constructed [9]. We need a NEW single (or multiple) pass induction apparatus with a room temperature warm bore [10]. A moderate outlay of funds and laboratory space will be needed to perform this search. The location of the measurements needs to be determined. For Be beam pipes, the residual radioactivity is presumably from impurities, and tractable for "off-site" processing. However, it would probably be preferable to have the apparati moved "on-site," especially in view of other hazards of Be, and some on-site help from Fermilab personnel would be welcomed [11].

ASSUMPTIONS NEEDED for the PHYSICS ANALYSIS

Trapping of the monoples in the "thin" beam pipes requires ranging out by energy losses and binding to the atomic or nuclear structures contained therein.

With an ionization loss of some 10 GeV/gram [12], 0.05 cm thick beryllium of density of 1.8 g/cc, gives a small but useful average kinetic energy loss of T=1.5 GeV [13].

Monopoles with a kinetic energy less than this will be stopped in the beam pipe. There they can be trapped by the binding of their magnetic charge with the magnetic moments of the atoms or the nuclei of the material. For beryllium, 100% ^{9}Be with an unpaired $d_{(3/2)}$ neutron, it is probable that the monopole will bind with the nucleus [14], but certainly molecularly with the whole atom [15]. D0 has no magnetic field and the earth's field is too weak to dislodge any monopoles trapped there. The energy required to move a monopole L cm by a field of H gauss/cm is E (keV) = 20.55 H L. For a monopole "skipping" from atom to atom, a few Angstroms at at time in the 0.5 gauss/cm field of the earth corresponds to an energy change of $20*0.5*(5*10^{-8})$ keV = $5*10^{-5}$ eV, very much less than the "atomic" binding energy in ^{9}Be. For CDF, the situation is 5000/0.5 worse, or 0.5 eV which is still a factor well below atomic binding; however, a slow "diffusive" walking down through the beam pipe (following the magnetic field lines) might occur. We will neglect this possibility; only a factor of two reduction in any limits obtained will be had if this is not so. We will assume, as a reasonable working hypothesis, that any monopoles originally trapped stay trapped.

We need to estimate the acceptance for trapping. In the Eberhard, et al [6] analysis with the fixed target exposures at Fermilab, it was assumed that the "pair" mass M of the pair of produced monopoles was a "delta" function at twice the monopole mass 'm.' This would lead in our case to complete trapping of all the monopoles produced (as the transverse kinetic energy of M would be negligible). This is clearly unrealistic. Thus we need some function describing the M distribution. Since magnetic monopoles interact electomagnetically, the Drell-Yan [16] process can be invoked (see also [3]). The Drell-Yan total cross-section above M gives one estimator of this distribution. However, threshold phase space effects are not included, that is, one expects a zero cross-section at M=2m in general. We give a second estimator as the Drell-Yan cross-section modified by the two-body phase space factor p^*/E^* of one of the monopoles, which is p^*/m near the threshold M. This factor reduces the acceptance for the cross-section from M to M+2T to 8% of the first estimator for a value m=200 GeV, and scales like $m^{-0.5}$. The Drell-Yan cross-section is shown linearly (solid), above 200 GeV, corresponding to m=100 GeV in Fig. 2, and as modified by the p^*/E^* phase space factor (dashed). One can roughly estimate from looking at the figure that the Drell-Yan piece between M and M+3 GeV is a few percent, and for the modified one less than a percent. The actual acceptances are shown in Fig. 3. These lead to improved limits to be added to Fig. 1 as shown in Fig. 4. Since the CDF/D0 exposures are 5.3 orders of magnitude greater than the quoted result of Price et al [3], we would improve the limits, including the acceptances estimated here, by 3 to 4 orders of magnitude. This allows limits that lie below the Drell-Yan expectations shown out to monopole masses of some 400 GeV. We believe this proposal provides a significant extension of the "classical" Dirac monopole searches to warrant its approval by the Laboratory.

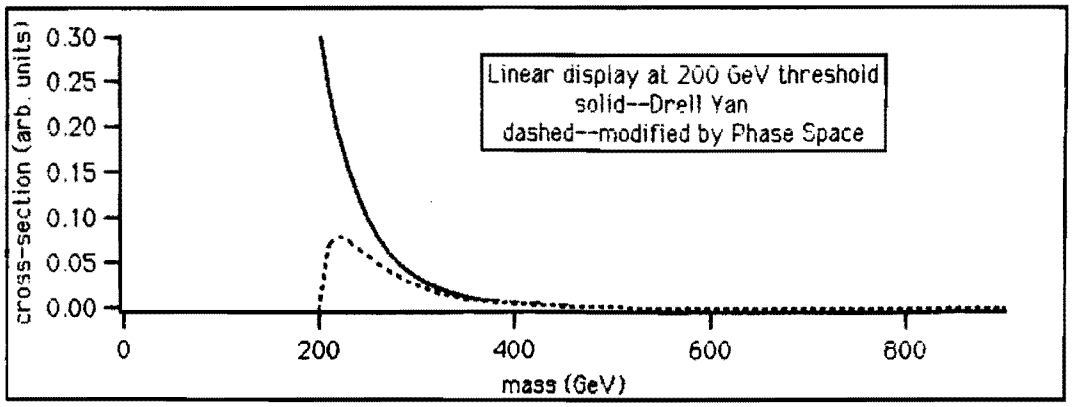

Fig. 2--Mass distributions

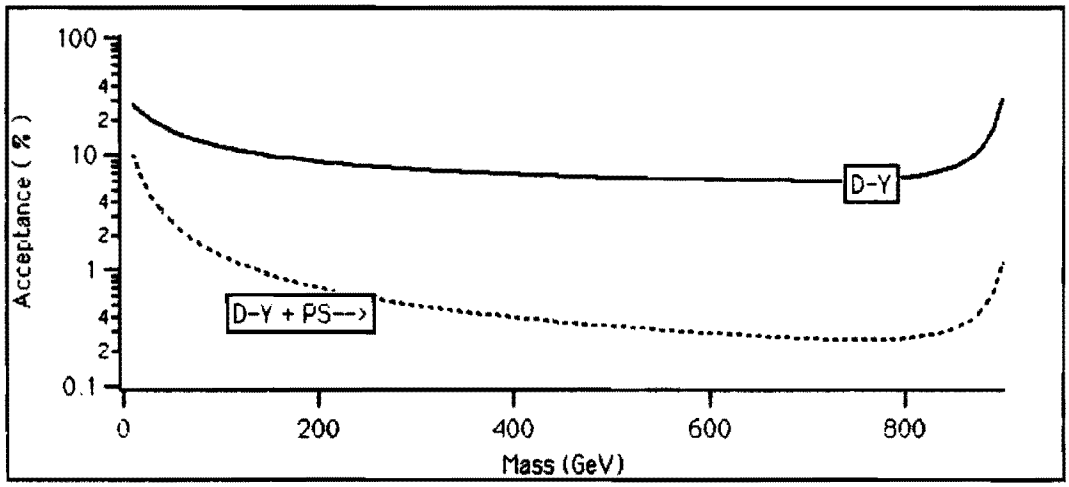

Fig. 3--Acceptances

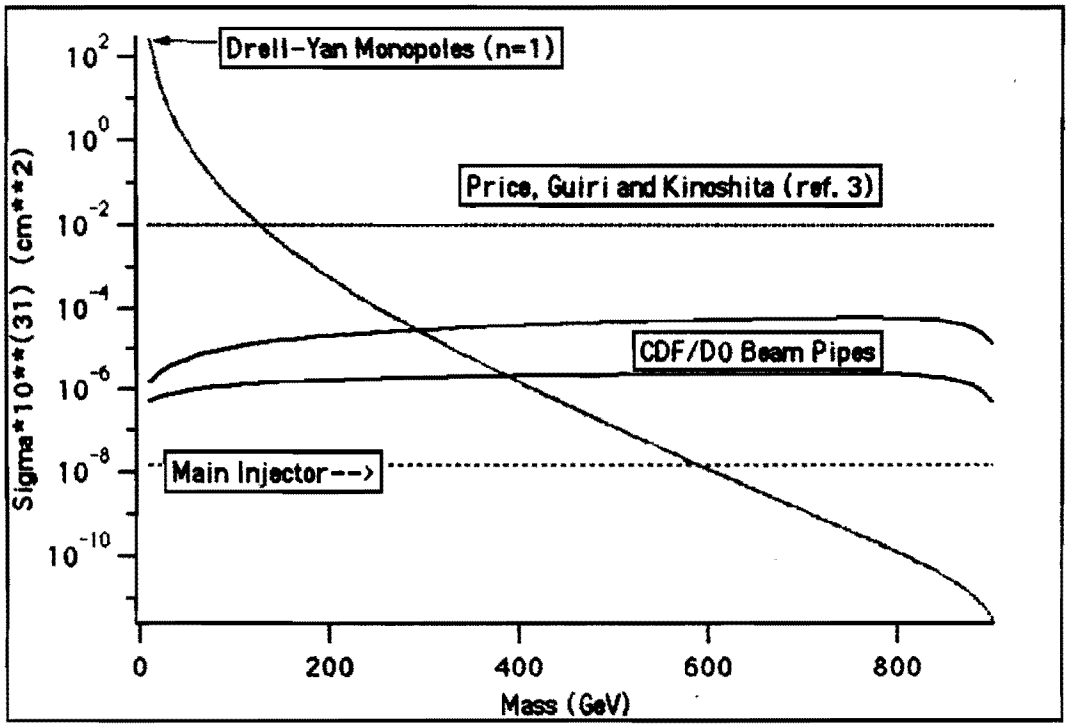

Fig. 4--Expected Crossections(D-Y) and Limits (95% CL) as labeled. Band between solid lines is result expected from this proposal. MI=Main Injector

FUTURE EXTENSION

With future running to 2 fb^{-1} or more with the Main Injector, with a suitable segmented totally absorbing ("trapping") cylinder of material with 100% acceptance surrounding a (dedicated) interaction region (as it destroys the region for general physics) one can reach the limits also shown in Fig. 4. This extends the expected Drell-Yan exclusion region out to 600 GeV in monopole mass. Successful execution of the proposal above would "prototype" this future possibility, and gives additional argument for granting approval.

REFERENCES and FOOTNOTES:

1) Q. Shafi, gave a talk recently emphasizing that searches for TeV mass monopoles should not be overlooked (R. Carrigan, private communication); we shall be talking to him. Also, SO(10) models allow ~1 TeV monopoles (J. Preskill, "Magnetic Monopoles," Ann. Rev. Nucl. Sci. **34**, 461 (1984)).
2) G. Giacomelli, Lake Louise Conference talk, 1994 (and other of his papers).
3) P. B. Price, J. Guiri and K. Kinoshita, PRL **65**, 149 (1990).
4) P. B. Price,R. Guoxiao and K. Kinoshita, PRL **59**, 2523 (1987).
5) P. H. Eberhard, *et al* PR **D4**, 3260 (1971) and R. R. Ross, *et al* PR **D8**, 698 (1973), discussing limits from "lunar material" searches.
6) P. H. Eberhard, *et al* PR **D11**, 3099 (1975), searching "targets" exposed at Fermilab.
7) R. Carrigan, private communication.
8) Consideration of overcoming the Coulomb barrier vis-a-vis the magnetic attraction of the pole-nuclear atom and the antipole-nuclear atom must be addressed.
9) R. R. Ross and R. Carrigan, private communications.
10) Such a device is reported in H. Jeon and M. J. Longo, "Search for Magnetic Monopoles Trapped in Matter," (preprint) just published in PRL **75**, 1443 (1995). We will talk to Longo regarding whether to "buy, borrow or collaborate (with)" his apparatus, or to build our own.
11) Moyses Kuchnir of Fermilab would be interested in helping in some way. He has extensive experience with cryogenics and reasonable familiarity with SQUIDs.
12) S. P. Ahlen, "Monopole Energy Loss and Detector Excitation Mechanisms," in Magnetic Monopoles (ed. R. A. Carrigan, Jr. and W. P. Trower, Plenum Press, 1982), p.259.
13) We average the perpendicular thickness Rperp=.05cm x 1.8 g = 0.9 g equiv. to 0.9 GeV (at 10 GeV/g). This gives Ravg (over solid angle)= Int(R*2pi*d(costheta)/4pi =0.5 Int(Rperp*dtheta) =pi*Rperp/2 equiv. to 1.5 GeV/monopole, since R=Rperp/sin(theta).
14) K. A. Milton calculations and considerations; he expects to do spin 3/2 calculations soon. Some other (non-relativistic) spin 1/2 binding energy calculations are given in L. Bracci and G. Fiorentini, NP **B232**, 236 (1984), and D. Sivers, PR **D2**, 2048 (1970), although this latter paper contains serious errors. Relativistic treatments for spin 1/2 have been made by Y. Kazama and C. N. Yang (and A. S. Goldhaber). PR **D15**, 2300 (1977) (and PR **D15**, 2287 (1977)). Unpaired neutrons can bind monopoles in many cases (depending on the gyromagnetic moment value and the reduced mass of the system).
15) W. V. R. Malkus, PR **83**, 899 (1951) did the first binding energy calculations for monopoles (non-relativistic and correct). For ^{9}Be, he obtains (his Table IV) a value of 25 times the hydrogen atom ground state binding energy (ie about 0.3 keV).
16) For Drell-Yan, see **e.g.** (textbook) I. A. Aitchison and A. J. G. Hey, "Gauge Theories in Particle Physics," Adam Hill, publishers (1989), pp.224, 235-238 and 244-245. We parameterized the data shown in Fig.7.2 and 7.13 to calculate the curves in our Figs.

ADDENDUM to

A Search for Low Mass Monopoles

George R. Kalbfleisch, Kimball A. Milton and Michael Strauss
University of Oklahoma, Norman, Oklahoma

November 15, 1995

Introduction

This addendum supplies additional information (**Part I**) relative to the proposal (of October 3, 1995) and improves upon various of the supporting calculations. An "ad hoc" committee was appointed by Director J. Peoples to review our proposal (copy of charge included), chaired by Dr. F. Nezrick. Questions raised by the committee are also answered herein (**Part II**). More information regarding the execution of the experiment is also included.

The Experiment

A single monopole "trapped" in bulk matter can be unambiguously detected by the "magnetic induction" technique of Alvarez (ref. 6, 7 `main proposal) and others. Many of the monopole pairs that may have been produced by Tevatron antiproton-proton collisions over the last few years of operation of the CDF and D0 experiments should have been "bound" in material comprising these detectors. We propose to search for the monopoles "bound" in the Be beam pipes, Al drift chamber supports and some other pieces of the CDF and D0 detectors by the magnetic induction technique. We will use the "Longo" apparatus (letter of loan enclosed) with, hopefully, a new DC SQUID magnetic detection system (in addition or replacing the older RF one) which we intend to purchase.

The UNIVERSITY of MICHIGAN DEPARTMENT of PHYSICS

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Phone: (313) 764-4445
e-mail: mlongo@umich.edu

October 10, 1995

Prof. George Kalbfleisch
Department of Physics and Astronomy
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Norman, OK 73109

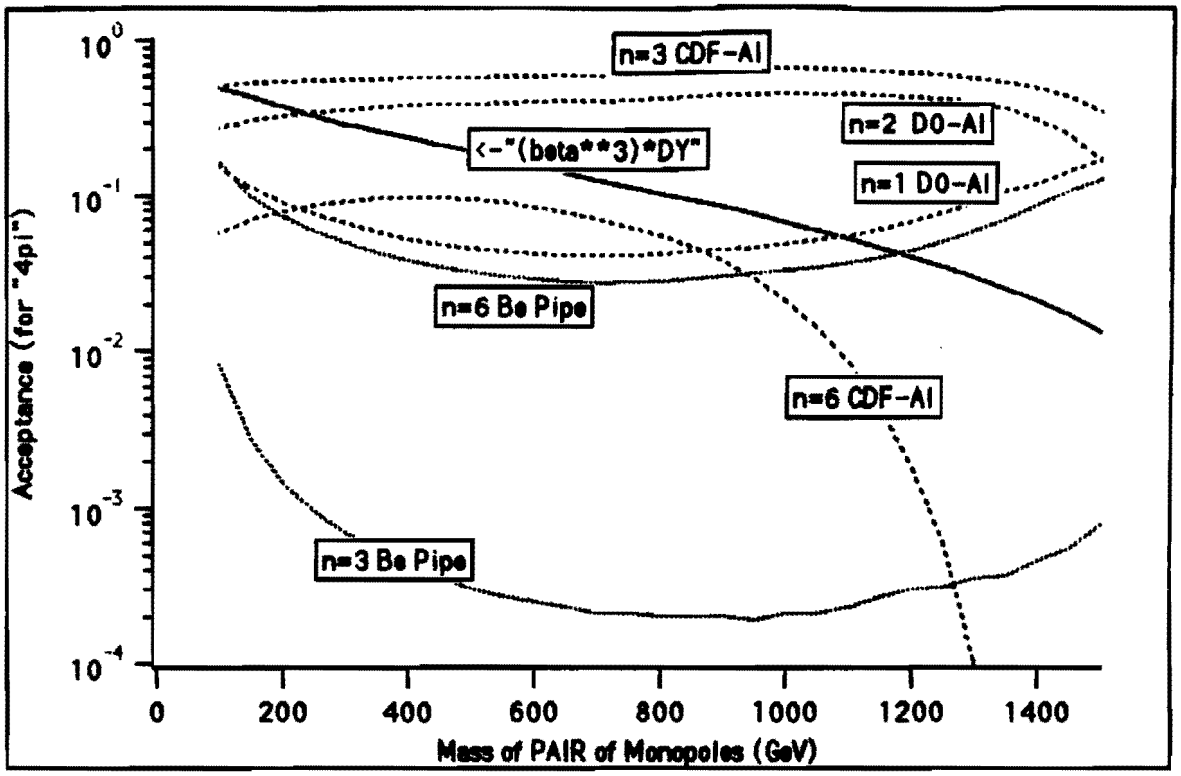
Dear George:

The apparatus we used in our search for trapped monopoles is essentially mothballed. You are welcome to borrow it for a search for trapped monopoles produced at Fermilab. It will require some work to get it going again. We can work out the details of its transfer or its use at Michigan at a future date.

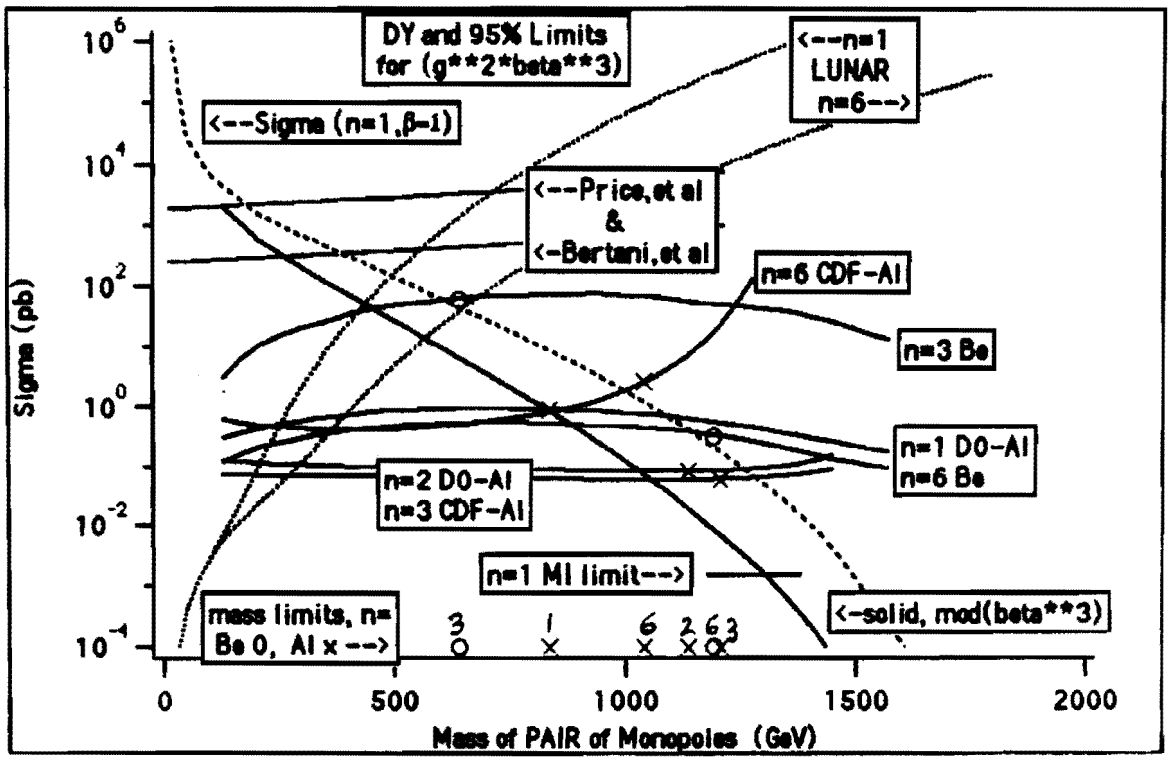
Sincerely,

Michael J. Longo

Michael J. Longo



Revised Fig. 3b)--beta**3 Acceptances



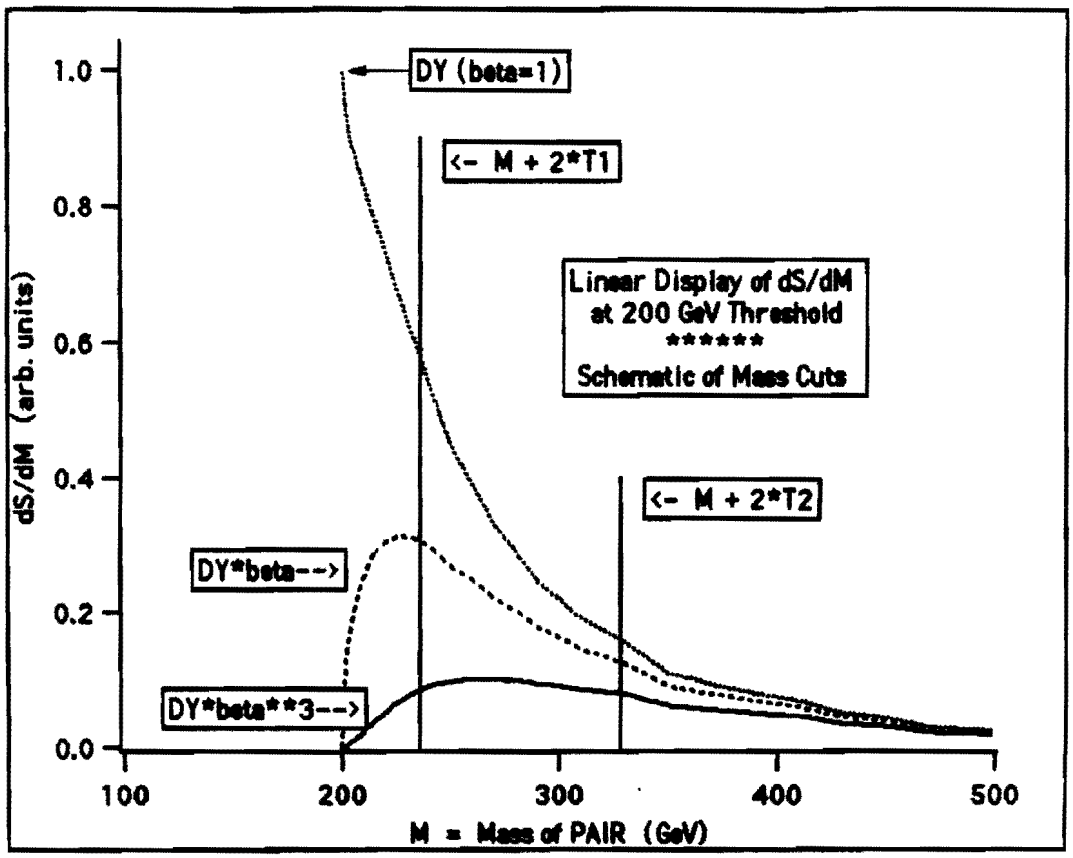
Revised Fig. 4b)--SigmaDY dashed, times "S3/S1" to get "mod(beta**3)" to compare with "Limits/acceptances" (solid) +Lunar + Price/Bertani

Part I--Additional or Improved Information.

