New Limits on the Production of Magnetic Monopoles at Fermilab

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First results from an experiment (Fermilab E882) searching for magnetically charged particles bound to elements from the CDF and D0 detectors will be reported. The experiment will be described, and limits on magnetic monopole pair production cross sections for magnetic charges 1, 2, 3, and 6 times the Dirac pole strength will be presented. These limits are hundreds of times smaller than those found in previous Fermilab searches. Using simple model assumptions for the photonic production of monopoles, we can convert these cross section limits into mass limits in the hundreds of GeV range.

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The most obvious virtue of introducing magnetic charge is the symmetry thereby given to Maxwell's equations:

$$\nabla \cdot \vec{E} = 4\pi \rho_e \qquad \vec{\nabla} \cdot \vec{B} = 4\pi \rho_m$$

$$\nabla \times \vec{B} = \frac{1}{c}\frac{\partial}{\partial t}\vec{E} + \frac{4\pi}{c}\vec{J}_e \qquad -\nabla \times \vec{E} = \frac{1}{c}\frac{\partial}{\partial t}\vec{B} + \frac{4\pi}{c}\vec{J}_m$$

These are invariant under duality transformation:

$$\xi = (\vec{E}, \rho_e, \vec{J}_e) \quad \mathcal{M} = (\vec{B}, \rho_m, \vec{J}_m)$$

$$\xi \to \xi \cos\theta + \mathcal{M} \sin\theta \qquad \theta = \text{const.}$$
$$\mathcal{M} \to \mathcal{M} \cos\theta - \xi \sin\theta$$

or

$$\xi \to \mathcal{M}, \quad \mathcal{M} \to -\xi$$

• Introduction of fictitious magnetic charge simplifies many calculations — viz, Bethe, Schwinger on waveguides

J.J. Thomson (1904) observed the remarkable fact that a static system of electric and magnetic charges possesses an angular momentum

$$\vec J = \int (d\vec r)\, \vec r \times \vec G = \int (d\vec r)\, \vec r \times \frac{\vec E \times \vec B}{4\pi c}$$

$$= \frac{1}{4\pi c}\int (d\vec r)\, \vec r \times \left[\left(\