Improved Calculations

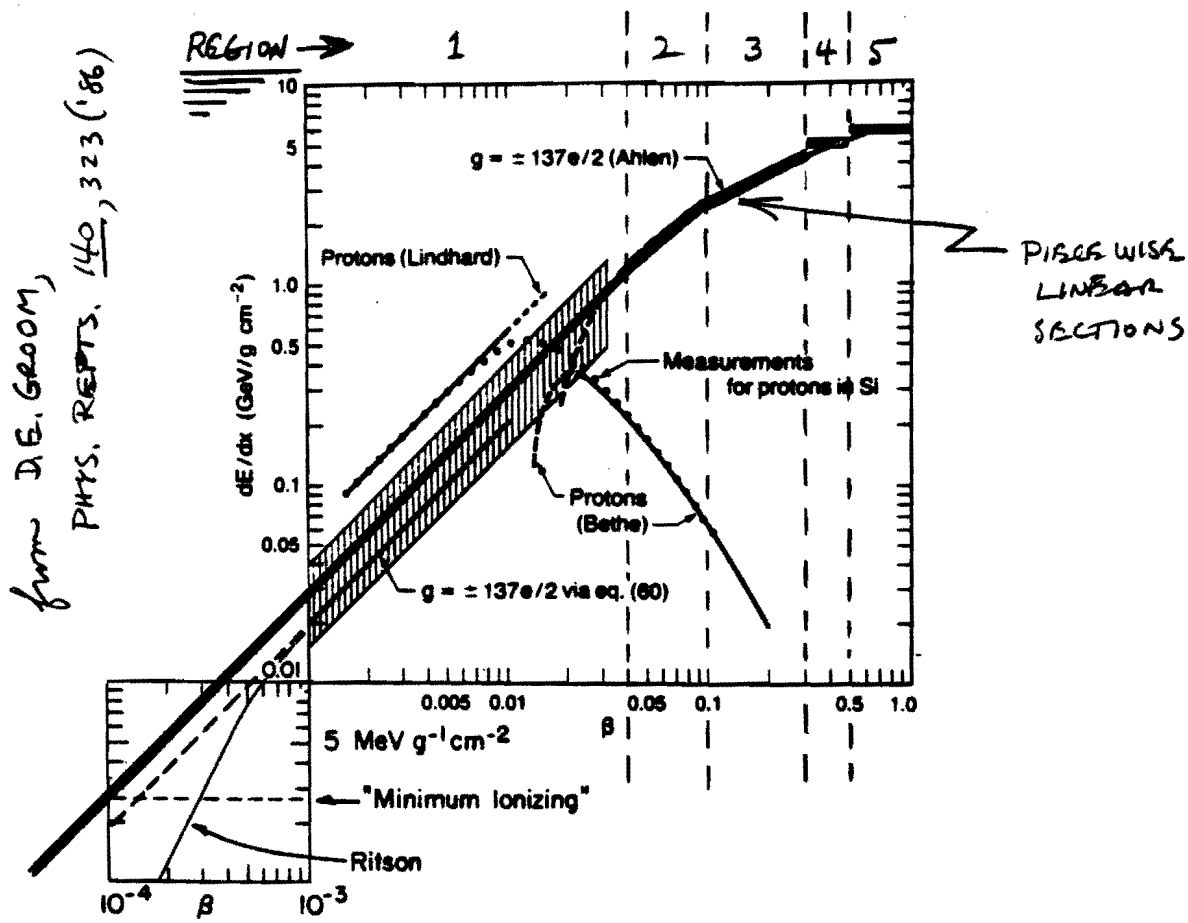
The acceptances and the mass limits shown in the Proposal as Fig. 3b) and 4b) are updated here as Fig. 3b) revised and 4b) revised; see these figures on the preceding page. The 95% CL experimental limits are labeled e.g. "n=1 D0-Al" etc.; interpretation as regards monopole mass come from the crossing points of these limits with the "solid" curve labeled "mod(beta**3)." The updating is MAJOR; the vertex dependence of the Drell-Yan coupling to monopoles is velocity dependent (as also in the dT/dx versus velocity curves). The p/E (= β) threshold effect becomes $(p/E)^3$ when this is taken into account, suppressing thin absorbers more. This comes about because the Lorentz force equation for magnetic charges is $\vec{F} = g(\vec{H} + \vec{v} \times \vec{D})$, where $\vec{D} = \kappa\vec{E}$ and where κ is the dielectric constant, giving a $g\beta E$ coupling, i.e. a factor of $(g\beta)^2$ to the crossection from the γgg-vertex. However, the material ignored previously becomes relevant. Between the Be beam pipe and the Al cylinders is additional material; tracking chamber stuff of ~1 gram (i.e. g/cm^2) in CDF and 2.5 grams (TRD plastic foils mainly) in D0 that "mask" the smaller values of β^3 near threshold, giving reasonable acceptances for most of the cases of magnetic charge "n" versus samples. Thus the "mass cut" range is in general not (2m, 2m+2T) but $(2m+2T_1, 2m + 2T_2)$ as illustrated in the update of Fig. 2 of the proposal shown below; these T_1 and T_2 values are given in a table below also. Mass limits from 320 to 600 GeV are obtainable under the various assumptions previously presented, which are significant improvements over earlier accelerator limits (by a factor of 3-6). They also exceed the "lunar" limits that have been a "general" guide. The lunar limits are roughly a factor of two high because they assumed that the maximum monopole pair mass could reach the total center-of-mass ("c.m.") energy of a given cosmic ray-nucleus interaction, whereas, due to the parton submomenta, the cross-sections fall off substantially at about half of the c.m. energy.

These updates also use "improved" stopping power calculations with a "piece-wise" linearization of the Ahlen dT/dx versus velocity (β) curves for monopoles. The earlier single power law was valid over a somewhat limited range of β, but allowed for factorization of the range of monopoles from their angular dependence and allowed a direct scaling of the mass dependence. The "improved" calculation requires an averaging of the range over solid angle in the range calculation routine for each material of each thickness for each monopole charge "n" and mass. The range dependence on mass for



UPDATED Fig. 2--Kinetic Energy Cuts

"IMPROVED" STOPPING POWER



from D.E. GROOM, PHYS. REPTS. 140, 323 ('86)

Fig. 10. Monopole energy loss as calculated by Ahlen and Kinoshita [100], and as extended by Ritson [105]. Except for the lower decade, the figure is adapted from ref. [100]. ← ("AHLEN, REF. 13 MAIN TEXT — SEE "STOPPING POWERS, above).

5 REGIONS — PIECEWISE LINEAR → $\frac{dT}{dx} = -\alpha \beta^{2\delta}$

WHERE $(\alpha = n^2 \alpha_1 \;,\; 2\delta \le 1 \;,\; \alpha' = \alpha (2/m)^{\delta})$

NR $\beta = \sqrt{\frac{2T}{m}}$ R(elativistic) → take $2\delta = 0$

R = RANGE

So: $T_{i\lambda}^{1-\delta_j} = T_{j\lambda}^{1-\delta_j} + (1-\delta_j)\alpha_j' \Delta R_{ij}$, λ = REGION

& $\alpha', \delta = f(i,j)$

PARAMETERS

	REGION	2δ	α_1 GeV/g	(β_i, β_j)
NR	1	1.0	35	(0, 0.04)
	2	0.8	21	(0.04, 0.1)
	3	0.5	7.5	(.1, .3)
R	4	0	5	(.3, .5)
	5	0	6	(.5, 1.)

SEE "SOLID" CURVE ON FIG. ABOVE!

each of these situations can then be empirically fitted: each fits an "empirical" power law which is used in the acceptance calculation. The "improved" stopping power parameterization for the 5 piecewise regions is attached. The averaged (over solid angle) minimum and maximum kinetic energies $\langle T_1 \rangle$ and $\langle T_2 \rangle$ are (for 100 GeV monopole mass) are:

Monopole Charge n=	Be Beam Pipe	CDF 1/4" Al Cyl.	D0 3/8" Al Cyl.
1	0, 0.16 GeV	2.8, 11.8 GeV	14, 31 GeV
2	0, 1.4	18, 64	74, 143
3	0, 4.1	48, 151	175, 330
6	0, 24.	211, 625	718, 1340

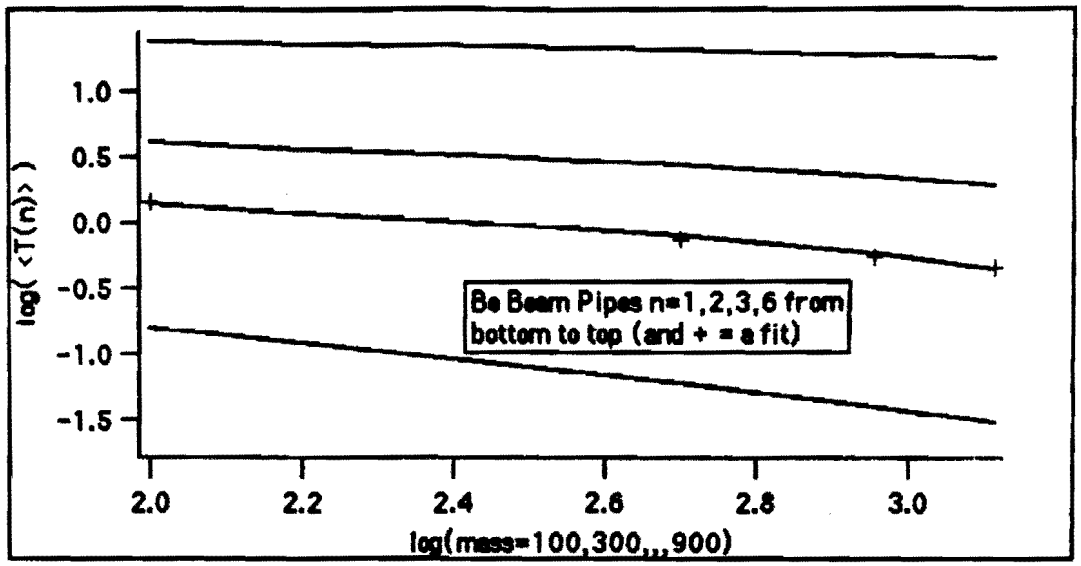
and the "power" values for $\langle T(\text{mass}) \rangle = \langle T(100) \rangle (\text{mass}/100.)^{\text{power}}$ are:

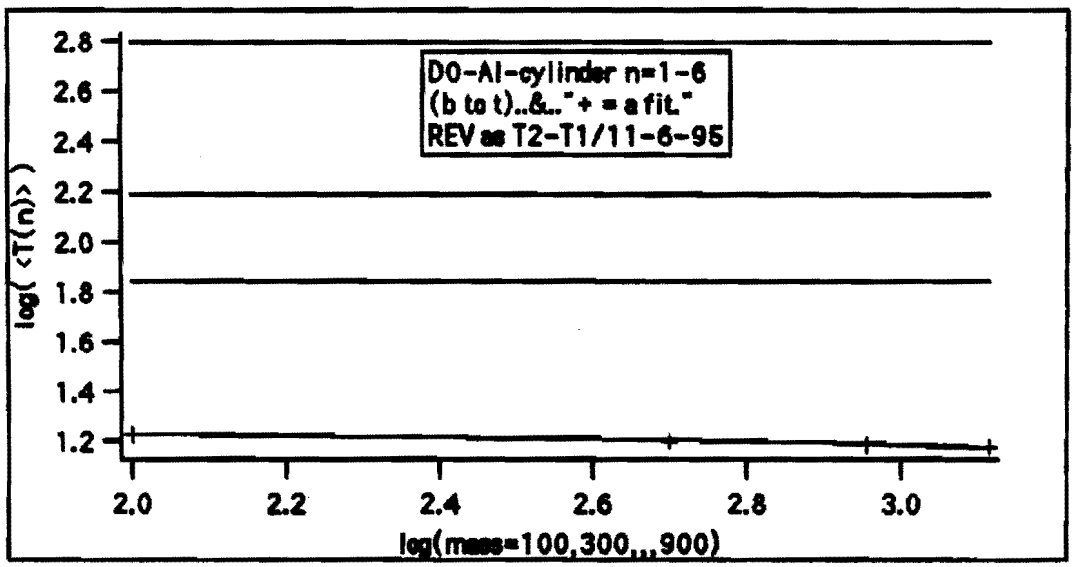
1	-0.9	-0.4	-0.4
2	-0.6	-0.1	-0.1
3	-0.4	0	0
6	-0.2	0	0 .

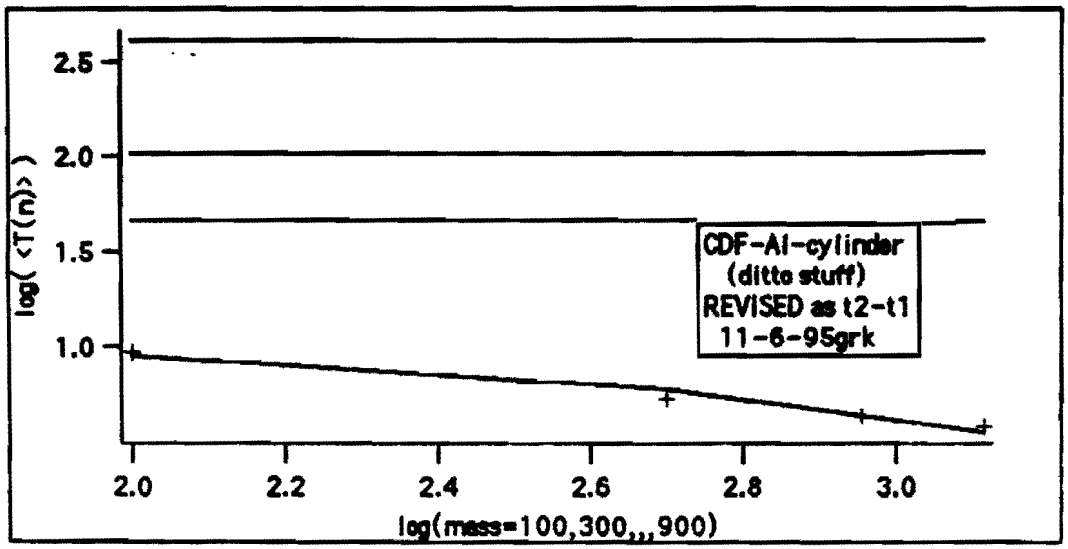
The curves of $\langle T(n,\text{mass}) \rangle$ versus mass are given below.

The acceptance calculations were also improved by using more recent quark distributions. From the "Handbook of Perturbative QCD" by G. Sterman, *et al* (RMP **67**, 157 (1995)) (see attachment next page), we used an "average" of the two "valence" and three "sea" quark distributions parameterized there and shown in the Fig. in the following pages with comparison to our original TRUNCATED (at high x) distributions. This yields the Drell-Yan dS/dM muon pair distributions shown following, and compared to the UA2 [J. Alitti, *et al* Phys. Letters **B275**, 202 (1992)] and CDF pbar-p data, as well as the E-605 pN data [previously referenced]. From these Sterman distributions, the UPDATED Figs. 3b), 4b) above were constructed. We also show expectations for Fermilab (Main Injector plus Tevatron) in comparison to CERN (for both SpbpS and LHC) in the next several pages. Monopole masses (for n=1) up to 740, 200 and 2800 GeV are possible for these three cases, respectively.

Despite these major revisions, updates and improvements, the limits shown in the updated figures are compatible with those in the original proposal. The experimental method proves to be very robust in determining monopole mass limits.


1.0
0.5
0.0
-0.5
-1.0
-1.5
log(<T(n)>)
Be Beam Pipes n=1,2,3,6 from
bottom to top (and + = a fit)
2.0
2.2
2.4
2.6
2.8
3.0
log(mass=100,300,,,900)


2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
log(<T(n)>)
D0-Al-cylinder n=1-6
(b to t)..&.."+ = a fit."
REV as T2-T1/11-6-95
2.0
2.2
2.4
2.6
2.8
3.0
log(mass=100,300,,,900)


2.5
2.0
1.5
1.0
log(<T(n)>)
CDF-Al-cylinder
(ditto stuff)
REVISED as t2-t1
11-6-95grk
2.0
2.2
2.4
2.6
2.8
3.0
log(mass=100,300,,,900)

from "HANDBOOK OF PERTURBATIVE QCD"
G. STERMAN, et al, RMP 67, 157 (1995)

c. Nucleon distributions

The earliest utility of continuum dilepton production was as an important test of the parton model and, with the acceptance of the parton model, determination of the momentum distributions of the partons participating in the collision, especially the quark "sea."

With incident-proton beams, the parton distributions of the proton can be extracted in a manner not dissimilar from the procedure in deeply inelastic scattering. Through the comparison of incident-proton and antiproton beams, NA3 at CERN was able to extract both the valence and the sea-quark momentum content.

By parametrizing a scaling set of valence and sea distributions by shape parameters,

$$u(x)=Ax^{\alpha}(1-x)^{\beta_v} ,$$

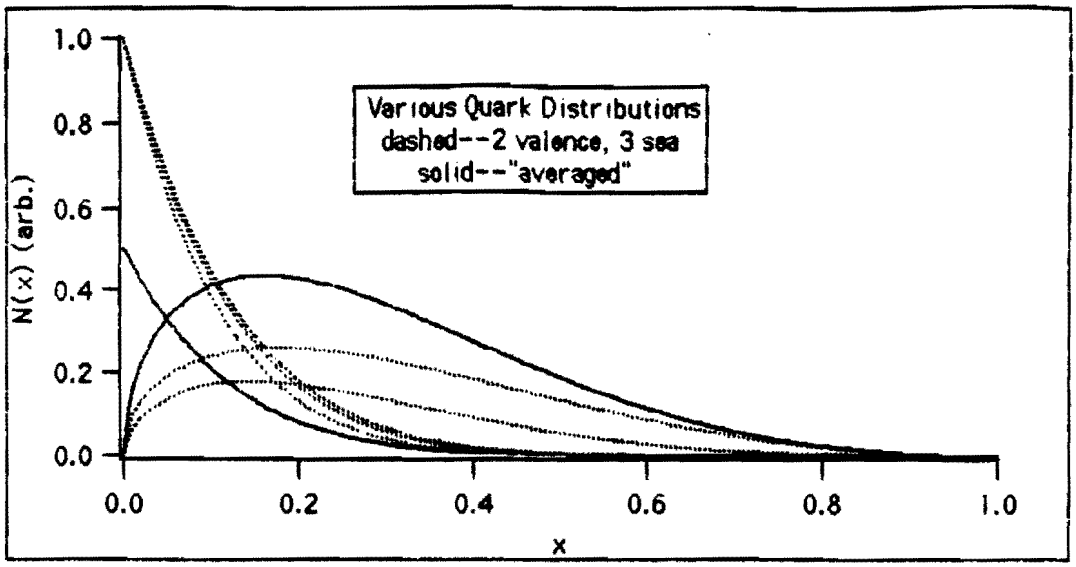
$$d(x)=0.57u(x) ,$$

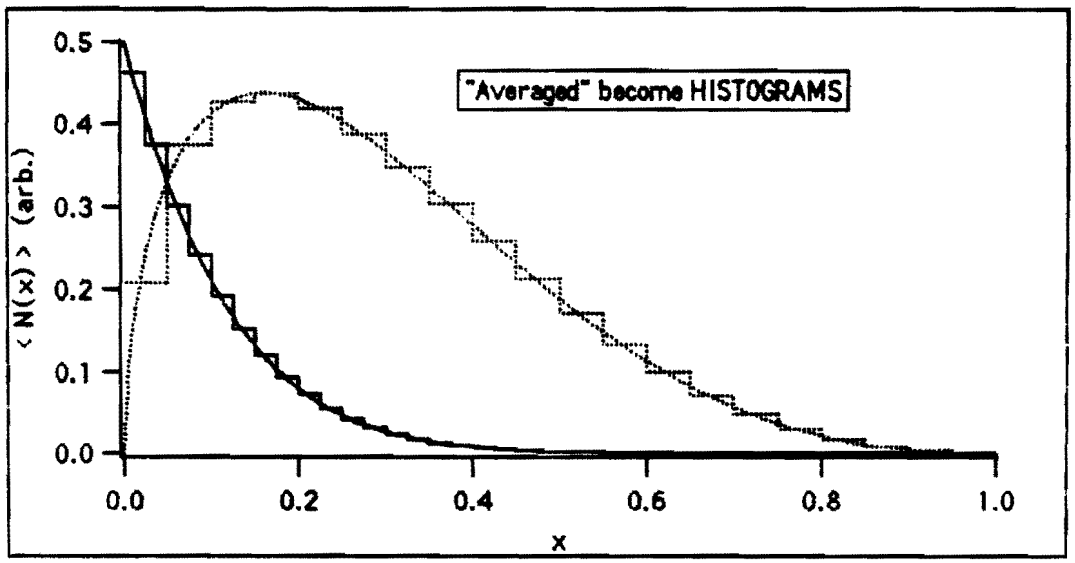
$$S(x)=C(1-x)^{\beta_s} ,$$

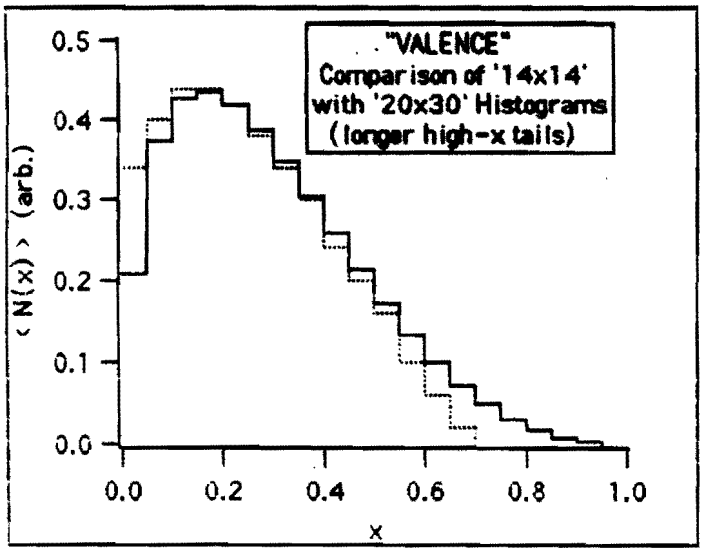
NA3 found (Badier *et al.*, 1980) the results in Table I (from Rutherfoord, 1979). For comparison, the CDHS results (de Groot *et al.*, 1979) from neutrino scattering are also shown, as are the results of E288 (Ito *et al.*, 1981) from Fermilab, which made DIS-inspired parametrizations of the valence distributions.

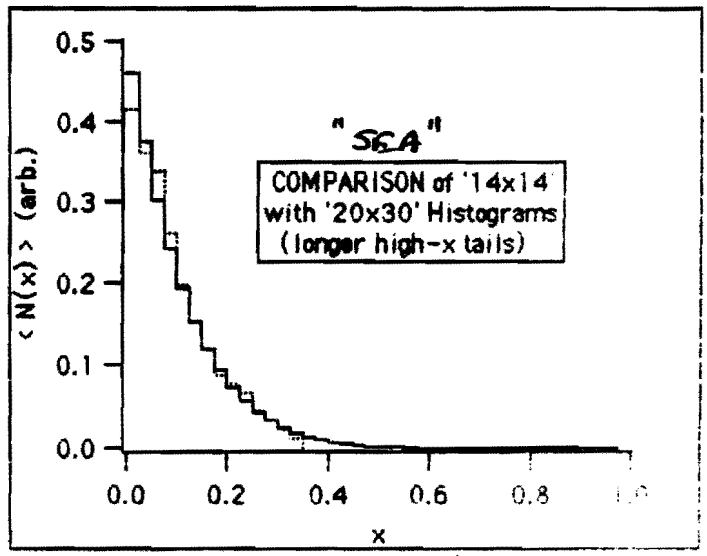
TABLE I. Representative shape parameters for parton distributions (Rutherfoord, 1979). The experiments listed were conducted by the CDHS Collaboration (CERN, Dortmund, Heidelberg, and Saclay) and E288 (Ito *et al.*, 1980) at Fermilab and NA3 (Badier *et al.*, 1980) at CERN.

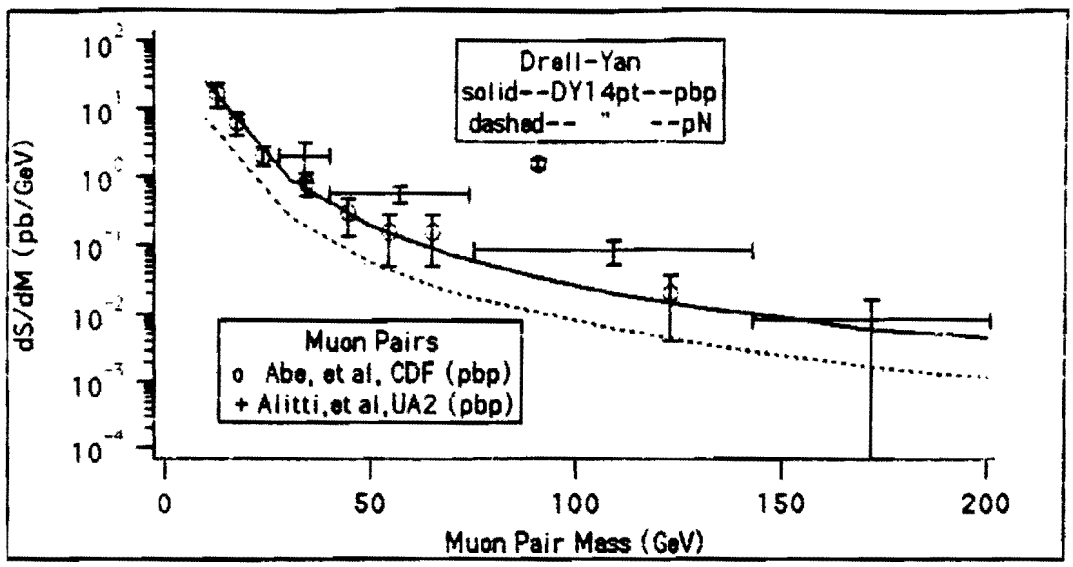
	CDHS	NA3	E288
α	0.51±0.07	0.60±0.08	
β_v	2.38±0.09	3.59±0.14	
β_s	8.0±0.7	9.03±0.30	7.62±0.08

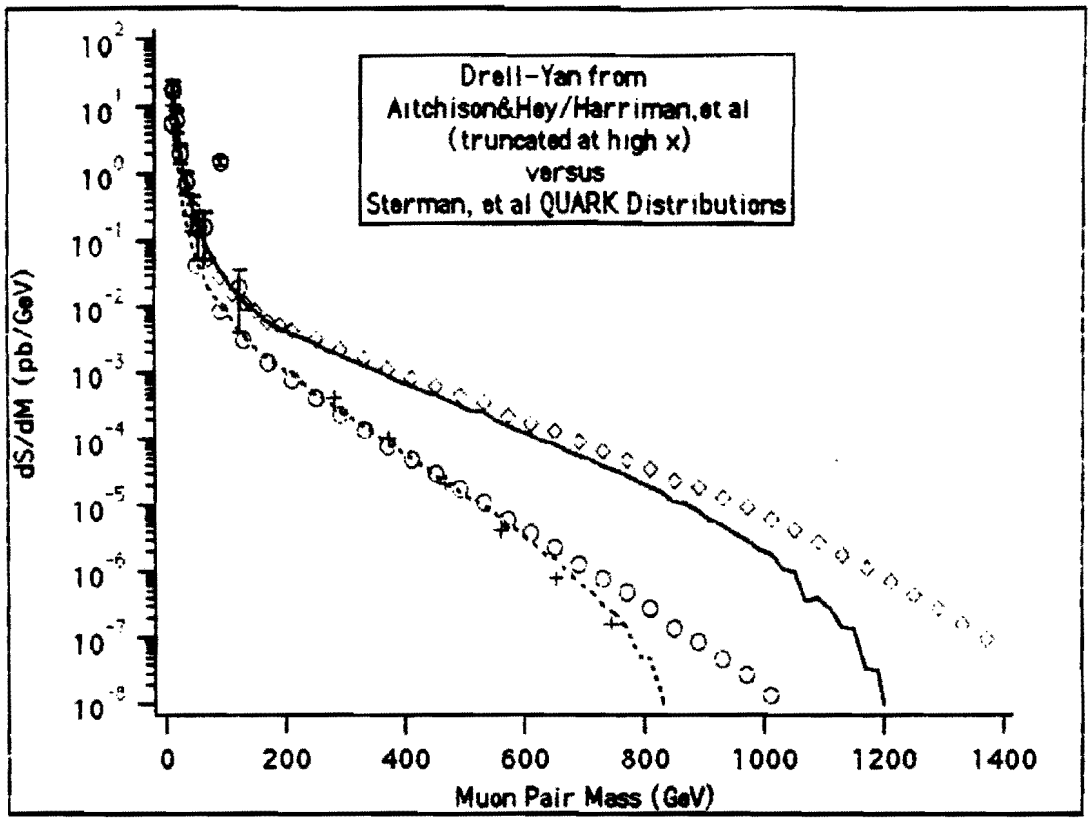

Various Quark Distributions
dashed--2 valence, 3 sea
solid--"averaged"
N(x) (arb.)
x

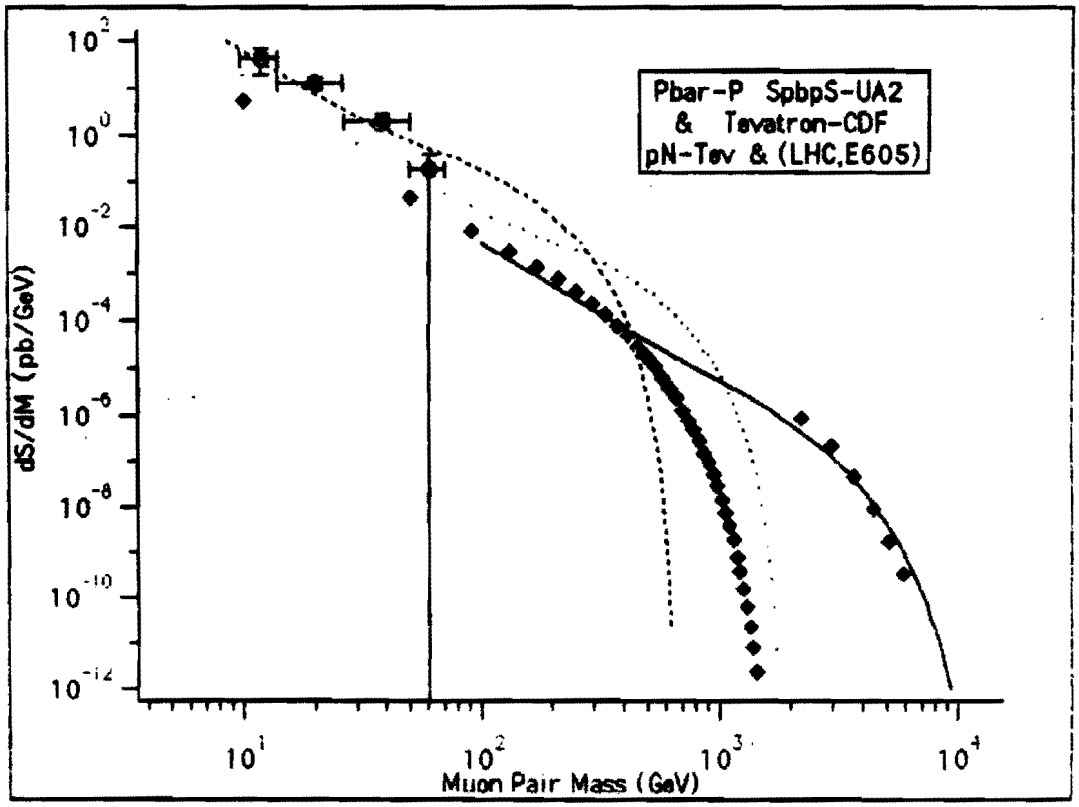

"Averaged" become HISTOGRAMS
< N(x) > (arb.)
x

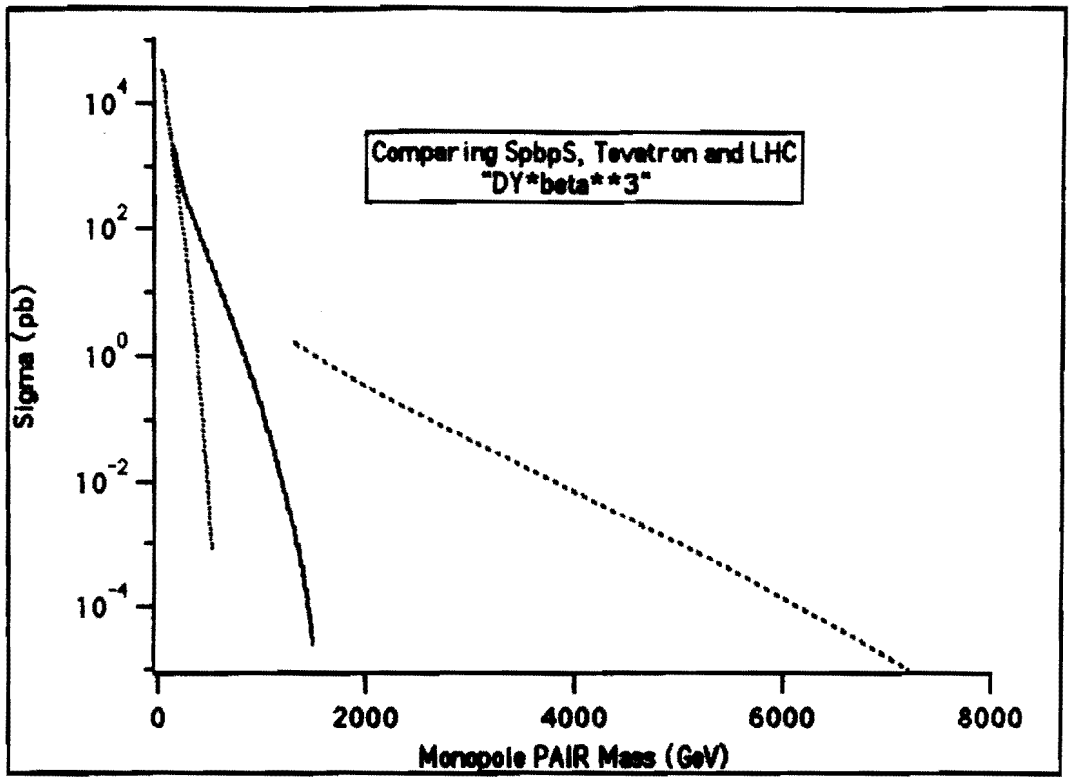

"VALENCE"
Comparison of '14x14'
with '20x30' Histograms
(longer high-x tails)
< N(x) > (arb.)
x

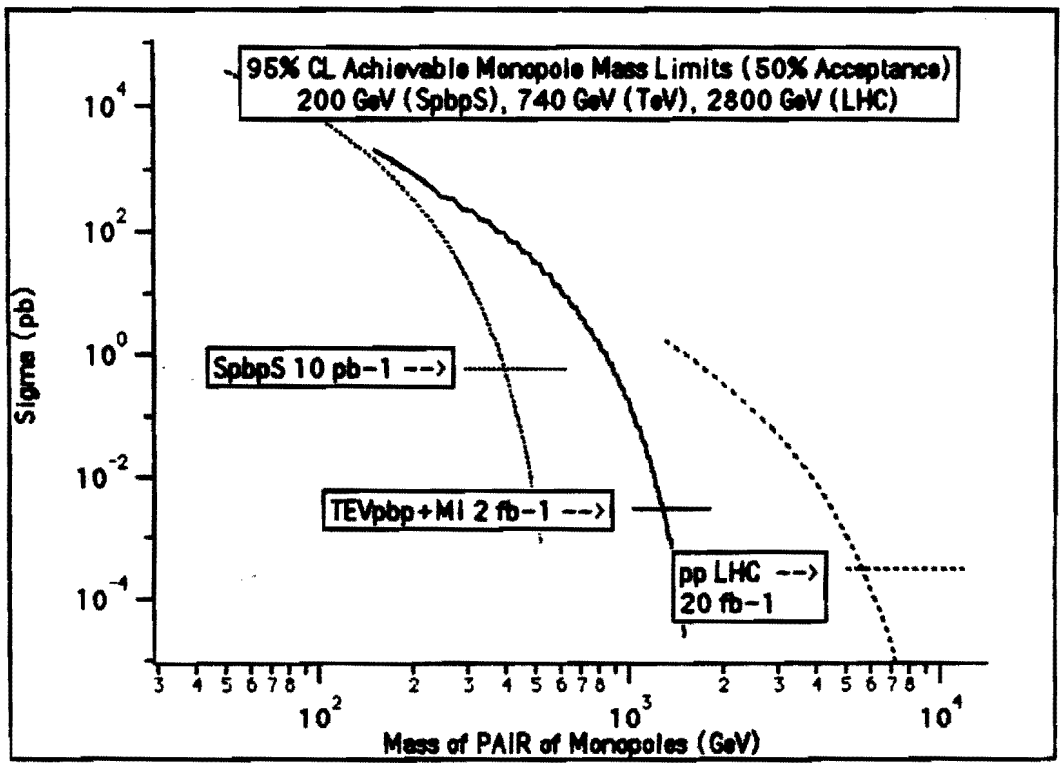

"SEA"
COMPARISON of '14x14'
with '20x30' Histograms
(longer high-x tails)
< N(x) > (arb.)
x


Drell-Yan
solid--DY14pt--pbp
dashed-- " --pN
Muon Pairs
o Abe, et al, CDF (pbp)
+ Alitti,et al,UA2 (pbp)
dS/dM (pb/GeV)
Muon Pair Mass (GeV)
0
50
100
150
200


Drell-Yan from
Aitchison&Hey/Harriman,et al
(truncated at high x)
versus
Sterman, et al QUARK Distributions
dS/dM (pb/GeV)
Muon Pair Mass (GeV)


Pbar-P SpbpS-UA2
& Tevatron-CDF
pN-Tev & (LHC,E605)
dS/dM (pb/GeV)
Muon Pair Mass (GeV)


Comparing SpbpS, Tevatron and LHC
"DY*beta**3"
Sigma (pb)
10^4
10^2
10^0
10^{-2}
10^{-4}
0
2000
4000
6000
8000
Monopole PAIR Mass (GeV)


95% CL Achievable Monopole Mass Limits (50% Acceptance)
200 GeV (SpbpS), 740 GeV (TeV), 2800 GeV (LHC)
SpbpS 10 pb-1 -->
TEVpbp+MI 2 fb-1 -->
pp LHC -->
20 fb-1
Sigma (pb)
10^4
10^2
10^0
10^{-2}
10^{-4}
10^2
10^3
10^4
Mass of PAIR of Monopoles (GeV)

Various Expectations

A. Binding

Kim Milton's "Summary of Monopole Binding..." writeup is attached next. We see that "anomalous magnetic moments" parallel to the angular momentum lead to the expectation that monopoles bind to nuclei (exception, neutrons should bind). That is heavy high spin "Protons" bind wheras heavy high spin "Neutrons" do not; electrons have a negligible anomalous moment, and only bind in a special way. Thus the Be pipe ("heavy neutron") is not expected to bind monopoles, whereas the Al cylinders ("heavy proton") should. However, all this is model dependent, and we wish to study both cases **experimentally**. But the Be can also trap (negative) electrically charge monopoles ("dyons"). And the theoretical "lore" of monopoles may not be correct. For example, polarization of the nuclei by the presence of the magnetic monopole has not been taken into account; the energy splitting due to the L-S coupling for Al's $d_{5/2+}$ unpaired proton is ~1 MeV [Meyerhof, 'Elements of Nuclear Physics," McGraw-Hill (1967), p.56] compared to an estimated monopole binding energy of 2.5 MeV [see K. Milton "..Binding.." below]. Thus the rearrangement of the nucleons may provide binding in other unpaired cases (e.g. the unpaired $p_{3/2-}$ neutron in ^{9}Be) if these polarization deformations are taken into account (i.e. "free" neutrons supposedly bind to monopoles).

Summary of Monopole Binding to Magnetic Moments

Kim Milton

October 23, 1995

We consider the binding of a monopole of magnetic charge g to a nucleus of charge Ze, mass $M = Am_p$, and magnetic moment

$$\boldsymbol{\mu} = \frac{e}{2m_p}\gamma \mathbf{S}, \tag{1}$$

$\mathbf{S}$ being the spin of the nucleus. (I will assume here that the monopole mass $\gg M$, this restriction could be easily removed.) Other notations for the magnetic moment are

$$\gamma = 1 + \kappa = \frac{g}{2}. \tag{2}$$

The charge quantization condition is taken to be

$$|eg| = \frac{n}{2}, \quad n = 1, 2, 3, \ldots. \tag{3}$$

Because the nuclear charge is Ze, the relevant angular momentum quantum number is

$$q = \frac{nZ}{2}. \tag{4}$$

We do not address the issue of dyons [7].

1 Nonrelativistic binding for $S = 1/2$

The references here are [1] and [2]. (There is also [3], but this reference seems to contain errors.)

The neutron ($Z = 0$) is a special case. Binding will occur in the lowest angular momentum state, $J = 1/2$, if

$$|\gamma| > \frac{3}{2n} \tag{5}$$

Since $\gamma_n = -1.91$, this condition is satisfied for all n.

In general, it is convenient to define

$$\hat{\gamma} = \frac{A}{Z}\gamma, \quad \hat{\kappa} = \hat{\gamma} - 1. \tag{6}$$

This expresses the magnetic moment in terms of the mass and charge of the nucleus. Binding will occur in the special lowest angular momentum state $J = q - \frac{1}{2}$ if

$$\hat{\gamma} > 1 + \frac{1}{4q}. \tag{7}$$

Thus binding can occur here only if the anomalous magnetic moment $\hat{\kappa} > 0$. The proton, with $\kappa = 1.79$, will bind.

Binding can occur in in higher angular momentum states J iff

$$|\hat{\kappa}| > \kappa_c = \frac{1}{q}\left|J^2 + J - q^2\right|. \tag{8}$$

For example, for $J = q + \frac{1}{2}$, $\kappa_c = 2 + 3/4q$, and for $J = q + \frac{3}{2}$, $\kappa_c = 4 + 15/4q$. Thus ${}^3_2$He, which is spin 1/2, will bind in the first excited angular momentum state because $\hat{\kappa} = -4.2$.

Unfortunately, to calculate the binding energy, one must regulate the potential at $r = 0$. The results shown in Table 1 assume a hard core.

2 Nonrelativistic binding for general S

The reference here is [4]. The assumption here is that $q \geq S$. (There are only 3 exceptions, apparently: ^{2}H, ^{8}Li, and ^{10}B.)

Binding in the lowest angular momentum state $J = q - S$ is given by the same criterion as in spin 1/2: (7). Binding in the next state, with $J = q - S + 1$ occurs if $\lambda_\pm > \frac{1}{4}$ where

$$\lambda_\pm = \left(S - \frac{1}{2}\right)\frac{\hat{\gamma}}{S}q - 2q - 1 \pm \sqrt{(1+q)^2 + (2S - 1 - q)\frac{\gamma}{S}q + \frac{1}{4}q^2\left(\frac{\gamma}{S}\right)^2}. \tag{9}$$

The previous result for $S = 1/2$ is recovered, of course. $S = 1$ is a special case: Then λ_- is always negative, while $\lambda_+ > \frac{1}{4}$ if $\hat{\gamma} > \gamma_c$, where

$$\gamma_c = \frac{3}{4q}\frac{(3 + 16q + 16q^2)}{9 + 4q}. \tag{10}$$

For higher spins, both $\lambda_\pm$ can exceed 1/4:

$$\lambda_+ > \frac{1}{4} \quad \text{for} \quad \hat{\gamma} > \gamma_{c-} \tag{11}$$

$$\lambda_- > \frac{1}{4} \quad \text{for} \quad \hat{\gamma} > \gamma_{c+} \tag{12}$$

where for $S = \frac{3}{2}$

$$(\gamma_c)_\mp = \frac{3}{4q}(6 + 4q \mp \sqrt{33 + 32q}). \tag{13}$$

For ${}^9_4$Be, for which $\hat{\gamma} = -2.66$, we cannot have binding because $3 > \gamma_{c-} > 1.557$, $3 < \gamma_{c+} < 8.943$. For $S = \frac{5}{2}$,

$$(\gamma_c)_\mp = \frac{36 + 28q \mp \sqrt{1161 + 1296q + 64q^2}}{12q}. \tag{14}$$

So ${}^{27}_{13}$Al will bind in either of these states, or the lowest angular momentum state, because $\hat{\gamma} = 7.56$, and $1.67 > \gamma_{c-} > 1.374$, $1.67 < \gamma_{c+} < 4.216$.

3 Relativistic spin-1/2

The reference is [5]. See also [6] and [7].

In addition to the bound states found nonrelativistically, deeply bound states, with $E_{\text{binding}} = M$ are found. These states always exist for $J \geq q + 1/2$. For $J = q - 1/2$, these (relativistic) $E = 0$ bound states exist only if $\kappa > 0$. Thus (modulo the question of form factors) Kazama and Yang [5] expect that electrons can bind to monopoles. (I suspect that one must take the existence of these deeply bound states with a fair degree of skepticism. See also [8].)

As expected, for $J = q - 1/2$ we have weakly bound states only for $\kappa > 1/4q$, which is the same as the nonrelativistic condition, and for $J \geq q + 1/2$, only if $|\hat{\kappa}| > \kappa_c$, where κ_c is given in (8).

4 Relativistic spin-1

The reference is [9].

In this case, no bound states exist, unless an additional interaction is introduced (this is similar to what happens nonrelativistically, because of the bad behavior of the Hamiltonian at the origin). Bound states are found if an "induced magnetization" interaction (quadratic in the magnetic field) is introduced. Binding is then found for the lowest angular momentum state $J = q - 1$ again if $\hat{\kappa} > 1/4q$. For the higher angular momentum states, the situation is more complicated:

- for $J = q$: bound states require $q \geq 16$, and
- for $J \geq q + 1$: bound states require $J(J+1) - q^2 \geq 25$.

But these results are probably highly dependent on the form of the additional interaction. The binding energies found are inversely proportional to the strength λ of this extra interaction.

Nucleus	Spin	γ	$\hat{\gamma}$	J	E_b	Notes	Ref
n	$\frac{1}{2}$	-1.91		$\frac{1}{2}$	350 keV	NR,hc	[3]
${}^{1}_{1}$H	$\frac{1}{2}$	2.79	2.79	$q - \frac{1}{2} = 0$	15.1 keV	NR,hc	[2]
					320 keV	NR,hc	[3]
					50–1000 keV	NR,FF	[4]
					263 keV	R	[6]
${}^{2}_{1}$H	1	0.857	1.71	$q - 1 = 0$ $(n = 2)$	$\frac{130}{\lambda}$ keV	R,IM	[9]
${}^{3}_{2}$He	$\frac{1}{2}$	-2.13	-3.20	$q + \frac{1}{2} = \frac{3}{2}$	13.4 keV	NR,hc	[2]
${}^{27}_{13}$Al	$\frac{5}{2}$	3.63	7.56	$q - \frac{5}{2} = 4$	2.6 MeV	NR,FF	[4]
${}^{27}_{13}$Al	$\frac{5}{2}$	3.63	7.56	$q - \frac{5}{2} = 4$	560 keV	NR,hc	[10]
${}^{113}_{48}$Cd	$\frac{1}{2}$	-0.62	-1.46	$q + \frac{1}{2} = \frac{49}{2}$	6.3 keV	NR,hc	[2]

Table 1: Weakly bound states of nuclei to a magnetic monopole. The angular momentum quantum number of the lowest bound state is indicated. In Notes, NR means nonrelativistic and R relativistic calculations; hc indicates an additional hard core interaction is assumed, while FF signifies use of a form factor. IM=induced magnetization, the additional interaction employed for the relativistic spin-1 calculation. We use $n = 1$ except for the deuteron, where $n = 2$ is required for binding.

5 Conclusion

Clearly, this summary indicates that the theory of monopole binding to nuclear magnetic dipole moments is rather primitive. The angular momentum criteria for binding is straightforward; but in general (except for relativistic spin 1/2) additional interactions have to be inserted by hand to regulate the potential at $r = 0$. The results for binding energies clearly are very sensitive to the nature of that additional interaction. It cannot even be certain that binding occurs in the allowed states. I intend to work intensively on this problem (particularly the relativistic case for arbitrary S) during the next few months. Perhaps a more definitive conclusion can be reached then.

References

[1] W. V. R. Malkus, Phys. Rev. **83**, 899 (1951).

[2] L. Bracci and G. Fiorentini, Nucl. Phys. **B232**, 236 (1984).

[3] D. Sivers, Phys. Rev. D **2**, 2048 (1970).

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[5] Y. Kazama and C. N. Yang, Phys. Rev. D **15**, 2300 (1977).

[6] K. Olaussen, H. A. Olsen, P. Osland, and I Øverbø, Nucl. Phys. **B228**, 567 (1983).

[7] P. Osland and T. T. Wu, Nucl. Phys. **B247**, 421, 450 (1984); **B256**, 13, 32 (1985); P. Osland, C. L. Schultz, and T. T. Wu, Nucl. Phys. **B256**, 449 (1985); P. Osland and T. T. Wu, Nucl. Phys. **B261**, 687 (1985).

[8] T. F. Walsh, P. Weisz, and T. T. Wu, Nucl. Phys. **B232**, 349 (1984).

[9] H. A. Olsen, P. Osland, and T. T. Wu, Phys. Rev. D **42**, 665 (1990); H. A. Olsen and P. Osland, Phys. Rev. D **42**, 690 (1990).

[10] C. J. Goebel, in *Monopole '83*, ed. J. L. Stone (Plenum, New York, 1984), p. 333.

Various Expectations (continued)

B. Cosmological

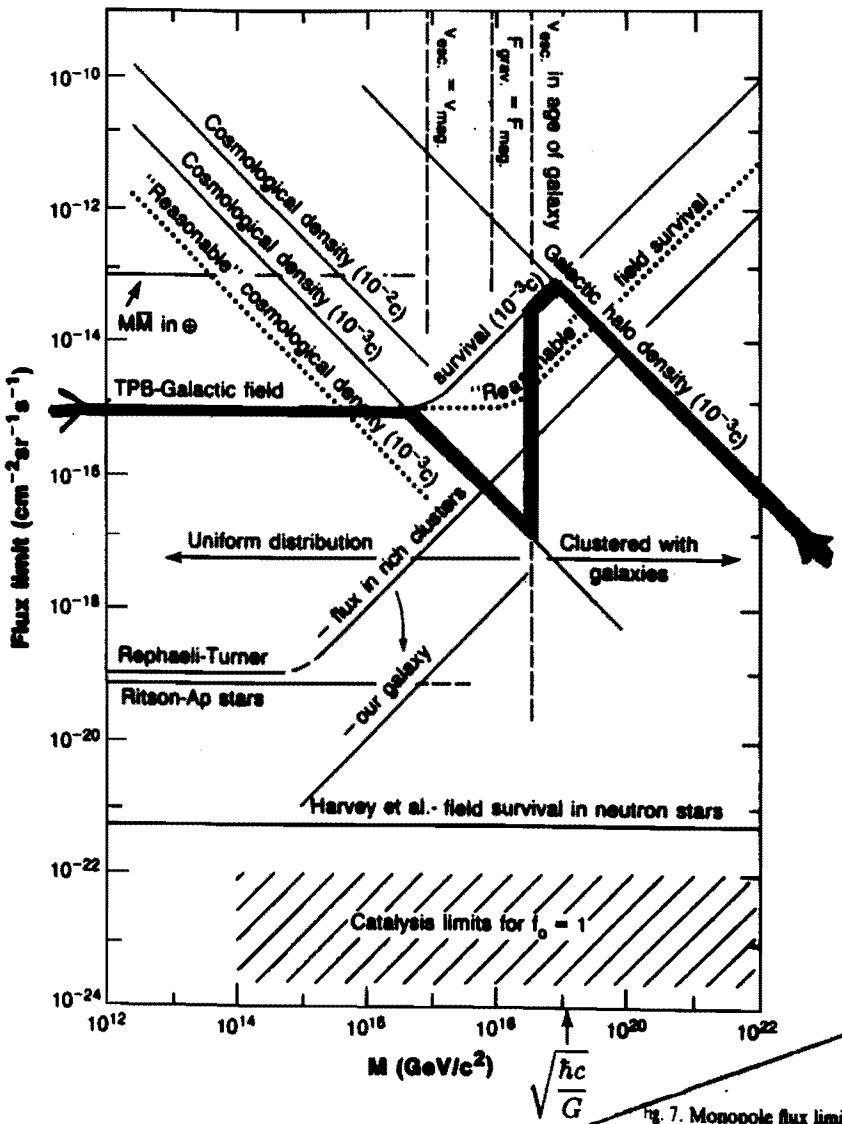
In addition, one might worry about "cosmological" expectations. Limits for magnetic monopoles from cosmological considerations, and from measurements of the relic monopole fluxes (super-heavy GUT style or (low mass) otherwise) from Groom and Preskill and the current "MACRO" experiment, as well as the older "lunar" search, are given here[references given on figures included]. Michael Turner [Phys. Lett. **B115**, 95 (1982)] has a "universal" curve that relates (the lower limit to) the monopole flux (given as a ratio to the gamma flux) versus 'x'-mass/temperature. We attach this also, along with mass closure, induction and lunar search upper limits. Turner's curve gives the relic monopole density as a function of $x = m/T$, where m is the monopole mass and T is the temperature at which the thermal production of monopoles commences. Thus if electroweak symmetry-breaking monopoles are produced at a temperature of 250 GeV, the cosmological limit on monopole density says that the mass of the monopole must be greater than 10 TeV. Coincidentally, 10 TeV is the lower limit of the mass expected in a simple model [e.g., Kirkman and Zachos, Phys. Rev. **D24**, 999 (1981)]. If we naively used Turner's curve to estimate the temperature corresponding to a 1 TeV monopole, we would obtain a production temperature of < 25 GeV. This could suggest less reheating after inflation. [M. Turner, private communication.] But this temperature is implausibly low for SU(2) X U(1) symmetry breaking; and such a monopole seems much too light to have such an origin. Nevertheless, there is every reason to explore this regime, since monopoles could well exist for reasons which have nothing to do with standard model or GUT considerations.

Ownership

In the event of observation of monopoles in this experiment, the question of "ownership" needs to be addressed. We the experimenters would expect to be acknowledged as the custodians of these monopoles, but that ownership belongs more globally, specifically to Fermilab (and the DOE). However, we would expect that further experimentation with these monopoles would continue with ourselves along with Fermilab and other collaborators as appropriate. A whole series of experiments would follow, as well as further efforts to create a larger "stockpile" of these valuable stable objects.

Fig. 1. Astrophysical limits on the monopole flux. The net optimistic upper limit as a function of monopole mass, set by density and galactic field survival considerations, is indicated by the heavy line. The dotted lines indicate limits obtained with our "reasonable" set of parameters, as given in table 1. "$M\bar{M}$ in ⊕" refers to Carrigan's limit based upon terrestrial heating based upon annihilation [29]. The catalysis bounds and the Harvey et al. limit are exclusive.

D.E. Groom, In search of the supermassive magnetic monopole



D.E. Groom, In search of the supermassive magnetic monopole

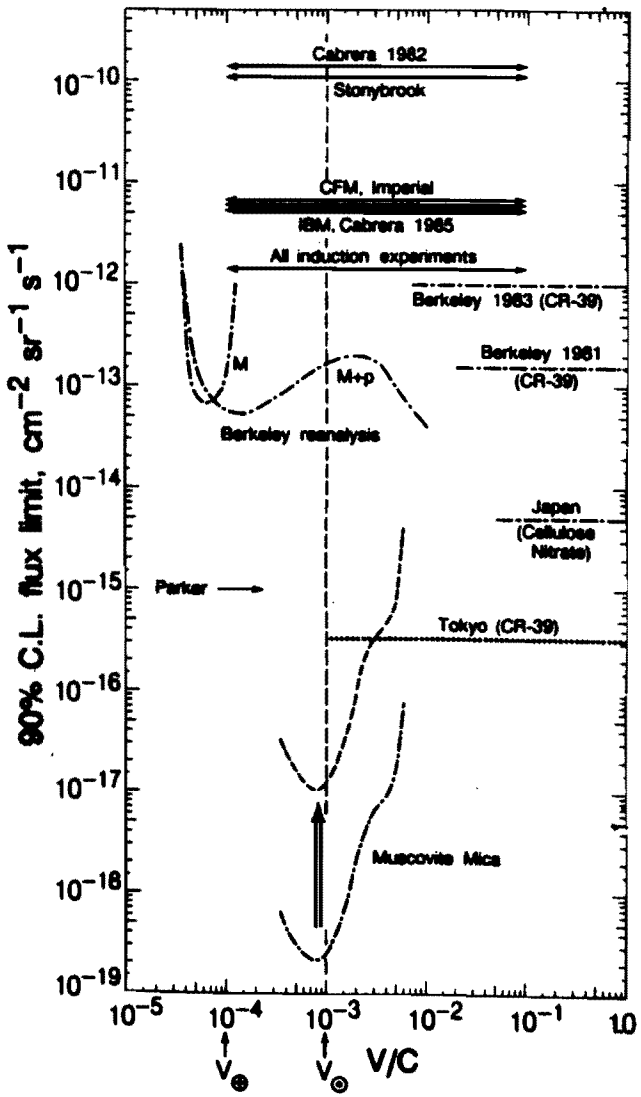


Fig. 7. Monopole flux limits obtained with induction detectors (solid lines independent of velocity) and track-etch detectors (dash-dotted lines). Early results of several groups have been omitted. The displaced mica curve indicated by the arrow shows what is believed to be the maximum correction for early proton capture. The dotted line indicates the one-year limit for a planned experiment.

D.E. GROOM, PHYS. REPTS. 140, 323 (1986)

"ARNS" 34, 461 (1984)

"PRESKILL"

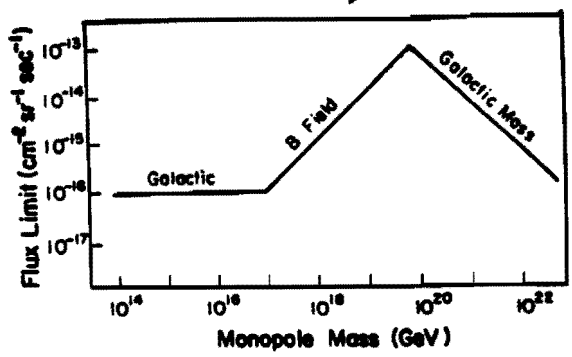


Figure 8 Astrophysical limits on the monopole flux as a function of monopole mass. "Galactic *B* field" labels the limit based on the energetics of the galactic magnetic field. "Galactic mass" labels the limit based on the total mass of the galaxy.

S. AHLEN, et al, PRL 72, 608 (1994)

"MACRO"

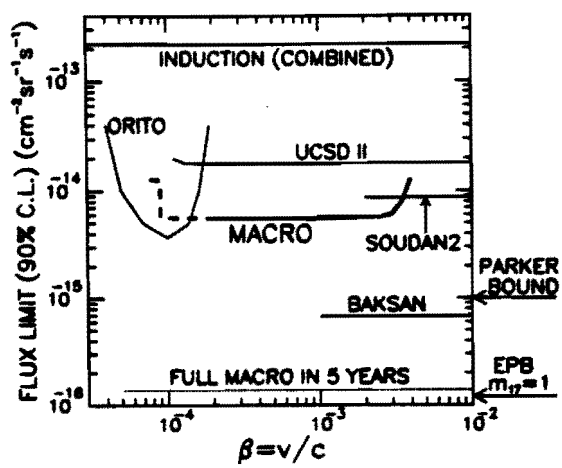


FIG. 3. The upper limit on GUT monopole flux at 90% confidence level established by MACRO. The bold solid curve indicates the sensitive velocity range for bare monopoles, and the dashed step shows the additional velocity range for dyons. Also shown are the anticipated limits reachable by the full MACRO detector after five years of operation, the Parker bound [2], the extended Parker bound (EPB) for monopoles of mass 10^{17} GeV/c^2 ($m_{17} = 1$) [3], and the results from several previous searches: induction (combined) [17], UCSD II (He-CH_4, for bare monopoles only) [18], Soudan 2 (Ar-CO_2) [20], Baksan (scintillator) [21], and Orito (CR-39) [22].

PRD 8, 698 (1973)

"LUNAR"

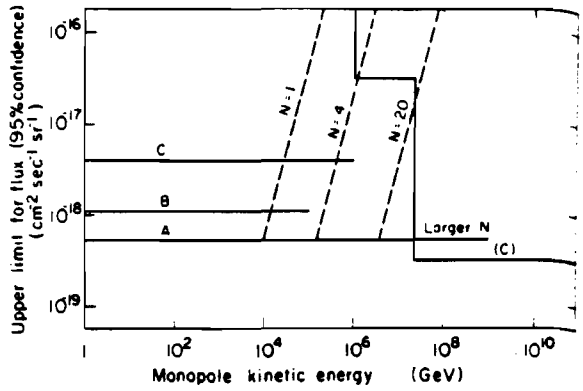


FIG. 3. Upper limit (95% confidence level) on the flux of cosmic monopoles as determined in recent monopole searches. A from this work, B from Ref. 7, C from Ref. 8.

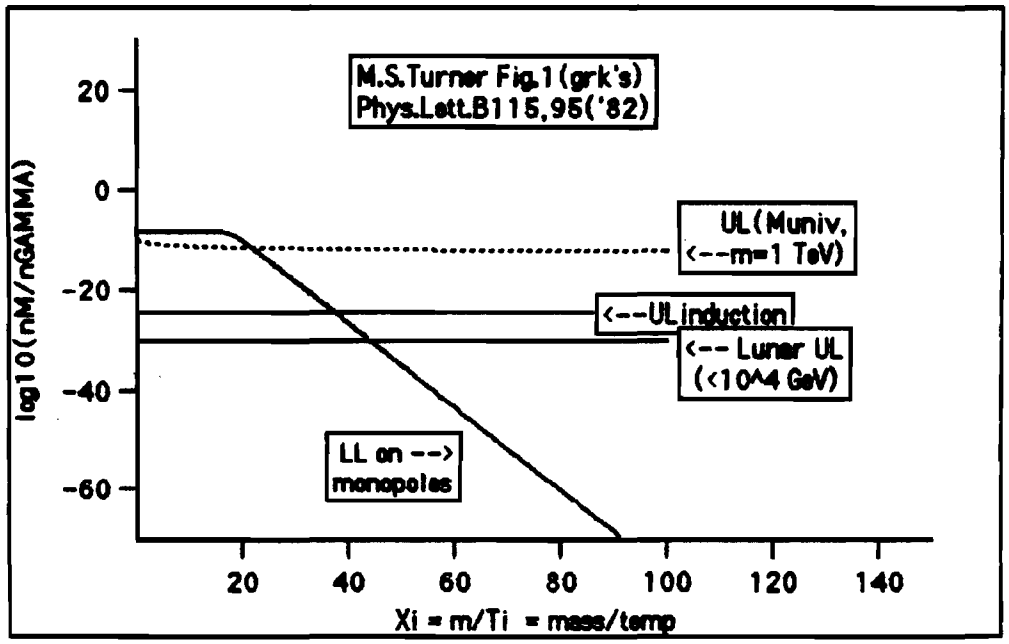


Figure--Turner's LL with UL's of Universe Closure and Other Monopole Searches implies m/T > ~45

Part II--Questions and Answers

Director Peoples letter to the *ad hoc* committee, the letter from chair Nezrick with the Questions for us to answer and our Answers are given here.

In addition, we summarize here the (to be replaced) parts of CDF and D0 we desire that should sooner or later could be made available to us:

1. D0's Be beam pipe
2. D0's CDC assembly (being replaced) including Al cylinder and extensions, etc.
3. CDF's Be beam pipe
4. CDF's CDT array surrounding the CTC
5. CDF's FEM covering forward/backward 10°'s outside of central tracking.

These are all likely to be available early, while the following should be available later:

6. CDF's CTC (being held in "arrears" as a backup for Run II at this time).

Fermilab

September 7, 1995

To: F. Nezrick
H. Frisch
J. Incandela
S. Somalwar

From: John Peoples

Thank you for agreeing to serve on an *ad hoc* committee to evaluate an experimental proposal "A Search for Low Mass Monopoles", submitted by G. Kalbfleisch. I am asking Frank Nezrick to act as the Chairman of the Committee. The first step will be to identify what information is necessary in order to evaluate the technical feasibility and realistic sensitivity attainable by the specific technique proposed. When you feel that sufficient information has been obtained, you should get together with Kalbfleisch and his colleagues. After the meeting, I want you to write me a report about your evaluation of the scientific merit and technical feasibility, including cost and technical manpower. I will also ask CDF, D0, and the Accelerator Division to estimate the cost and manpower associated with the removal and relocation of the beam pipes to carry out this experiment. If this process is completed by mid-December, I will put this proposal on the agenda for the PAC at its January 19 meeting. I will distribute your report to the members of the PAC to aid their discussion. Thank you in advance for your help.

cc: G. Kalbfleisch
K. Stanfield
T. Yamanouchi
D. Finley
J. Cooper
E. Fisk
R. Morrison

Fermilab

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Frank A. Nezrick • MS122 • (708) 840-4604

November 3, 1995

Prof. George R. Kalbfleisch
University of Oklahoma
Department of Physics and Astronomy
440 W. Brooks, Rm 131 NH
Norman, OK. 73019-0225

Dear George,

The committee formed to evaluate your proposal "A Search for Low Mass Monopoles" has convened. We have made a preliminary pass at the revised version of the proposal dated October 3, 1995. Since the proposal is rather brief, we have questions which must be answered before we can continue our evaluation. The questions are attached. As soon as I receive your written response, I will schedule another committee meeting. My goal is to have our evaluation process completed by mid-December so that your proposal can be placed on the agenda for the January 19, 1996 PAC meeting. Please feel free to call me if any of the questions need clarification.

Sincerely yours,

Frank

Frank A. Nezrick
Chairman, ad hoc committee for your proposal

attachment

QUESTION LIST

1. Are the nucleus-monopole binding energy calculations of Olausen and Sollie believable for real nuclei with non-point-like dipole moments?

2. Address the slow migration of "bound" monopoles in a magnetic field over periods of years, e.g. the CDF situation.

3. If the monopoles are not bound in the Be beam pipe, where do they finally get bound as they are pulled along the field lines?

4. Why bother with the Be beam pipe? Why not concentrate initially on materials with a large binding energy and potentially high monopole density.

5. Are there other parts of the CDF and D0 detectors, possibly outside the central regions, which might be more advantageous monopole samples, e.g. they might be smaller, more accessible, have a potentially higher density of lighter mass monopoles or be available earlier? Specifically, how much is the sensitivity increased by using the outer bore can and Be pipes as you propose over using more easily accessible pieces?

6. What is the sensitivity of detector noise and systematics on the n=1 mass limit? Show from past experience with the Longo detector what can be expected.

7. What has been the operational experience with the Longo detector, i.e. reliability, up-time, drifting, etc.?

8. What is the collaboration experience with cryogenic and SQUID detector techniques?

9. What must be done (e.g. additional electronics and computers) to make the Longo detector operational as a fully functioning monopole detector?

10. Outline the space and support requirements for the detector setup and operational area. Are these resources available at U. Oklahoma or U. Michigan?

11. What are the manpower commitments in FTE to this experiment?

12. Submit a budget estimate to assemble, operate and complete this experiment. Include expected sources of funding.

13. Give a schedule for the experiment including milestones for detector assembly, detector initial operation, and experiment completion. This should be consistent with CDF and D0 plans to release the sample material.

Question 1. Are the nucleus-monopole binding energy calculations of Olaussen and Sollie believable for real nuclei with non-point-like dipole moments?

Basically YES, because Olaussen and Sollie included form factors. Not surprisingly however the results are sensitive to the form used for these form factors. Hard-core calculations tend to give lower binding energies, as one might expect, because the form factors allows the nucleus to see more of the singular $1/r^2$ potential. They remark that their "binding energies" are somewhat larger than those estimated by Goebel (see K. Milton, Part I), since he considers the 'worst case' of hard core repulsion." One of us (KM) will continue to refine our understanding of these issues.

Question 2. Address the slow migration of "bound" monopoles in a magnetic field over a period of years, e.g. the CDF situation.

This is a simple tunneling situation. The decay rate is estimated by the WKB formula

$$\Gamma \sim \frac{1}{a} e^{-2\int_a^b \sqrt{2M(V-E)}}, \tag{1}$$

where the potential is

$$V = -\frac{\mu g}{r^2} - gBr, \tag{2}$$

M is the nuclear mass $\ll$ monopole mass, and the inner and outer turning points, a and b are the zeroes of $E - V$. Provided the following equality holds,

$$(-E)^3 \gg g^3 \mu B^2, \tag{3}$$

which should be very well satisfied, since the right hand side equals $10^{-20} n^3$ MeV^3, we can write the decay rate as

$$\Gamma \sim n^{-1/2} 10^{23} \mathrm{s}^{-1} \exp\left[-\frac{8\sqrt{2}}{3 \cdot 137}\left(\frac{-E}{m_e}\right)^{3/2} \frac{B_c}{nB} A^{1/2} \left(\frac{m_p}{m_e}\right)^{1/2}\right], \tag{4}$$

where the critical field, defined by $eB_c = m_e^2$, is 4×10^9 T. If we put in $B = 1.5$T, and $A = 27$, $-E = 2.6$MeV, appropriate for $^{27}_{13}$Al, we have for the exponent -2×10^{11}, corresponding to a rather long time! To get a 10 yr lifetime, the binding energy would have to be only around 1eV. Monopoles bound with kilovolt or more energies will stay around forever.

The question then arises of whether the entire Al atom can be extracted with the 1.5 T magnetic field present in CDF. The answer seems to be unequivocally NO. The point is that the atoms are rigidly bound in a lattice, with no nearby site into which they can jump. A major disruption of the lattice would be required to dislodge the atoms, which would probably require kilovolts of energy [J. Furneaux, private communication]. Some such disruption was made by the monopole when it came to rest and was bound in the material, but that disruption would be very unlikely to be in the direction of the accelerating magnetic field. Again, a simple Boltzmann argument shows that any effective binding slightly bigger than 1 eV will result in monopole trapping "forever." This argument applies equally well to binding of monopoles in ferromagnets. If monopoles bind strongly to nuclei there, they will not be extracted by 5 T fields, contrary to the arguments of E. Goto, H. Kolm, and K. Ford [Phys. Rev. **132**, 387 (1963)]. The corresponding limits on monopoles from ferromagnetic samples [R. A. Carrigan, Jr., B. P. Strauss, and G. Giacomelli, Phys. Rev. D **17**, 1754 (1978)] are suspect.

Question 3. If the monopoles are not bound in the Be beam pipe, where do they finally get bound as they are pulled along the field lines?

Of those monopoles that get ranged out in the Be beam pipe, they will diffuse down and follow the field lines towards some flux return path. For D0 the field lines are those of the earth, at some angle upwards/downwards to the horizontal, and so will encounter some other material, principally the Al cylinder and its end plates, and get bound there, along with those higher energy monopoles that ranged out there originally. For the CDF situation, they migrate horizontally, and acceleration of the poles will occur when they get to "open" spaces. They will largely follow field lines to the flux returns and get trapped there (by "image charge" most likely), unless they encounter other material first.

Question 4. Why bother with the Be beam pipe? Why not concentrate on the materials with a large binding energy and potentially high monopole density?

The aluminum cylinders have the large binding energy and high monopole density; that is why we "upgraded" our request to utilize them. However, the Be beam pipe is easy to process, and covers "4π". The angular momentum of monopoles is not specified, so that one needs to consider monopole production to be roughly isotropic, so that "4π" coverage is to be desired. However, since the Be pipe is so thin (especially in light of the "β^3") production suppression near threshold), only high "n" charged monopoles gives significant stopping power. But the Be pipes should not be excluded because they can trap (negative) electrically charged monopoles (dyons). Finally, the theoretical "lore" of monopoles may not be correct. For example, polarization of the nuclei by the presence of the magnetic monopole has NOT been taken into account; the L-S coupling for Al's $d_{5/2+}$ unpaired proton is ~1 MeV (see Part I) compared to an estimated binding energy of 2.5 MeV. Thus the rearrangement of the nucleons may provide binding in other unpaired cases if the polarization deformations are taken into account (ie. "free" neutrons supposedly bind to monopoles). **We wish to cover all the possibilities experimentally**, and the limits shown in the FINAL Fig. 4b earlier, as a function of mass reflect the experimental situation. The "interpretaion" as a limit on the monopole mass requires taking the β^3-DY theory seriously, subject to the "constraints" of binding, etc.

Question 5. Are there other parts of the CDF and D0 detectors, possibly outside (of) the central regions, which might be more advantageous monopole samples, e.g. they might be smaller, more accessible, have a potentially higher density of lighter mass monopoles or be available earlier? Specifically, how much is the sensitivity increased by using the outer bore can and Be pipes as you propose over using more easily accessible pieces?

The amount of material which a monopole will traverse before stopping is dependent on the magnetic charge of the monopole and its kinetic energy. The attached Table shows

the (maximum) amount of material (in "grams", ie. g/cm^2) that monopoles will traverse.

Table-Range (grams) for Monopoles with
Maximum Kinetic Energies (Tmax= 900-m, GeV)

Mass m	Charge n=1	n=2	n=3	n=6
100 GeV	135	34	15	4
300	105	26	12	3
500	70	18	8	2
700	35	9	4	1

Thus one can see that NO monopole created by the Tevatron, that enters, will exit the electromagnetic calorimetry of CDF or D0. D0 is almost fully "4π" centrally, while CDF has the forward/backward 10° open to displaced "endcap" calorimeters. (See schematic drawings of the CDF and D0 detectors on following pages.)

The D0 collaboration will NOT be replacing any of the EM calorimetric components, which leaves only tracking components and their support structures as potential search material. The entire tracking chamber consisting of the Vertex Drift Chamber (VTX), the Central Drift Chamber (CDC), the Transition Radiation Detector (TRD) and the Forward Drift Chamber (FDC) will be replaced (J. Christensen, D0, private communication). The outer support cyclinder of the CDC is the D0-Al cylinder we have requested; it has attached to it in addition 0.5" diameter 0.5m long extension tubes on each end (M. Rijssenbeek, D0, private communication). These tubes give additional material for the search. The solid angle coverage including these extension tubes is increased some 70% to 85 %.

The CDF collaboration's Forward Drift Chambers will not be used in the upgrade and MAY be more accessible than other components of the tracking system. CDF will be replacing some of the forward EM calorimetry (FEM) as well. The front face of this calorimeter is covered with 1.0 inch (2.5 grams) of scintillator which will reduce the energy of particles entering the FEM. So the FEM (consisting of Al, Fe supports and Pb, all of which should bind stopped monopoles) could provide samples to be searched. **The FEM's cover 0.03 of the solid angle and should then give a limit of order ~1 pb**, comparable to but somewhat worse than the "n=1 D0 Al" shown in the FINAL β^3-DY Fig.4b) results (in Part I of this Addendum). Also if CDF chooses to replace rather than upgrade the Central Tracking Chamber (CTC) then the 2.0 inch aluminum endplates should be useful, but they are no more accessible than the CTC outer support cyclinder. (As we understand it, CDF plans to replace the CTC, but is keeping the current CTC as a backup until it is clear that the replacement will meet the timetable of the upgrade). However, the CTC is surrounded by the CDT (three layers of stainless steel tubes of 0.2 mm wall thickness) which are being discarded; these will be equivalent (at 1.4 grams) to half of the "n=1,2 D0 Al" (the CTC giving 2.8 grams of material in front of it like the D0 TRD plastic). **These CDT tubes should be available early also.**

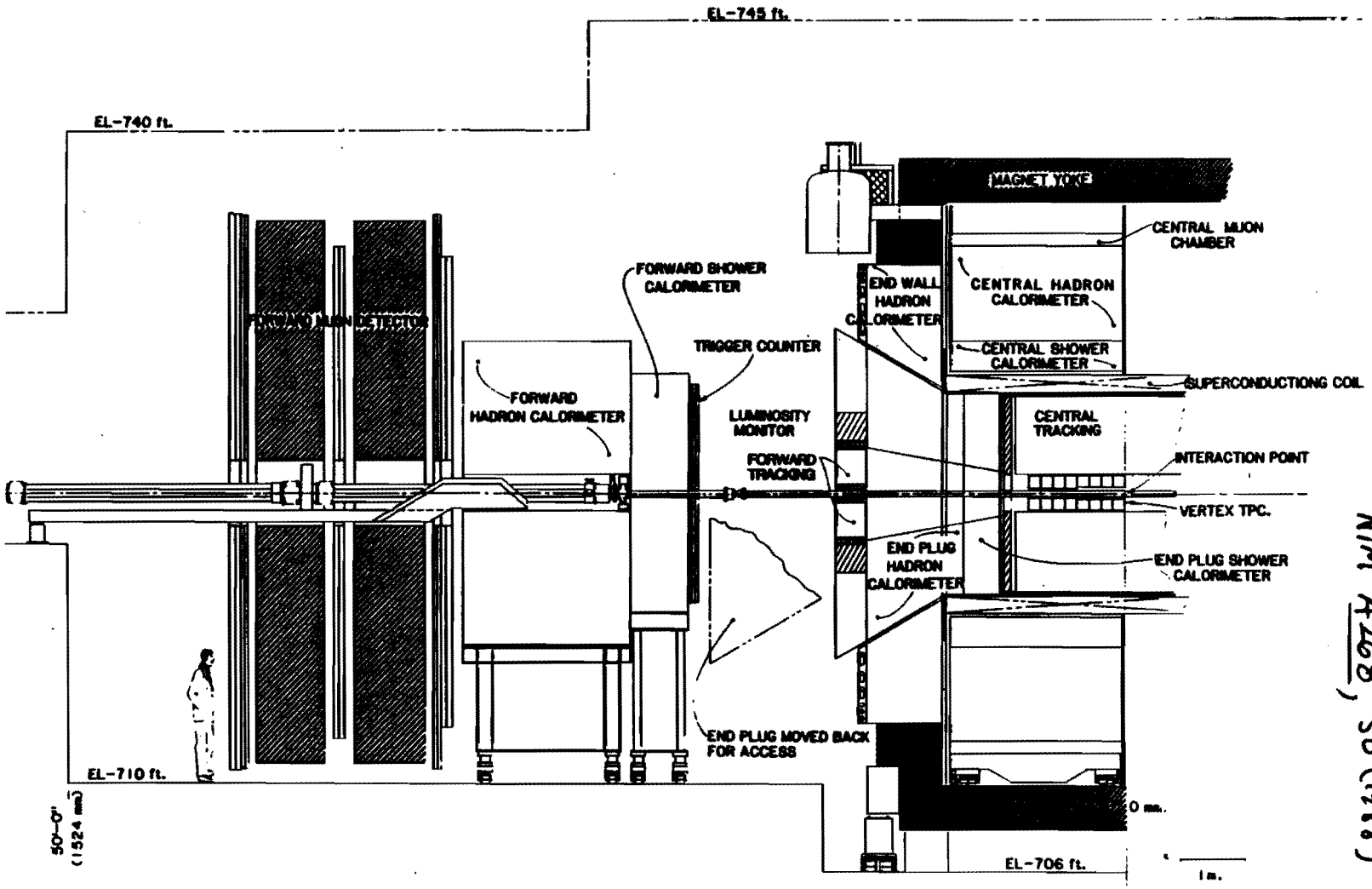

Fig. 1. Cross section through a vertical plane of one half the CDF detector. The detector is symmetric about the midplane and roughly symmetric around the beam axis.

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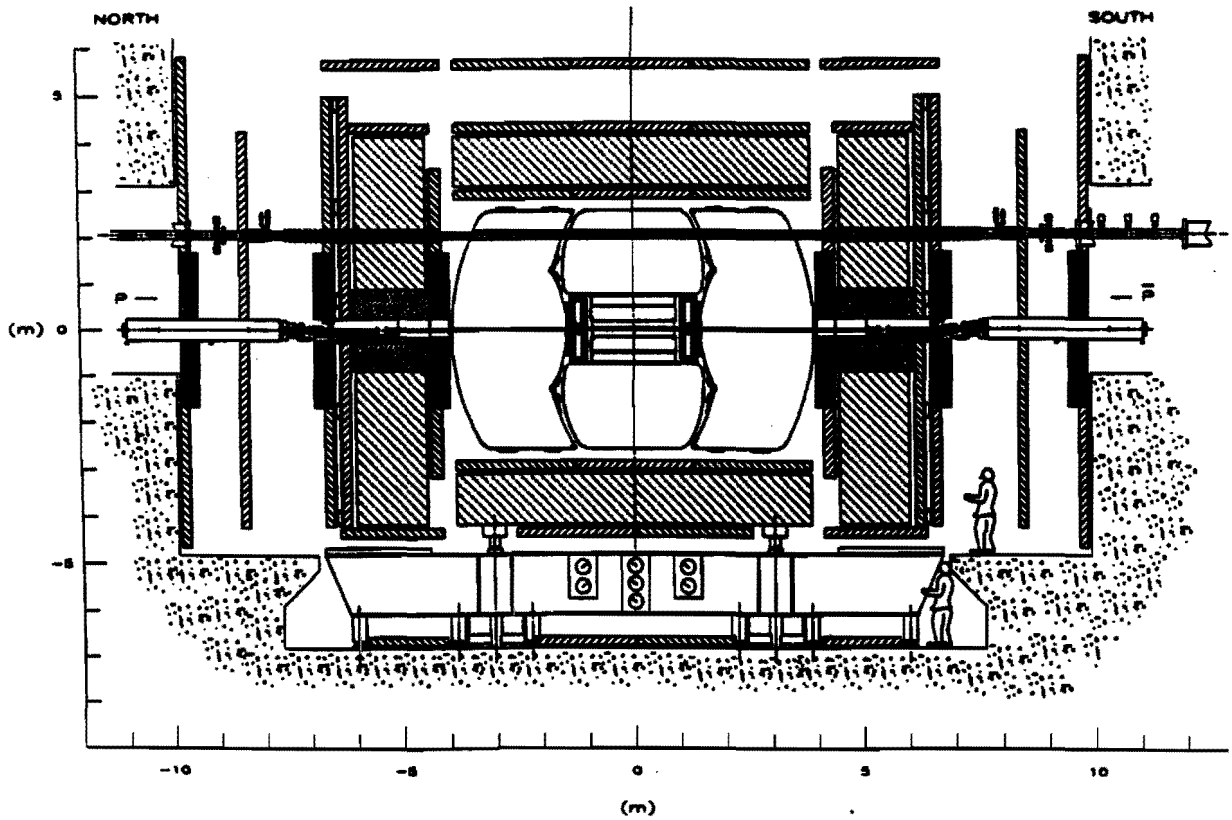


Fig. 2. Elevation view of the DØ detector. The scales are in meters.

Question 6. What is the sensitivity of detector noise and systematics on the n=1 mass limit? Show from past experience with the Longo detector what can be expected.

The thesis of H-M. Jeon (PhD, U. Michigan, Longo) discusses this to a limited extent. The thermal noise with their "SHE" rf-SQUID is inconsequential (sigma <0.01 n=1 pole, p.41 thesis), as it is (probably) for all such measurements. The systematic errors from "geometric" changes in the apparatus (from boiling vibrations of the liquid He, environmental shocks and "cool-down" distortions) must be monitored. After a "settling" period, the systematics are manageable; a linear, rather than a flat, backgound may come in, upon which the "n=1 signals" (simulated by a "pseudo-" pole) can easily be seen. The residual systematics look comparable to the fast (10 Hz sampling rate) fluctuations. These are documented in Jeon's Fig. 4.11 c,d (p. 50 thesis) which are attached. From Fig. 4.11d, one sees fast fluctuations of +/-(0.05 to 0.5) of one pole, giving a sigma (averaged over 10 seconds, ie 100 samples) of about 0.025 pole. The linear rise is about 0.7 of a pole over the 50 second scan, and can be "subtracted" to be flat to <0.01 pole. Thus an overall signal to noise (per scan) of about 30:1 should be attained for n=1.

Question 7. What has been the operational experience with the Longo detector, i.e. reliability, up-time, drifting, etc.?

Operation of the Longo detector was typically from 0100-0700 (AM) to avoid environmental vibrations (trucks, elevator, etc.). A LHe fill would last, if filled and allowed to fully boil off, about 30 liters, in excess of 12 hours, of which the middle 4 or so hours were "quiet" operation, as discussed in Q&A 6 above. This matched a possible way of proceeding that they adopted. After initial troubles with vacuum leaks and ougassing, the apparatus apparently was reliable, with drifting under control as shown above (Q&A 6). Our "repeat" rate for bad runs should be much reduced for our non-ferromagnetic samples since large intrinsic dipole moments should not be encountered as was the case with Longo's&Jeon's meteorites.

Question 8. What is the (ie the OU group's) collaboration experience with cryogenic and SQUID detector techniques?

Clearly not extensive (cryogenics some, SQUID's not, including "solid staters" in our own Physics Department). Kalbfleisch had some cryogenic and superconducting experience at Fermilab in charge of the R&D for the QA,QB,QC development of the Tevatron quadrupoles up through the beginning of the actual production fabrication of those quadrupoles. As for SQUID's, the technology is mature; one buys and uses them as a "commercial" package. They must be installed inside the cryogenic and vacuum spaces of the apparatus (see below). We will learn as necessary. We note that Kalbfleisch and Bahran mastered the low energy atomic and nuclear techniques to pursue the "17 keV neutrino" back into oblivion in tritium decay at Oklahoma.

SEE ALSO!

H. JEON & M. J. LONGO,
"SEARCH FOR MAGNETIC MONOPOLES TRAPPED IN MATTER,"
PHYS. REV. LETTERS 75, 1443 (1995).

SEARCHING FOR MAGNETIC MONOPOLES TRAPPED IN BULK MATERIALS

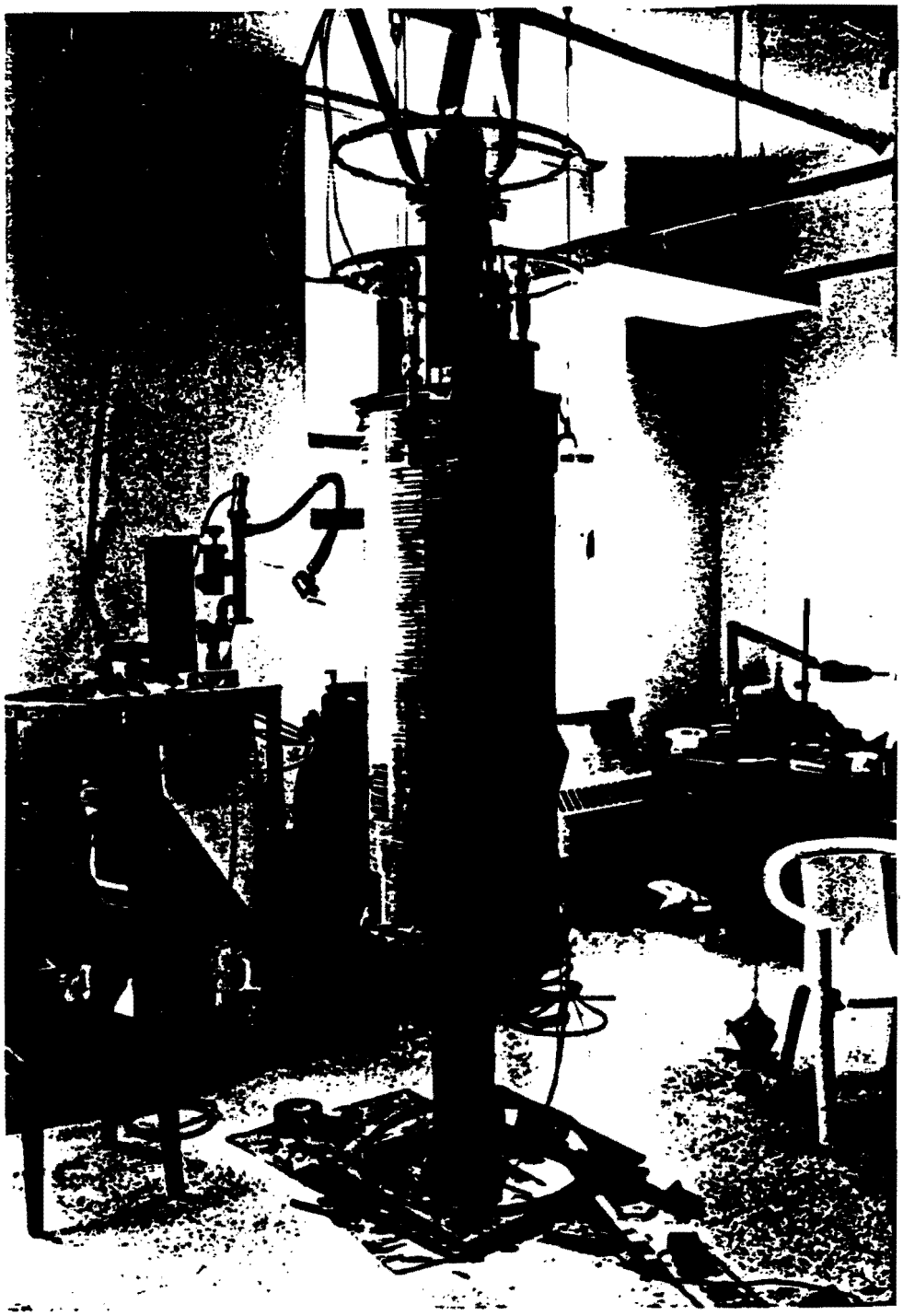
by

Hun-Moo Jeon

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
(Physics)
in The University of Michigan
1995

Doctoral Committee:

Professor Michael J. Longo
Professor C. Tristram Coffin
Professor Karl T. Hecht
Professor Joel A. Smoller
Research Scientist H. Richard Gustafson



The monopole detector

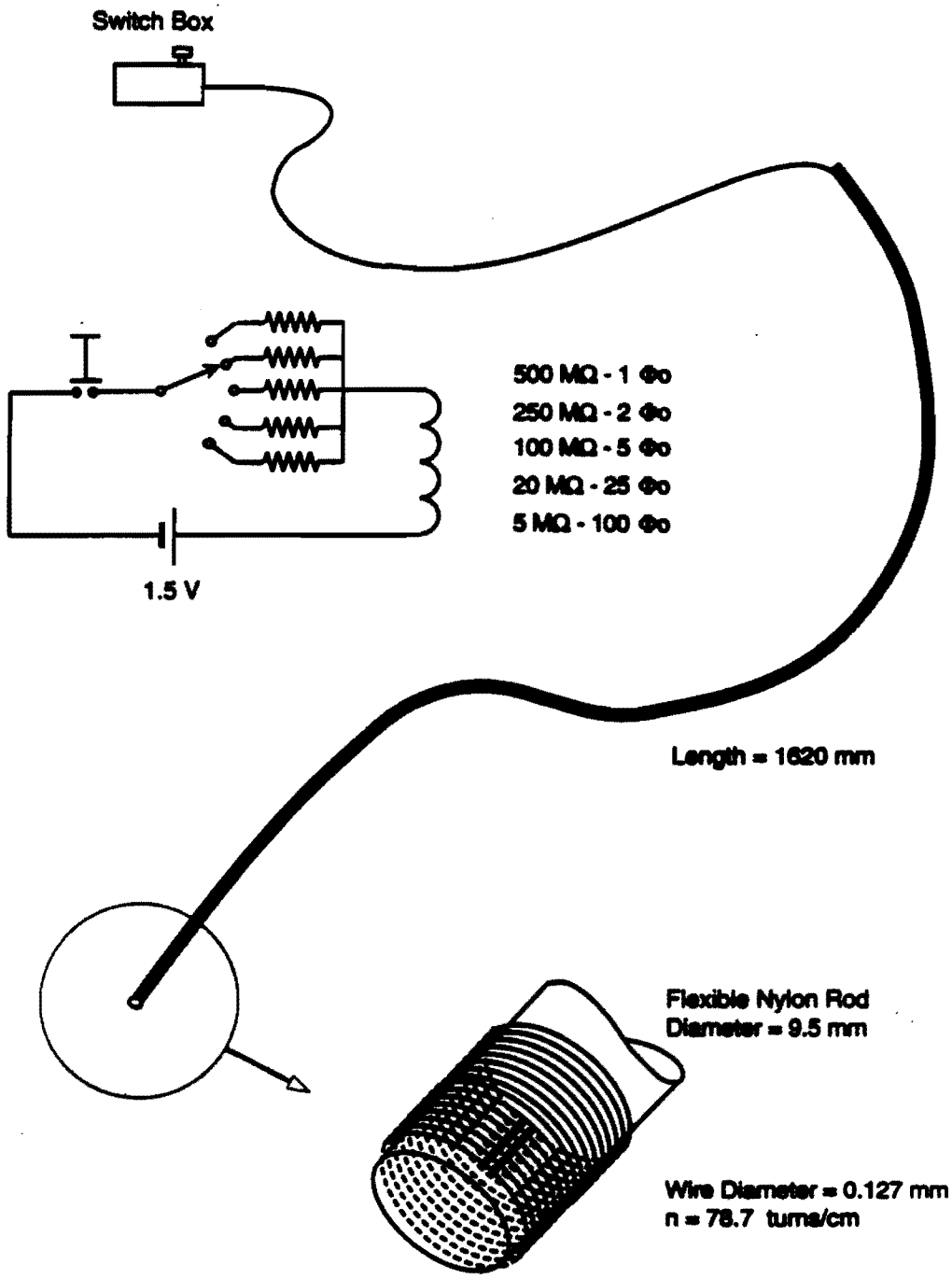


Figure 4.6 The Pseudopole - a simulated Dirac monopole.

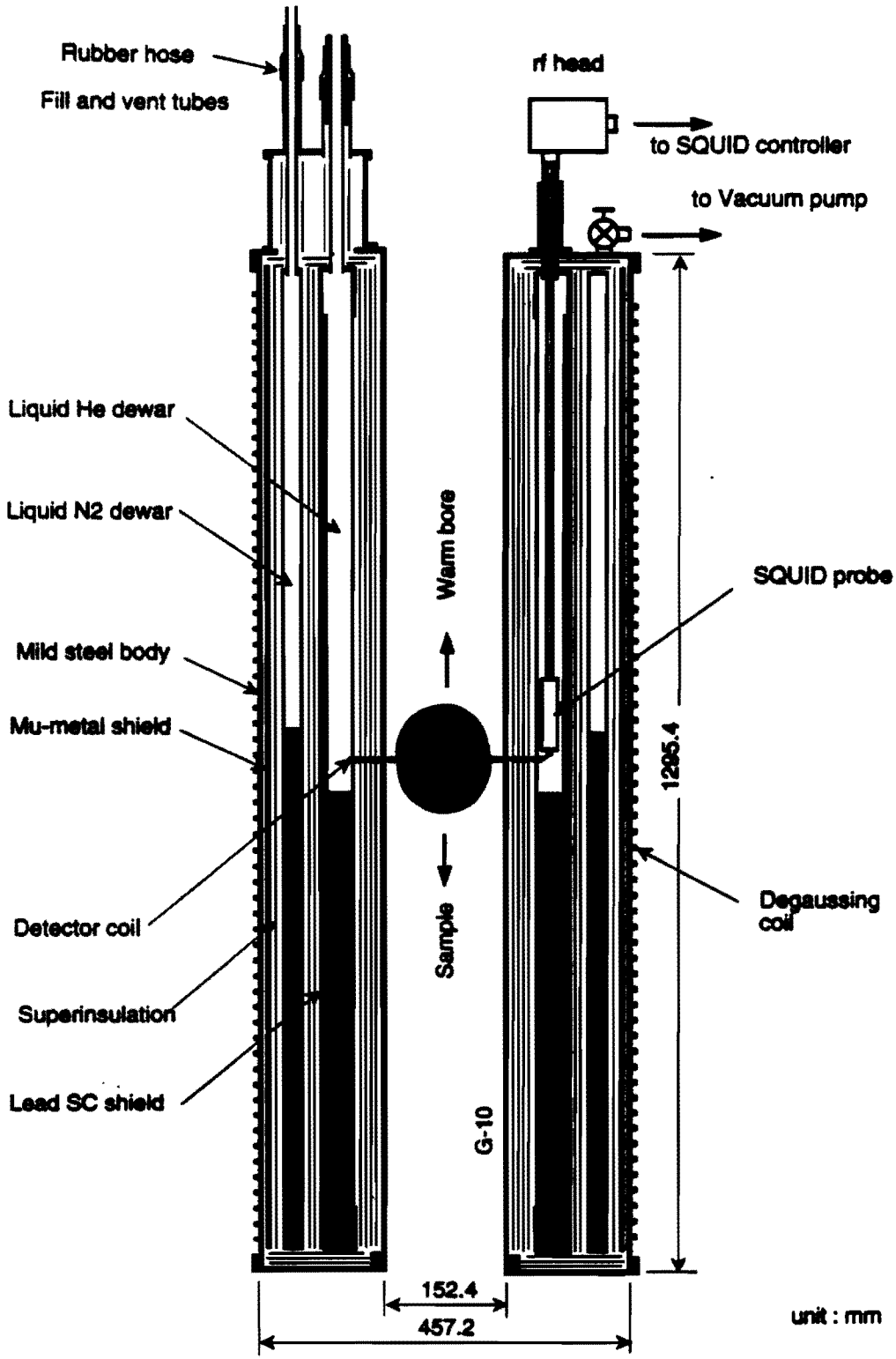


Figure 4.7 The monopole detector – section through the centerline.

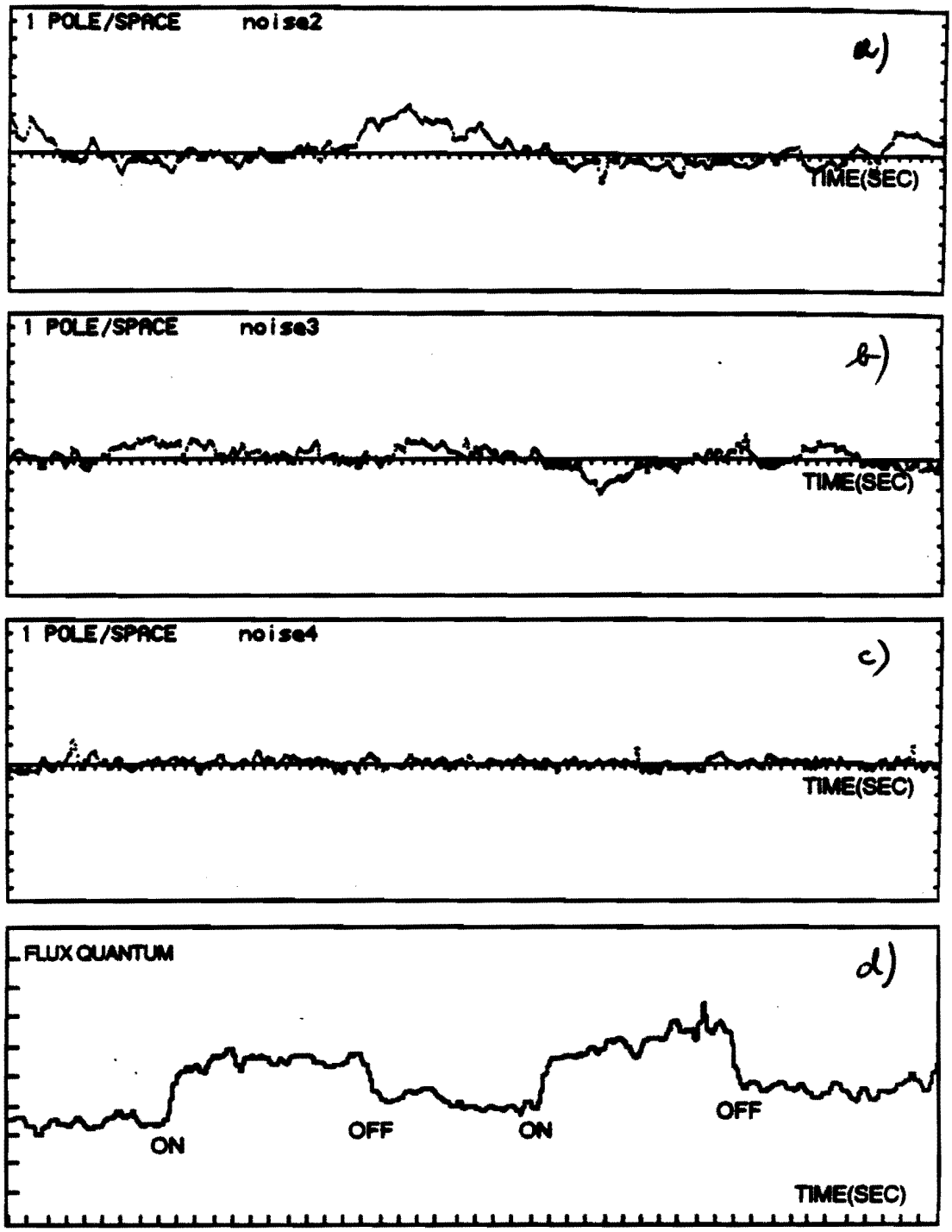


Figure 4.11 Noise of the monopole detector - from the top - measured 2 hours after, 3 hours after and 4 hours after filling liquid helium. Bottom figure is the SQUID signal for 2 flux quanta (= 1 Dirac monopole) more than 4 hours after filling.

Question 9. What must be done (e.g. additional electronics and computers) to make the Longo detector operational as a fully functioning detector?

Negotiations regarding the "borrowing" of the Longo detector (see letter from Longo in Part I), in regard to whether all components would be "loanable," have not been made. Kalbfleisch expects to visit Michigan soon and "view" the apparatus first hand. Longo says it is "mothballed" and will "require some work to get it going again." We expect to do the following: 1) supply the computer (Mac(s) running LabView, which we have), 2) purchase a new DC-SQUID and controller, 3) dismantle, move and re-establish the apparatus (with hopefully the old and new SQUIDs both installed), 4) construct and install 3 external Helmholz coil pairs (mutually orthogonal) to cancel the earth's field to less than 5 mGauss and 5) make shake-down runs with the "pseudo-"pole to verify its operational qualities, equal to or better than Jeon's. We have the power supplies to power these new coils. Cancellation of the earth's fields with these new coils (radius ~1.5 m) should greatly improve some of the systematics encountered by Jeon and Longo. Such a Helmholz arrangement has been used (by others) here at OU for sensitive atomic physics experiments (Na-electron scattering at a few eV).

Question 10. Outline the space and support requirements for the detector setup and operational area. Are these resources available at U. Oklahoma or U. Michigan?

Answering the second part first: yes, as the Longo apparatus was operated at U. Michigan for their meteorite search. At OU, space can be made available, and we have an excellent instrument shop with 3 FTE machinists/instrument makers. At OU they have built many high vacuum systems for the atomic, solid state and even the high energy group over the years; this involves machining (although large pieces are fabricated via outside vendors) and the "vacuum-tight" welding of many small and large joints on these pieces. It turned out that the cryogenic vacuum jacket of a purchased18 Tesla superconducting magnet system needed repair. As the manufacturer was in England, and in any case had gone bankrupt, our instrument shop personnel were able to dismantle, fix and reinstall to operating order this magnet; the solid state group claims it was "better than new." LHe 250 liter dewars and a 3000 liter LN_2 supply exist at OU; and a new "plasma" welder has recently been acquired.

Fermilab is central and would allow participation by others there (eg. Dr. M. Kuchnir, with his complementary experience), and has all the requisite infrastructure (space may be tight?) and has the "raw" materials on-site. If not Fermilab, Oklahoma has greatest convenience for the OU team (less travel, easier scheduling of data taking "binges", etc.) although possibly a somewhat longer execution time of the total experiment would ensue (more "learning curve" etc.). Michigan would not be the site, unless Longo should opt to join (he has said he is really too busy, but did not completely rule out participating in it

would put an unreasonable demand from us on Michigan to provide this service for a year or more. Michigan and Longo participating would not (?) require relocating the apparatus, which requires some dismantling, etc. as mentioned above, Of course, installing a second SQUID requires this anyway; keeping it at Michigan would probably mitigate against installing the second SQUID, with its attendant improvement in sytematics, redundancy,etc.

The space required is of order 30x10x10 ft^3 for the Helmholz coils plus induction apparatus to be located and reconfigured (ie disassemble, weld, assemble etc.) and for dissection of the raw material and the handling of (250 l) LHe dewars, and a small "office" for computer, data taking and analysis space next door. Technician or "instrument maker" help to reconfigure the apparatus, and to "dissect" the samples. Power requirements are minimal, although some clean power for the SQUID controllers would be advisable. The space would ideally be located where environmental vibrations (elevators, large volume road traffic, etc.) are not a problem.

Overall, operation at Oklahoma is feasible and sensible.

Question 11. What are the manpower commitments in FTE to this experiment?

If in Oklahoma, the three protagonists (at 0.3 of their research time each) plus a PhD. thesis student (already identified), i.e. ~1.5 FTE, and instrument-maker help as required, another ~0.5 FTE, for the ~2 year extent of the experiment.

[If at Fermilab or Michigan, include another 0.2 FTE (for Kuchnir or Longo).]

(For comparison, the "17 keV" neutrino in tritium experiment was Bahran and Kalbfleisch, about ~0.7 FTE for some 5 years. This included starting from "scratch" and solving all of the unknown, by anyone, effects and problems, and the lengthy complicated analyses. Some six publications plus Bahran's thesis were also completed in this time.)

Question 12. Submit a budget estimate to assemble, operate and complete this experiment. Include expected sources of funding.

We expect to obtain supplemental funding of ~$50K (mostly DOE, but with some OU matching, via preliminary discussions) for purchase of DC-SQUID and controller + miscellaneous electronics ($7.5K) and for shipping of Longo apparatus, Helmholz coil fabrication, LHe for the experiment, (requisite travel to/from point of operation) and miscellaneous supplies, contingency etc. In addition, we expect contributions of the appropriate tech/instrument-maker time (from Fermilab if there) to reconstruct the apparatus and for space, power, etc. The costs associated with retrieving the "raw"

materials are assumed to be covered by Fermilab, and cannot be assessed(by us) at this time, until we know which pieces will be available and when. However total costs to Fermilab should be much less than $50K for these services (the materials exist and have previously been paid for and used, and are being discarded).

Question 13. Give a schedule for the experiment including milestones for detector assembly, detector initial operation and experiment completion. This should be consistent with CDF and D0 plans to release sample material.

From time zero, T0, +three months till apparatus transferred to site (F, OU or UM)

- T0 + 3 mos, +three months till operational
- T0 + 6 mos, +three months of testing, "pseudo-"pole etc possible receipt and preparation of "raw" materials·
- T0 + 9 mos, +six months to run most of the samples through the apparatus, and analysis of data
- T0 + 15 mos, prepare publication of first results (3 mos.), consideration of other options that may present themselves, etc.
- T0 + 18 mos, basic completion of initial phase.

"T0" would be Feb. '96 at the earliest (PAC/MOU/etc); summer '96 would be the earliest that CDF and D0 detector disassembly would yield "raw" materials for testing. These times are most likely consistent (as can be known at this time,Nov. '95).

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Proposal to Fermilab, Batavia, Illinois

A Search for Low Mass Monopoles

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REVISED October 3, 1995

ABSTRACT

A magnetic induction search for monopoles trapped in the CDF and D0 beam pipes **and** drift chamber support cylinders is proposed. Significant improvements on the limits for low mass monopoles (up to several hundred GeV) can be attained.

INTRODUCTION

Although the present experimental emphasis has concentrated on thinking about and looking for super-heavy GUT monopoles via cosmic ray bombardment of the earth, expanding the search for accelerator created monopoles to the highest masses and lowest cross-sections available should also be continued [1, 2].

Since the Price, et al [3,4], exposures at the Tevatron in 1990 at some initial low luminosity, CDF and D0 have amassed more than 200 pb^{-1}. This suggests extending the cross-section limits some 1-5 orders of magnitude smaller. The current limits on cross-sections are given in Fig. 1 (Fig. 1 of Price [3]); the shaded region shows the area exporable in this proposal [5].

As shown in Eberhard, et al, and Ross, et al [6, 7], all searches for monopoles have various differing (implicit or explicit) assumptions that modify the interpretation or validity of the limits quoted. This is true for this proposed search as well; we will discuss these below and indicate how much of the shaded area of Fig. 1 can be accessed with some suitable assumptions. We believe that this extension warrants approval of this modest search.

In addition, the next collider runs of the Tevatron with the Main Injector in a few years will lead to a luminosity increase of a factor of ten or more, and with suitable improvements (including possibly a dedicated intersection region, or the use of an existing one for a suitable period of time) a search with less restrictive assumptions

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FIG. 1

FROM PRICE, GUIRI, KINOSHITA

PRL 65, 149 (1990) [ref. 3]

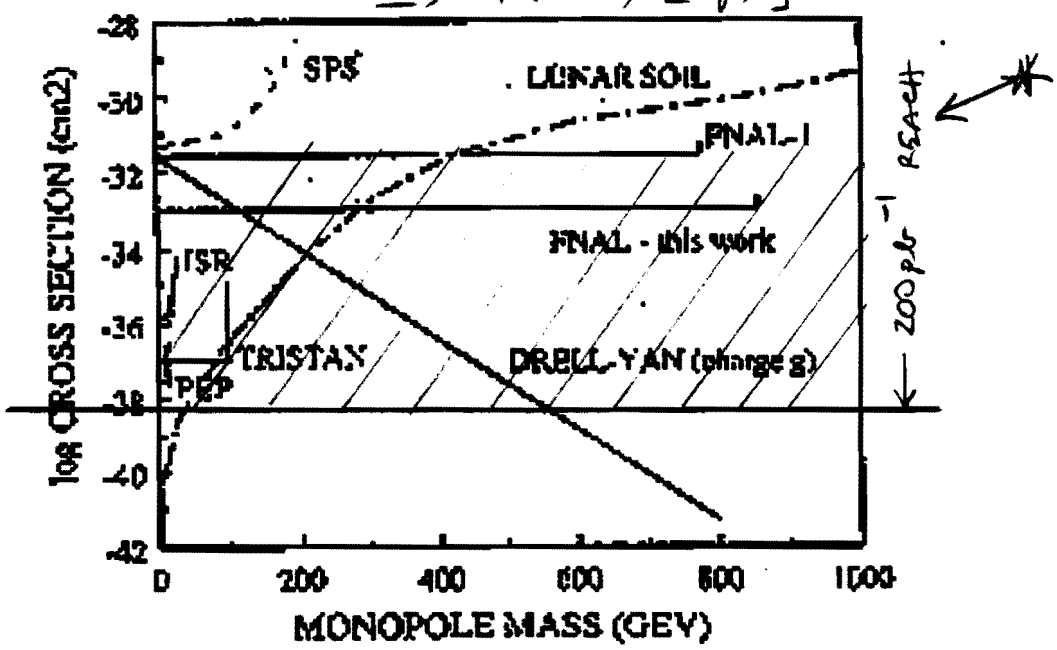


FIG. 1. Upper limits on monopole production cross section. References are as follows: PEP, Ref. 9; ISR, Ref. 11; TRISTAN, Ref. 10; SPS, Ref. 7; lunar soil, Ref. 8; FNAL-1, Ref. 5.

EXPERIMENTAL TECHNIQUES

The CDF and D0 experiments have been exposed to a high integrated luminosity for several years now. The beryllium beam pipes, and the aluminum support cylinders of their drift chambers (CTC and CDC respectively) [5] of these experiments are presumed to be replaced in future running, but in any case are expendable/replaceable elements. Although the total amount of material in these materials is not massive, the very large energy loss rate of monopoles in matter allows for the expectation of a reasonable trapping fraction for such monopoles under suitable assumptions.

Techniques to be used could encompass ALL previous ones, if done in a suitable order. The techniques previously used are 1) multiple (Alvarez induction method [6]) or single (Cabrerra induction method) traversals of a superconducting loop, 2) extraction with a (pulsed) high magnetic field (Carrigan method [8]), and 3) acceleration by magnetic fields into suitable etchable plastics such as Lexan or CR39, etc (Price method [4]). **We intend to use the magnetic induction method.**

In addition, one can contemplate a chemical method whereby one "dissociates" the material in a 4) magnetic field-free environment and looks for the "annihilation" of the pole-antipole pairs that are attracted to each other during diffusion through the "liquid" medium or 5) in a configured field environment to concentrate the monopoles for additional testing via the other four methods. Apart from the annihilation method, any candidate samples found can obviously be rerun "ad nauseum" to verify the observations. Measurement of the total annihilation energy [9] for any verified monopole candidates will measure their mass. Note that the rate of dissociation, and the fractions to be dissociated, of the samples can also be controlled. Care and redundancy will be practiced.

The detectors of Alvarez and Carrigan are either obsolete or have been "cannibalized," so that new ones must be found or constructed [10]. **We need a NEW single (or multiple) pass induction apparatus with a room temperature warm bore [11].** A moderate outlay of funds and laboratory space will be needed to perform this search. The location of the measurements needs to be determined. For beam pipes and support cylinders, the residual radioactivity is presumably from impurities, and tractable for "off-site" processing. However, it would probably be preferable to have the apparati moved "on-site," especially in view of other hazards of Be, and some on-site help from Fermilab personnel would be welcomed [12].

ASSUMPTIONS NEEDED for the PHYSICS ANALYSIS

Trapping of the monopoles in the relatively thin beam pipes and support structures requires ranging out by energy losses and binding to the atomic or nuclear structures contained therein.

With an ionization loss of some GeV's/gram [13], a small but useful average kinetic energy loss of $\langle T \rangle \sim$ GeV [14] can be obtained. Monopoles with a kinetic energy less than this can be stopped in the pipes/cylinders. Since monopoles can come with various magnetic charge $g_n = n\, g_1$, where $g_1 = (137/2)\, e$ is the standard monopole charge referenced to unit electronic charge, the $\langle T \rangle$ is a function of n^2. Values of n = 1, 2, 3, 6 correspond to various options relating to the quantization condition "looking like" spin (n=1) or orbital (n=2) angular momentum, and n = 3, 6 for basing the magnetic charge on that of (down) quarks of charge "1/3rd." The actual energy loss versus velocity used here is given in the "STOPPING POWER" attachment below. Those monopoles having low T can be stopped and possibly trapped by the binding of their magnetic charge with the magnetic moments of the atoms or the nuclei of the material. For beryllium, 100% ^{9}Be with an unpaired $d_{(3/2)}$ neutron, it turns out that the monopole is not expected to bind with the nucleus [15-17], and also not molecularly with the whole atom, although they may be weakly "chemically" bound [16]; this is due to the relatively large negative magnetic moment of the Be nucleus. However, ^{27}Al has an unpaired $d_{(5/2)}$ proton with a large positive magnetic moment which will bind monopoles with an estimated 2.6 MeV binding energy [17]. D0 has no magnetic field and the earth's field is too weak to dislodge any monopoles trapped there. The energy required to move a monopole L cm by a field of H gauss/cm is $E\,(\mathrm{keV}) = 20.55\, H\, L$. For a monopole "skipping" from atom to atom, a few Angstroms at at time in the 0.5 gauss/cm field of the earth corresponds to an energy change of $20 * 0.5 * (5 * 10^{-8})$ keV = $5 * 10^{-5}$ eV, very much less than the binding energy in Al (and possibly Be?). For CDF, the situation is 5000/0.5 worse, or 0.5 eV, but still well under control. We will assume, as a reasonable working hypothesis, that any monopoles originally trapped stay trapped.

We need to **estimate** the acceptance for stopping monopoles, so that they may be open to the possibility of being trapped. In the Eberhard, et al [7] analysis with the fixed target exposures at Fermilab, it was assumed that the "pair" mass M of the pair of produced monopoles was a "delta" function at twice the monopole mass "m." This would lead in our case to complete trapping of all the monopoles produced (as the transverse kinetic energy of M would be negligible). This is clearly unrealistic. Thus we need some function describing the M distribution. Since magnetic monopoles interact electomagnetically, the Drell-Yan [18] process can be invoked (see also [3]), as discussed in the Appendix (attached). The Drell-Yan (DY) total cross-section above M gives one estimator of this distribution. However, threshold phase space effects are not included, that is, one expects a zero cross-section at M=2m in general [19]. We give a second estimator as the Drell-Yan cross-section modified by the two-body phase space (PS) factor p^*/E^* of one of the monopoles, which is p^*/m near the threshold M. For an n=2 monopole, for example, this factor reduces the acceptance for the cross-section in the range (M to M+2T) to about 10% of the first estimator. The Drell-Yan cross-section is shown linearly (solid), above 200 GeV, corresponding to m=100 GeV in Fig. 2, and as modified by the p^*/E^* phase space

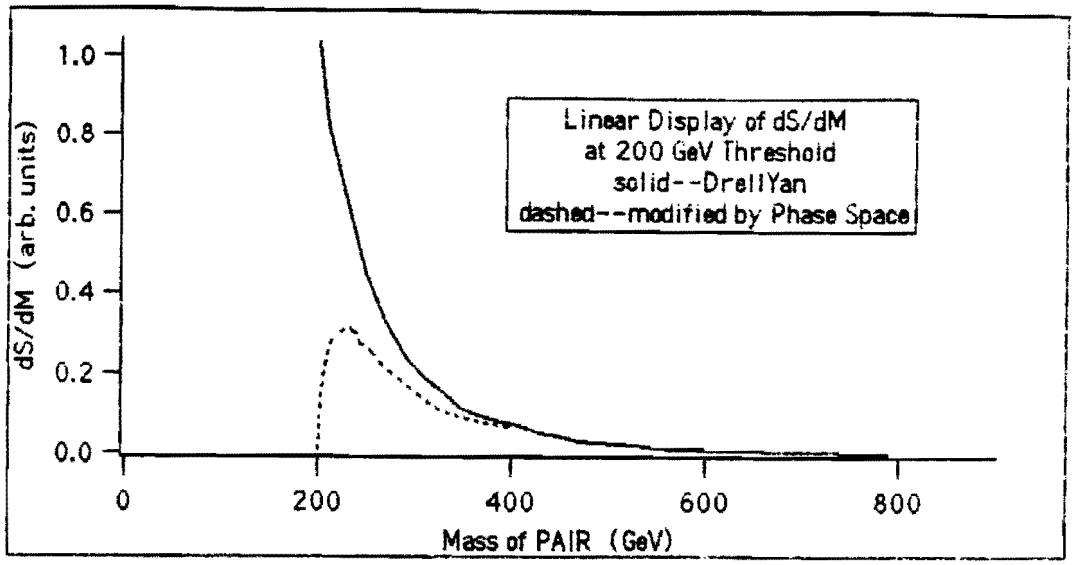
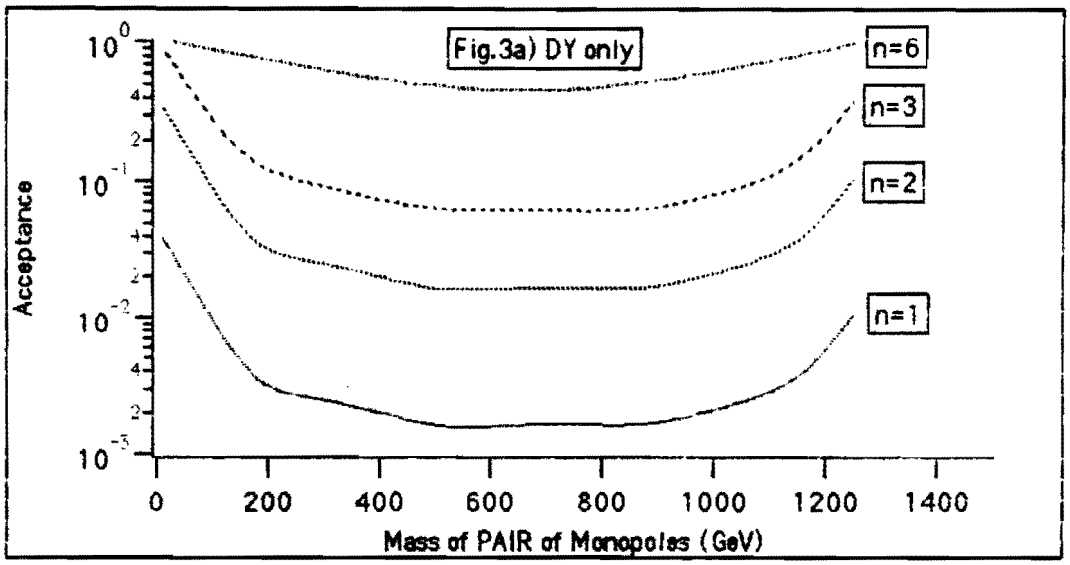


Fig.2--Mass Distributions



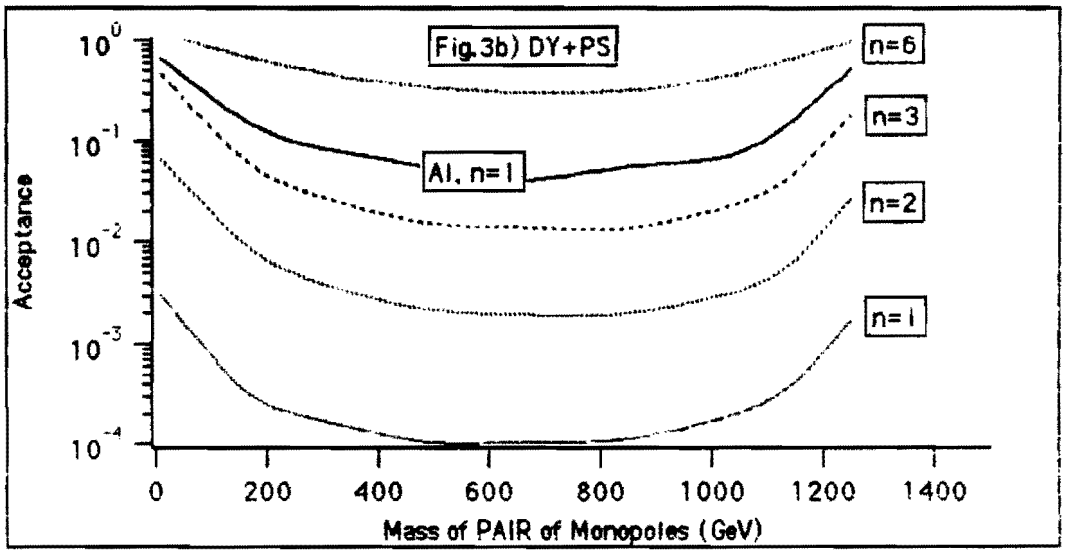


Fig.3--Acceptances

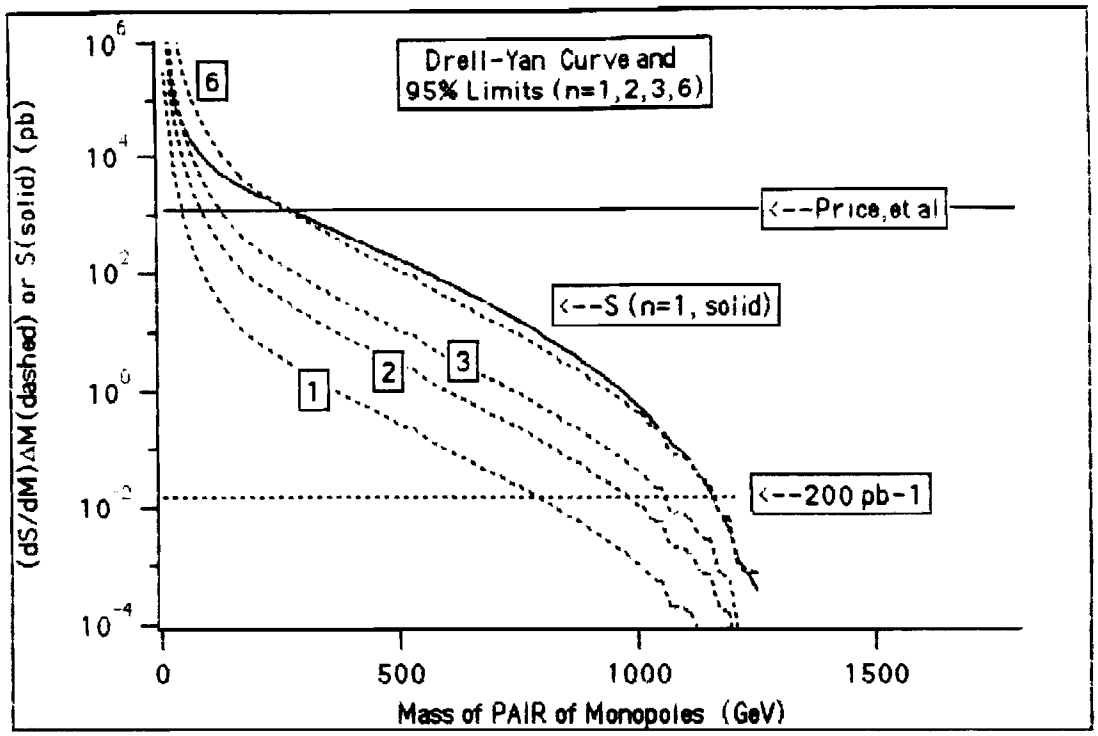


Fig.4a--Without Phase Space

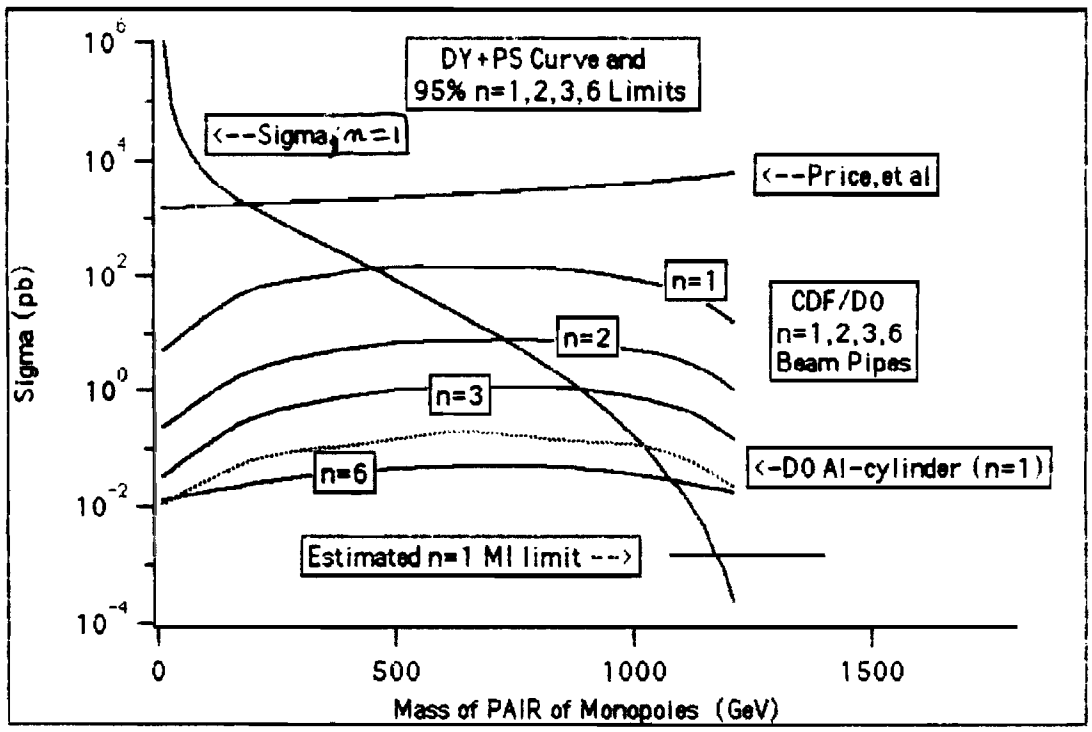


Fig.4b--(200 pb-1)/Acceptance with Phase Space

factor (dashed). One can roughly estimate from looking at the figure that the Drell-Yan piece between M and M+2 GeV is a few percent, and for the modified one less than a percent. The actual acceptances are shown in Fig. 3 a,b for DY and (DY+PS) respectively. These lead to improved limits to be added to Fig. 1 as shown in Fig. 4; the Drell-Yan cross-sections shown are conservative, we believe (see Appendix). Since the CDF/D0 exposures are 5 orders of magnitude greater than the quoted result of Price et al [3], we would improve the limits, including the acceptances estimated here, by 1 to 5 orders of magnitude, depending on the value of n. This allows limits that lie below the Drell-Yan expectations shown out to monopole masses of some several hundred GeV, as seen by the "crossing" of the limit and Drell-Yan curves (dashed with dashed, or solid with solid) at M ~ 400 to 1000 GeV pair mass. We believe this proposal provides a significant extension of the "classical" Dirac monopole searches to warrant its approval by the Laboratory.

FUTURE EXTENSION

With future running to 2 fb^{-1} or more with the Main Injector, with a suitable segmented totally absorbing ("trapping") cylinder of material with 100% acceptance surrounding an available interaction region (in the event that, at some point in time, one of the detectors is not ready after the Main Injector comes on-line) one can reach the limits also shown in Fig. 4. This extends the expected Drell-Yan exclusion region out to 600 GeV in monopole mass. One can also speculate on the possiblity of a "di-Tevatron", which at 10 fb^{-1} would give an upper limit in excess of 1 TeV for the monopole mass (see footnote [1]). Successful execution of the proposal above would "prototype" these future possibilities, and gives additional argument for granting approval.

LIST OF NEEDS

1. The beam pipes **and** drift chamber support cylinders: suitably protected, in one piece each if possible.

2. A "clean/safe" room "on site" to house experiment: vertical apparatus implies high ceiling/hole in floor to pass Be beam pipes through it vertically, if not initially "cut-up"; Al cylinders must be "cut-up" into initial slices.

3. An isolated "clean" area with lathe/milling machine for cutting pipes/cylinders into appropriate pieces in the room of 2) above.

4. The apparatus: buy, borrow, or collaborate [11] or build new at Fermilab.

5. Electronics: find, borrow and buy as necessary. New up-to-date SQUIDs.

6. One or two Fermilab collaborators: some "tech" support.

7. Other = ?.

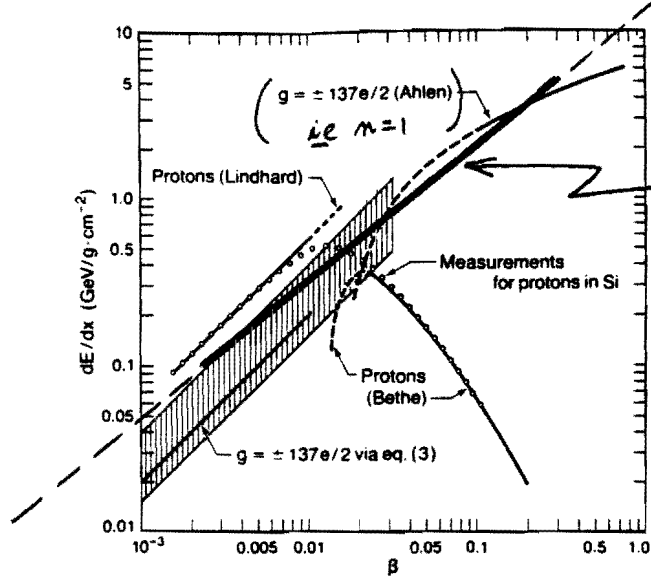
REFERENCES and FOOTNOTES:

1) Q. Shafi, gave a talk recently emphasizing that searches for TeV mass monopoles should not be overlooked (R. Carrigan, private communication); we shall be talking to him. Also, SO(10) models allow ~1 TeV monopoles (J. Preskill, "Magnetic Monopoles," Ann. Rev. Nucl. Sci. **34**, 461 (1984)).
2) G. Giacomelli, Lake Louise Conference talk, 1994 (and other of his papers).
3) P. B. Price, J. Guiri and K. Kinoshita, PRL **65**, 149 (1990).
4) P. B. Price,R. Guoxiao and K. Kinoshita, PRL **59**, 2523 (1987).
5) The CDC (Central Drift Chamber) of D0 is supported in an aluminum cylinder of 3/8" (ie. 0.95 cm) thickness, radius 74.5 cm and length 184 cm (Section 2.4 of S. Abachi, *et al* "The D0 detector," NIM **A338**, 185 (1994). The CTC (Central Tracking Chamber) of CDF is housed in a 1/4" thick aluminum cylinder of 2.76 m diameter and 3.2 m length (Fig.6, Section 4 of F. Bedeschi, *et al* "Design and Construction of the CDF Central Tracking Chamber," NIM **A268**, 50 (1988)). The fact that these two experiments have Be beam pipes is also mentioned in these articles.

6) P. H. Eberhard, *et al* PR **D4**, 3260 (1971) and R. R. Ross, *et al* PR **D8**, 698 (1973), discussing limits from "lunar material" searches.
7) P. H. Eberhard, *et al* PR **D11**, 3099 (1975), searching "targets" exposed at Fermilab.
8) R. Carrigan, private communication.
9) Overcoming of the Coulomb barrier vis-a-vis the magnetic attraction of the pole-nuclear atom and the antipole-nuclear atom for $Ze < ng_1$ (ie $Z < 63$ for $n=1$, and all Z for $n > 1$) is assured..
10) R. R. Ross and R. Carrigan, private communications.
11) Such a device is reported in H. Jeon and M. J. Longo, "Search for Magnetic Monopoles Trapped in Matter," (preprint) just published in PRL **75**, 1443 (1995). We have had a preliminary conversation with Longo regarding whether to "buy, borrow or collaborate (with)" his apparatus, or to build our own. He is currently considering "mothballing his apparatus: discussion continues.
12) Moyses Kuchnir of Fermilab would be interested in helping in some way. He has extensive experience with cryogenics and reasonable familiarity with SQUIDs.
13) S. P. Ahlen, "Monopole Energy Loss and Detector Excitation Mechanisms," in Magnetic Monopoles (ed. R. A. Carrigan, Jr. and W. P. Trower, Plenum Press, 1982), p.259.
14) We average the kinetic energy T over solid angle. We are thus approximating the correlation of T (theta) and dS/dM (theta) as factorable for the acceptance estimations made herein; this is sufficient for now. We obtain $<T(R)> = f * (pi/2) * F(n^2, Rperp)$, where f = suitable integral of some power of sin(theta) and R= Rperp/sin(theta).
15) Relativistic spin 1 bound state calculations have been made using the formulae of H.A. Olsen and P. Osland, PR **D42**, 690 (1990). Some other (non-relativistic) spin 1/2 binding energy calculations are given in L. Bracci and G. Fiorentini, NP **B232**, 236 (1984), and D. Sivers, PR **D2**, 2048 (1970), although this latter paper contains serious errors. Relativistic treatments for spin 1/2 have been made by Y. Kazama and C. N. Yang (and A. S. Goldhaber), PR **D15**, 2300 (1977) (and PR **D15**, 2287 (1977)).
16) W. V. R. Malkus, PR **83**, 899 (1951); P.A.M. Dirac, Proc. R. Soc. London **133**, 60 (1931).
17) Non-relativistic spin 3/2 and 5/2 considerations have been made by K. Olaussen and R. Sollie (NP **B255**, 465 (1985). They find a strong binding for Al, for example.
18) For Drell-Yan, see **e.g.** (textbook) I. A. Aitchison and A. J. G. Hey, Gauge Theories in Particle Physics," Adam Hill, publishers (1989), pp.224, 235-238 and 244-245. We parameterized the data shown in Fig.7.2 and 7.13 to calculate the curves in our Figures 2, 3 and 4.
19) We note that prior authors invoking Drell-Yan have not included this effect. We have corrected the Price limit accordingly in Fig. 4b).

STOPPING POWER – ATTACHMENT

(REF. 13)



"POWER LAW" USED HERE

$(0.003 < \beta < 0.3)$

Fig. 1. Stopping powers in silicon for protons and for monopoles with $g = \pm 137e/2$. Solid lines are calculations which are taken from Ref. 11 (high velocity proton curve labeled Bethe), Ref. 10 (high velocity monopole curve labeled Ahlen), Ref. 17 (low velocity proton curve labeled Lindhard) and Ref. 31 (labeled as Eq. (3) of that work). Dashed lines are extrapolation of the various theories into regions of questionable validity. Note that the Bethe theory as shown does not include shell corrections. The shaded region indicates estimated range of errors for the slow monopole stopping power. The open circles are the averaged values of high quality measurements of proton stopping power in silicon and are taken from Ref. 15.

SOLID LINE $\quad \frac{dT}{dx} = -\alpha\beta^{\delta} = -16\beta^{0.8} \ \frac{GeV}{g}\Big|_{n=1}$

SO $\int$ TO GET $T(R = \text{range})$, $R = \frac{R_\perp}{\sin\theta}$

ie. $\quad T = \left[0.6\,\alpha n^2 \left(\frac{2}{mass}\right)^{0.4} R\right]^{5/3}$ GeV

AVERAGING OVER $\sin\theta$ FOR PIPES/CYLINDERS $\left\{T_{TRAP} \le \langle T\rangle\right\} \Longrightarrow$

$\langle T\rangle$	0.05 cm Be	0.95 cm Al
$n=1$	0.18 GeV	15–26 GeV
2	1.83 "	~100+ "
3	7.06 "	
6	71.2 "	

APPENDIX--Drell-Yan Discussion

We expect that quark + anti-quark annihilate to a virtual photon of mass M which becomes a monopole anti-monopole pair (each of mass m), if M > 2m, similarly to the case of M to two (unlike) muons, except for the threshold effect of "very massive" monopoles and the vastly differing coupling strengths. The simplest Drell-Yan hypothesis is that there is an invariant

$$M^3\, dS/dM = f(\text{tau}), \text{ where } \text{tau} = M^2 / s$$

relating the cross-section S to the square of the center-of-mass energy, $s = (E^*)^2$. For elementary quark-antiquark collisions, $M^2 = s$, so the function "f" is a constant. We ignore other QCD variations.

We need the dS/dM distributions for collisions at 1800 GeV; we estimate these for both pbar-p and pN collisions as follows. For the quark and anti-quark fractional momentum distributions, we use the "valence" quark distribution from Fig. 7.2 of Aitchison and Hey (Attachment #1) and the (anti-) "sea" quark distribution from Fig. 11c of P. N. Harriman, *et al* PR **D42**, 798 (1990) (Attachment #2). We parameterize them in fourteen (14) bins of fractional momentum "x" with their associated probabilities ("weights") arbitarily summed (not integrated) to one. Then the 14 x 14 = 196 grid of values give the range in M for each of the corresponding values of the q-qbar subsystems "s" values (=sqrt(4 E_1 E_2) which are then summed (ie. integrated) according to their (product of) respective "weights." This is done separately for pN and pbar-p collisions, as the former is valence-quark on sea-antiquark, whereas the latter has a larger momentum range since it is valence-quark on valence-antiquarks. A simple Fortran program to calculate these distribtuions at $E^* = \text{sqrt}(s) = 1800$ GeV is given as Attachment #3. The results are given on the third page of that attachment, starting with a listing of the x's and their weights. It remains to adjust the normalization; we do this using experimental data.

We normalize both the pbar-p and the pN calculations (from above) to the pbar-p ---> muon pairs of the CDF collaboration (F. Abe, *et al* PR **D49**, R1 (1994)), and to the scaled (see *footnote* below) dimuon data of Fermilab E-605 (C. N. Brown, et al. PRL **63**, 2637 (1989), using a delta-y range of +/-1). (Note that the relevant Abe and Brown data are shown as Attachments #4 and #5). Since the del-x_F and the del-y ranges used are reasonably narrow, we believe that our cross-sections err on the low side, ie. that they are conservative. The resulting Drell-Yan dimuon dS/dM distributions, along with the direct &/or scaled experimental data, are shown in Fig. A1 a),b) of this Appendix; the agreement is good.

The pbar-p dS/dM dimuon distributions are multiplied by the much stronger coupling of the n=1 monopoles $(g/e)^2$ (= 4700) to get the dS/dM monopole distributions. For larger n values, this would need to be increased by another factor of n^2; thus the n=1 case is again a conservative one. Next we integrate these dS/dM distribtuions to get the total cross-section, either for a narrow range of del-M, as del-S = dS/dM * (del-M = 2 (T)), or by actually integrating dS/dM (ie summing*dM bin sizes) from M to sqrt(s). These are shown as "dashed" and "solid" curves in Fig. 4 (of main text) respectiveiv, where they are compared with the various limits obtained or expected. This procedure can be repeated for the case including the "phase space" factor p^*/E^* (in another program, a variant of the one shown here) as was done in order to get the " DY + PS" acceptance shown in the text's Fig. 3, which is some 10% of the DY acceptance of about 1%.

We realize that more sophisticated Drell-Yan computations for our situation may exist; we will be happy to compare any of these to ours. But since the high mass range of Drell-Yan at sqrt(s) = 1800 GeV has not been experimentally explored as of yet, we expect that our estimators are reasonable ones to make at this time.

---

footnote--We use the different scaling function given in Brown, *et al* to scale and compare their data with our pN calclulation. Also, the E605 data spanned a del-y = 0.2, but we use, at 1800 GeV, a more typical del-y = 2.

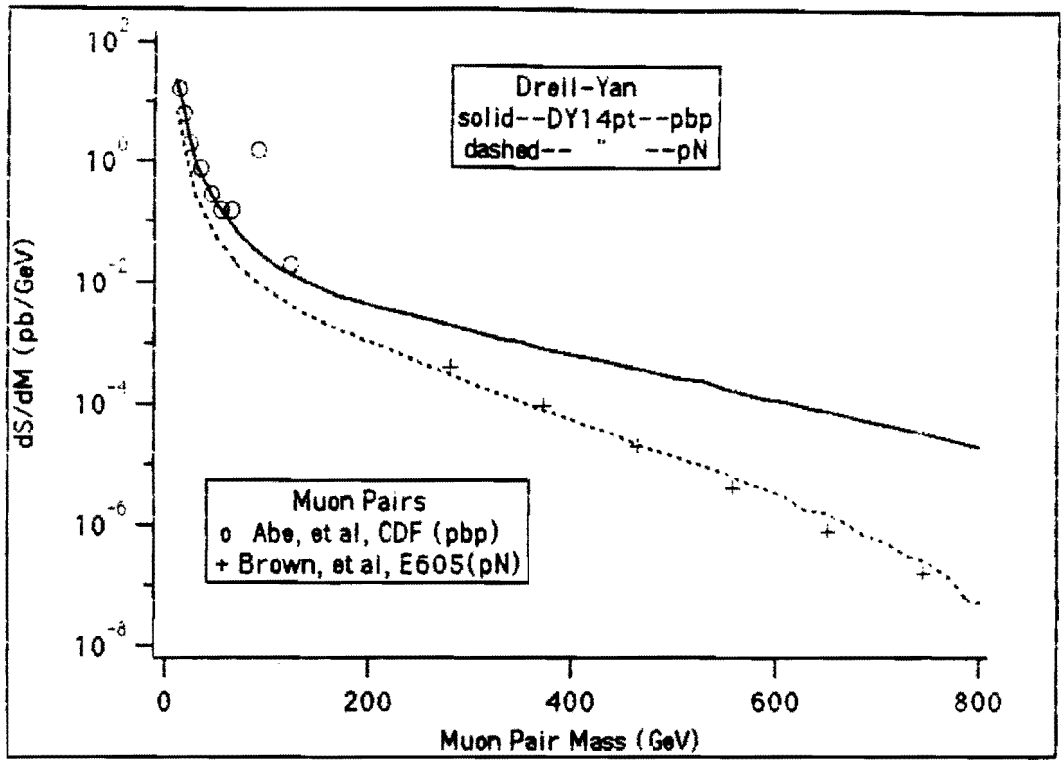


Fig. A1 a)

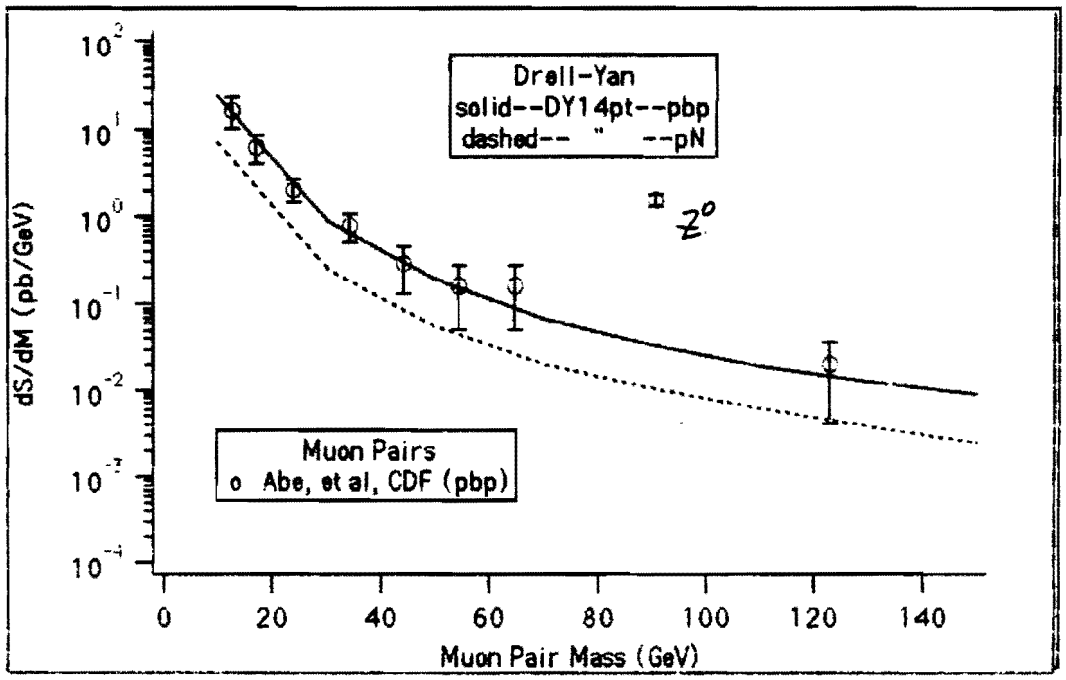


Fig. A1 b)

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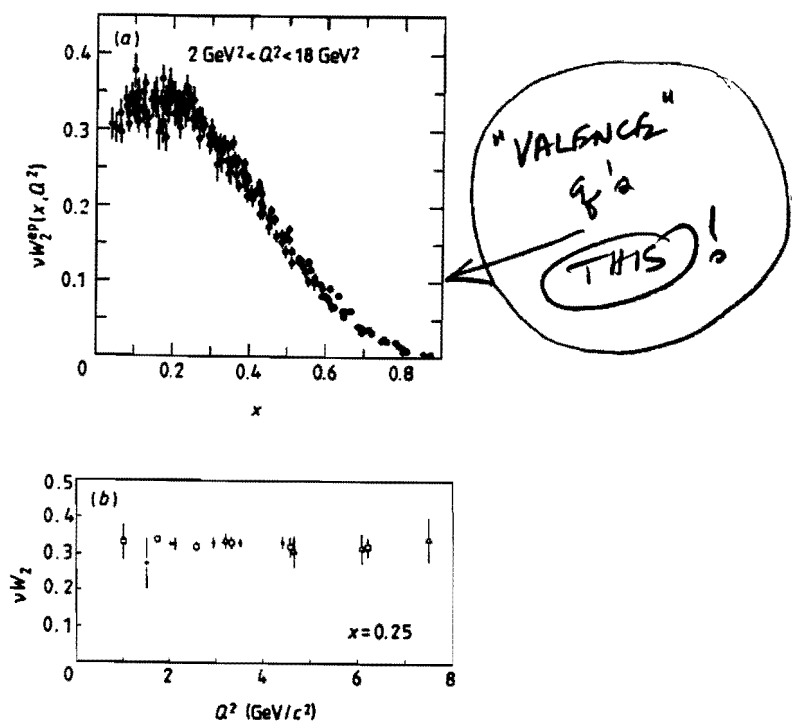

Figure 7.2 Bjorken scaling: the structure function νW_2 (*a*) plotted against x for different Q^2 values (Attwood 1980) and (*b*) plotted against Q^2 for the single x value, $x = 0.25$ (Friedman and Kendall 1972).

ATTACHMENT #1

PHYSICAL REVIEW D VOLUME 42, NUMBER 3 1 AUGUST 1990

Parton distributions extracted from data on deep-inelastic lepton scattering, prompt photon production, and the Drell-Yan process

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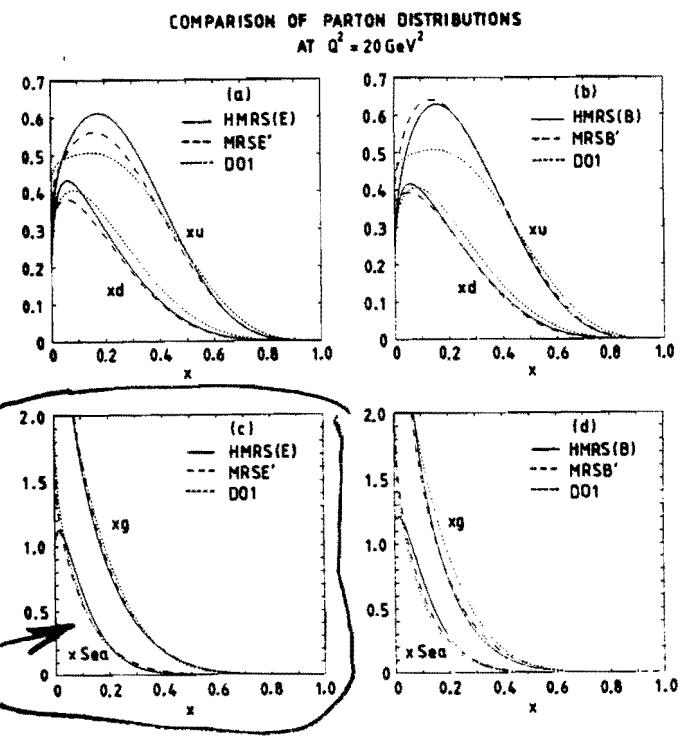
(Received 6 February 1990)

We present a next-to-leading-order QCD structure-function analysis of deep-inelastic muon and neutrino scattering data. In particular, we incorporate new $F_2^{\mu n}/F_2^{\mu p}$ data and take account of a recent reanalysis of SLAC data. The fit is performed simultaneously with next-to-leading-order fits to recent prompt photon and Drell-Yan data. As a result we are able to place tighter constraints on the quark and gluon distributions. Two definitive sets of parton distributions are presented according to whether the European Muon Collaboration or Bologna-CERN-Dubna-Munich-Saclay Collaboration muon data are included in the global fit. Comparisons with distributions obtained in earlier analyses are made and the consistency of data sets is investigated.

PR D42, 798 (1990).



THIS FOR "SEA" q's

FIG. 11. The continuous and dashed curves are the HMRS and MRS' (Ref. 5) parton distributions $xf_i(x,Q^2=20\ \mathrm{GeV}^2)$, respectively. The left- (right-)hand plots are the parton distributions obtained using data sets which include the EMC (BCDMS) $F_2^{\mu p}$ measurements. In each case, we show the distributions of Duke and Owens (DO) set 1 (Ref. 21) for comparison.

ATTACHMENT #2

```
      program DrellYanPS
      dimension f2q(14),f2qwts(14),f2qb(14),f2qbwts(14)
      dimension f2p_N(14,14),f2pbar_p(14,14)
      dimension fmpair(7200),dsdmpN(7200),dsdmpbp(7200)
      dimension indexpN(14,14),indexpbp(14,14)
      dimension indxpN(14,14),indxpbp(14,14)
      dimension PovE(7200)
      data f2q/.025,.075,.125,.175,.225,.275,.325,.375,
     x .425,.475,.525,.575,.625,.675/
      data f2qwts/.17,.2,.22,.22,.21,.19,.17,.15,.12,
     x .10,.08,.05,.03,.01/
      data f2qb/.0125,.0375,.0625,.0875,.1125,.1375,
     x .1625,.1875,.2125,.2375,.2675,.2875,.3125,.3375/
      data f2qbwts/.38,.33,.31,.24,.18,.14,.11,.08,
     x .07,.06,.04,.03,.02,.01/
      data dQ,dQb/0.025,0.0125/
      data kpt,fkbin,kkpair/1,10.0,0/
c....HERE...redefine kbin, kkpair for conv  reg-->PS..
      do 5 i=1,7200
      PovE(i)=1.
      dsdmpN(i)=0.
      dsdmpbp(i)=0.
      fmpair(i)=fkbin*i
    5 continue
      do 10 i=1,14
      do 10 j=1,14
              fmult=1800./fkbin
              jmult=fmult
      indexpN(i,j)=0.5*
     x sqrt(4.*(f2q(i)-dQ)*(f2qb(j)-dQb))*fmult
      indxpN(i,j)=.5*sqrt(4.*(f2q(i)+dQ)*(f2qb(j)+dQb))*fmult
              f2p_N(i,j)=f2qwts(i)*f2qbwts(j)
      indexpbp(i,j)=0.5*
     x sqrt(4.*(f2q(i)-dQ)*(f2q(j)-dQ))*fmult
      indxpbp(i,j)=.5*sqrt(4.*(f2q(i)+dQ)*(f2q(j)+dQ))*fmult
              f2pbar_p(i,j)=f2qwts(i)*f2qwts(j)
c....pN for proton-Nucleus...and...pbp fpr Pbar-P interactions
   10 continue
      do 20 k=1,14
      do 20 j=1,14
      do 30 i=1,jmult
c....sum WTD over #bins--dxi aare equal--so ( N(X)dX = M(Y)dy )
      if(i.ge.indexpN(j,k).and.i.lt.indxpN(j,k)) dsdmpN(i)=
     x      dsdmpN(i)+f2p_N(j,k)/(indxpN(j,k)-indexpN(j,k))
      if(i.ge.indexpbp(j,k).and.i.lt.indxpbp(j,k))dsdmpbp(i)
     x =dsdmpbp(i)+f2pbar_p(j,k)/(indxpbp(j,k)-indexpbp(j,k))
   30 continue
   20 continue
c....compute PovE phase space factor--choose GMPAIR  = 2.*Mpole
      GMPAIR=100.
      if(KKPAIR.le.0) go to 60
      Gmpole=GMPAIR/2.
      kk=0
      do 50 i=1,jmult
      PovE(i)=0.
      if(fmpair(i).le.GMPAIR)go to 50
      kk=kk+1
      if(kk.eq.1)kpt=i
      Epole=(fmpair(i)-GMPAIR)/2.+Gmpole
      Ppole=sqrt(Epole**2-Gmpole**2)
      PovE(i)=Ppole/Epole
   50 continue
c...now do 1/(m**3)...
   60 continue
      sum1=0.
      sum2=0.
      sum3=0.
      sum4=0.
      do 40 i=1,jmult
      dsdmpN(i)=dsdmpN(i)*((fmpair(i)/100.)**-3)
      if(i.eq.kpt)value1=dsdmpN(i)
```

```
        if(i.ge.kpt)sum1=sum1+dsdmpN(i)
        dsdmpN(i)=dsdmpN(i)*PovE(i)
        if(i.eq.kpt+1)value3=dsdmpN(i)
        sum3=sum3+dsdmpN(i)
        dsdmpbp(i)=dsdmpbp(i)*((fmpair(i)/100.)**-3)
        if(i.eq.kpt)value2=dsdmpbp(i)
        if(i.ge.kpt)sum2=sum2+dsdmpbp(i)
        dsdmpbp(i)=dsdmpbp(i)*PovE(i)
        if(i.eq.kpt+1)value4=dsdmpbp(i)
        sum4=sum4+dsdmpbp(i)
   40   continue
        write(21,98)f2q,f2qwts,f2qb,f2qbwts
   98   format(1x,7f12.5)
        write(21,97)((indexpN(i,j),indxpN(i,j),
     x  indexpbp(i,j),indxpbp(i,j),f2p_N(i,j)
     x  ,f2pbar_p(i,j),i=1,14),j=1,14)
   97   format(1x,2i5,5x,2i5,2f12.5)
        write(21,99)(fmpair(m),dsdmpN(m),dsdmpbp(m),
     x  m=1,130,2)
   99   format(1x,'mpair,dsdmpn,dsdmpbp(1,130,2)= '
     x  ,3e15.3)
        if(KKPAIR.le.0) stop
c....Q=3 GeV at threshold  and bins 2 GeV wide
        accept1=value1*3./(sum1*fkbin)
        accept2=value2*3./(sum2*fkbin)
c....and...PovE averaged is 1/sqrt(2) of value3,4...
        accept3=0.7*value3*3./(sum3*fkbin)
        accept4=0.7*value4*3./(sum4*fkbin)
        write(21,91)GMPAIR,accept1,accept2,accept3,accept4
   91   format(10x,'GMPAIR=',f8.0,' accept1,2,3,4=',4f10.4)
        stop
        end
```

THIS HAS BEEN REVISED FOR DEEPTONCES (KPAIR = 1)

0.02500	0.07500	0.12500	0.17500	0.22500	0.27500	0.32500
0.37500	0.42500	0.47500	0.52500	0.57500	0.62500	0.67500
0.17000	0.20000	0.22000	0.22000	0.21000	0.19000	0.17000
0.15000	0.12000	0.10000	0.08000	0.05000	0.03000	0.01000
0.01250	0.03750	0.06250	0.08750	0.11250	0.13750	0.16250
0.18750	0.21250	0.23750	0.26750	0.28750	0.31250	0.33750
0.38000	0.33000	0.31000	0.24000	0.18000	0.14000	0.11000
0.08000	0.07000	0.06000	0.04000	0.03000	0.02000	0.01000

0	6	0	9	0.06460	0.02890
0	9	0	12	0.07600	0.03400
0	11	0	15	0.08360	0.03740
0	12	0	18	0.08360	0.03740
0	14	0	20	0.07980	0.03570
0	15	0	22	0.07220	0.03230
0	16	0	23	0.06460	0.02890
0	18	0	25	0.05700	0.02550
0	19	0	27	0.04560	0.02040
0	20	0	28	0.03800	0.01700
0	21	0	29	0.03040	0.01360
0	22	0	31	0.01900	0.00850
0	22	0	32	0.01140	0.00510
0	23	0	33	0.00380	0.00170
0	9	0	12	0.05610	0.03400
6	12	9	18	0.06600	0.04000
9	15	12	22	0.07260	0.04400
11	18	15	25	0.07260	0.04400
12	20	18	28	0.06930	0.04200
14	22	20	31	0.06270	0.03800
15	23	22	33	0.05610	0.03400
16	25	23	36	0.04950	0.03000
18	27	25	38	0.03960	0.02400
19	28	27	40	0.03300	0.02000
20	29	28	42	0.02640	0.01600
21	31	29	44	0.01650	0.01000
22	32	31	45	0.00990	0.00600
22	33	32	47	0.00330	0.00200
0	11	0	15	0.05270	0.03740
9	15	12	22	0.06200	0.04400
12	19	18	27	0.06820	0.04840
15	22	22	31	0.06820	0.04840
18	24	25	34	0.06510	0.04620
20	27	28	38	0.05890	0.04180
22	29	31	41	0.05270	0.03740
23	31	33	44	0.04650	0.03300
25	33	36	46	0.03720	0.02640
26	34	38	49	0.03100	0.02200
28	36	40	51	0.02480	0.01760
29	38	42	53	0.01550	0.01100
31	39	44	56	0.00930	0.00660
32	41	45	58	0.00310	0.00220
0	12	0	18	0.04080	0.03740
11	18	15	25	0.04800	0.04400
15	22	22	31	0.05280	0.04840
19	25	26	36	0.05280	0.04840
22	28	31	40	0.05040	0.04620
24	31	34	44	0.04560	0.04180
26	33	38	47	0.04080	0.03740
29	36	41	50	0.03600	0.03300
31	38	44	54	0.02880	0.02640
33	40	46	56	0.02400	0.02200
34	42	49	59	0.01920	0.01760
36	44	51	62	0.01200	0.01100
38	45	53	64	0.00720	0.00660
39	47	56	67	0.00240	0.00220
0	14	0	20	0.03060	0.03570
12	20	18	28	0.03600	0.04200
18	24	25	34	0.03960	0.04620
22	28	31	40	0.03960	0.04620
25	31	35	45	0.03780	0.04410
28	34	40	49	0.03420	0.03990
31	37	44	53	0.03060	0.03570

33	40	47	56	0.02700	0.03150
36	42	50	60	0.02160	0.02520
38	45	53	63	0.01800	0.02100
40	47	56	66	0.01440	0.01680
42	49	59	69	0.00900	0.01050
44	51	62	72	0.00540	0.00630
45	53	64	75	0.00180	0.00210
0	15	0	22	0.02380	0.03230
14	22	20	31	0.02800	0.03800
20	27	28	38	0.03080	0.04180
24	31	34	44	0.03080	0.04180
28	34	40	49	0.02940	0.03990
31	38	45	54	0.02660	0.03610
34	41	49	58	0.02380	0.03230
37	44	53	62	0.02100	0.02850
40	46	56	66	0.01680	0.02280
42	49	60	69	0.01400	0.01900
44	51	63	73	0.01120	0.01520
47	53	66	76	0.00700	0.00950
49	56	69	79	0.00420	0.00570
51	58	72	82	0.00140	0.00190
0	16	0	23	0.01870	0.02890
15	23	22	33	0.02200	0.03400
22	29	31	41	0.02420	0.03740
26	33	38	47	0.02420	0.03740
31	37	44	53	0.02310	0.03570
34	41	49	58	0.02090	0.03230
38	44	53	63	0.01870	0.02890
41	47	58	67	0.01650	0.02550
44	50	62	71	0.01320	0.02040
46	53	66	75	0.01100	0.01700
49	55	69	78	0.00880	0.01360
51	58	73	82	0.00550	0.00850
53	60	76	85	0.00330	0.00510
56	63	79	89	0.00110	0.00170
0	18	0	25	0.01360	0.02550
16	25	23	36	0.01600	0.03000
23	31	33	44	0.01760	0.03300
29	36	41	50	0.01760	0.03300
33	40	47	56	0.01680	0.03150
37	44	53	62	0.01520	0.02850
41	47	58	67	0.01360	0.02550
44	50	63	72	0.01200	0.02250
47	54	67	76	0.00960	0.01800
50	56	71	80	0.00800	0.01500
53	59	75	84	0.00640	0.01200
55	62	78	88	0.00400	0.00750
58	64	82	91	0.00240	0.00450
60	67	85	95	0.00080	0.00150
0	19	0	27	0.01190	0.02040
18	27	25	38	0.01400	0.02400
25	33	36	46	0.01540	0.02640
31	38	44	54	0.01540	0.02640
36	42	50	60	0.01470	0.02520
40	46	56	66	0.01330	0.02280
44	50	62	71	0.01190	0.02040
47	54	67	76	0.01050	0.01800
50	57	72	81	0.00840	0.01440
53	60	76	85	0.00700	0.01200
56	63	80	89	0.00560	0.00960
59	66	84	93	0.00350	0.00600
62	68	88	97	0.00210	0.00360
64	71	91	101	0.00070	0.00120
0	20	0	28	0.01020	0.01700
19	28	27	40	0.01200	0.02000
26	34	38	49	0.01320	0.02200
33	40	46	56	0.01320	0.02200
38	45	53	63	0.01260	0.02100
42	49	60	69	0.01140	0.01900
46	53	66	75	0.01020	0.01700
50	56	71	80	0.00900	0.01500

53	60	76	85	0.00720	0.01200
57	63	81	90	0.00600	0.01000
60	66	85	94	0.00480	0.00800
63	69	89	98	0.00300	0.00500
66	72	93	102	0.00180	0.00300
68	75	97	106	0.00060	0.00100
0	21	0	29	0.00680	0.01360
20	30	28	42	0.00800	0.01600
28	36	40	51	0.00880	0.01760
35	42	49	59	0.00880	0.01760
40	47	56	66	0.00840	0.01680
45	52	63	73	0.00760	0.01520
49	56	69	78	0.00680	0.01360
53	60	75	84	0.00600	0.01200
57	63	80	89	0.00480	0.00960
60	67	85	94	0.00400	0.00800
64	70	89	98	0.00320	0.00640
67	73	94	103	0.00200	0.00400
70	76	98	107	0.00120	0.00240
73	79	102	111	0.00040	0.00080
0	22	0	31	0.00510	0.00850
21	31	29	44	0.00600	0.01000
29	38	42	53	0.00660	0.01100
36	44	51	62	0.00660	0.01100
42	49	59	69	0.00630	0.01050
47	53	66	76	0.00570	0.00950
51	58	73	82	0.00510	0.00850
55	62	78	88	0.00450	0.00750
59	66	84	93	0.00360	0.00600
63	69	89	98	0.00300	0.00500
66	73	94	103	0.00240	0.00400
70	76	99	107	0.00150	0.00250
73	79	103	112	0.00090	0.00150
76	82	107	116	0.00030	0.00050
0	22	0	32	0.00340	0.00510
22	32	31	45	0.00400	0.00600
31	39	44	56	0.00440	0.00660
38	45	53	64	0.00440	0.00660
44	51	62	72	0.00420	0.00630
49	56	69	79	0.00380	0.00570
53	60	76	85	0.00340	0.00510
58	64	82	91	0.00300	0.00450
62	68	88	97	0.00240	0.00360
66	72	93	102	0.00200	0.00300
69	76	98	107	0.00160	0.00240
73	79	103	112	0.00100	0.00150
76	82	108	116	0.00060	0.00090
79	85	112	121	0.00020	0.00030
0	23	0	33	0.00170	0.00170
22	33	32	47	0.00200	0.00200
32	41	45	58	0.00220	0.00220
39	47	56	67	0.00220	0.00220
45	53	64	75	0.00210	0.00210
51	58	72	82	0.00190	0.00190
56	63	79	89	0.00170	0.00170
60	67	85	95	0.00150	0.00150
64	71	91	101	0.00120	0.00120
68	75	97	106	0.00100	0.00100
72	78	102	111	0.00080	0.00080
76	82	107	116	0.00050	0.00050
79	85	112	121	0.00030	0.00030
82	89	117	126	0.00010	0.00010

BUT NORMALIZED TO DATA !

mpair,dsdmpn,dsdmpbp(1,130,2)=	0.100E+02	0.808E+02	0.337E+02
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.300E+02	0.299E+01	0.125E+01
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.500E+02	0.647E+00	0.270E+00
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.700E+02	0.236E+00	0.983E-01
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.900E+02	0.122E+00	0.479E-01
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.110E+03	0.704E-01	0.263E-01
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.130E+03	0.433E-01	0.173E-01
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.150E+03	0.287E-01	0.124E-01
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.170E+03	0.201E-01	0.85

mpair,dsdmpn,dsdmpbp(1,130,2)=	0.190E+03	0.149E-01	0.686E-02
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.210E+03	0.112E-01	0.544E-02
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.230E+03	0.815E-02	0.474E-02
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.250E+03	0.572E-02	0.389E-02
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mpair,dsdmpn,dsdmpbp(1,130,2)=	0.310E+03	0.231E-02	0.214E-02
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.330E+03	0.176E-02	0.176E-02
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.350E+03	0.134E-02	0.154E-02
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.370E+03	0.988E-03	0.122E-02
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.390E+03	0.767E-03	0.104E-02
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.410E+03	0.583E-03	0.878E-03
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.430E+03	0.457E-03	0.757E-03
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.450E+03	0.334E-03	0.636E-03
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.470E+03	0.237E-03	0.534E-03
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mpair,dsdmpn,dsdmpbp(1,130,2)=	0.530E+03	0.117E-03	0.366E-03
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.550E+03	0.857E-04	0.272E-03
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.570E+03	0.600E-04	0.221E-03
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.590E+03	0.486E-04	0.184E-03
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.610E+03	0.345E-04	0.163E-03
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.630E+03	0.215E-04	0.131E-03
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.650E+03	0.192E-04	0.117E-03
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.670E+03	0.128E-04	0.921E-04
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.690E+03	0.783E-05	0.778E-04
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.710E+03	0.619E-05	0.680E-04
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.730E+03	0.366E-05	0.551E-04
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.750E+03	0.283E-05	0.472E-04
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.770E+03	0.164E-05	0.391E-04
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.790E+03	0.642E-06	0.315E-04
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.810E+03	0.596E-06	0.260E-04
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.830E+03	0.171E-06	0.220E-04
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.850E+03	0.233E-07	0.155E-04
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.870E+03	0.217E-07	0.144E-04
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.890E+03	0.000E+00	0.116E-04
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.910E+03	0.000E+00	0.832E-05
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.930E+03	0.000E+00	0.697E-05
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.950E+03	0.000E+00	0.515E-05
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.970E+03	0.000E+00	0.421E-05
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.990E+03	0.000E+00	0.295E-05
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.101E+04	0.000E+00	0.255E-05
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.103E+04	0.000E+00	0.145E-05
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.105E+04	0.000E+00	0.136E-05
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.107E+04	0.000E+00	0.508E-06
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.109E+04	0.000E+00	0.567E-06
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.111E+04	0.000E+00	0.407E-06
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.113E+04	0.000E+00	0.201E-06
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.115E+04	0.000E+00	0.191E-06
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.117E+04	0.000E+00	0.486E-07
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.119E+04	0.000E+00	0.462E-07
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.121E+04	0.000E+00	0.627E-08
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.123E+04	0.000E+00	0.597E-08
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.125E+04	0.000E+00	0.569E-08
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.127E+04	0.000E+00	0.000E+00
mpair,dsdmpn,dsdmpbp(1,130,2)=	0.129E+04	0.000E+00	0.000E+00

PHYSICAL REVIEW D 49 R1 (1994)

Measurement of Drell-Yan electron and muon pair differential cross sections in $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV

F. ABE *et al.* (CDF Collaboration)

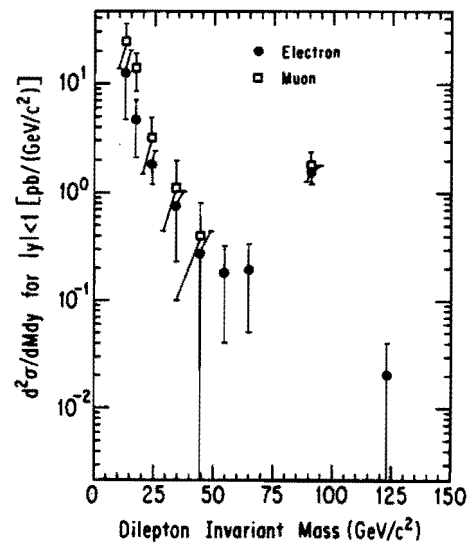

FIG. 3. The Drell-Yan differential cross section $d^2\sigma/dM\,dy$ as measured in the dielectron and dimuon samples plotted as a function of dilepton invariant mass.

TABLE II. $d^2\sigma/dM\,dy|_{y<1}$ for the dielectron, dimuon, and combined samples. The first uncertainty is statistical and the second is systematic for the dielectron and dimuon samples while the combined sample has the total statistical and systematic uncertainty.

Mass bin (GeV/c^2)	Mass centroid (GeV/c^2)	Dielectron [pb/(GeV/c^2)]	Dimuon [pb/(GeV/c^2)]	Combined [21] [pb/(GeV/c^2)]
11–15	12.7	$12.4\pm4.5^{+5.5}_{-7.0}$	24.4±8.8±6.4	16.4±6.3
15–20	17.1	$4.6\pm1.4^{+1.9}_{-2.3}$	13.8±4.2±3.2	6.3±2.3
20–30	23.8	$1.8\pm0.45^{+0.40}_{-0.45}$	3.2±1.4±1.0	2.0±0.6
30–40	34.2	0.74±0.29±0.09	1.1±0.82±0.23	0.78±0.28
40–50	44.3	0.27±0.17±0.03	0.43±0.40±0.09	0.29±0.16
50–60	54.5	0.18±0.14±0.02	—	0.16±0.11
60–70	64.8	0.19±0.14±0.02	—	0.16±0.11
70–110	90.7	1.52±0.19±0.17	1.77±0.46±0.30	1.56±0.23
110–150	122.8	0.02±0.02±0.003	—	0.02±0.016

"SHOWN IN FIG. A1"

ATTACHMENT #4

Dimuon Production in 800-GeV Proton-Nucleus Collisions

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(Received 5 September 1989)

A measurement of continuum dimuon production in proton-copper collisions at 800-GeV incident energy is presented. The dimuons observed in this experiment cover the mass range from 6.5 to 18 GeV near $y=0$ in the proton-nucleon center-of-momentum frame. Scaling forms of the cross section for the continuum are compared with the results of other experiments in the context of the parton model and quantum chromodynamics. The present limitations of such scaling comparisons are discussed.

PACS numbers: 13.85.Qk, 12.38.Qk, 25.40.Ve

PRL 63, 2637 ('89).

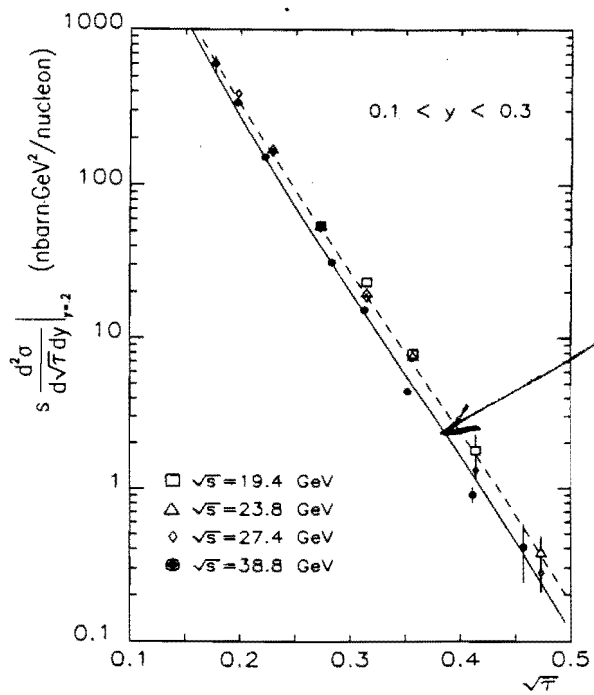

FIG. 3. Comparison of our data (●) at $y=0.2$ with the corrected E288 data. The dashed line corresponds to $\sqrt{s}=19.4$-GeV (solid line, $\sqrt{s}=38.8$ GeV) order-α_s QCD predictions of Martin, Roberts, and Stirling (Ref. 13).

a) SLOPE → $e^{-25\sqrt{\tau}}$

b) NORMALIZATION 300 nb-GeV² @ $\sqrt{\tau}=0.2$

c) SCALED TO $\sqrt{s}=1800$ GeV FOR $\Delta y=2$ (COLLIDER FLAT TO $y\simeq\pm1$). IN FIG A1(a).

ATTACHMENT #5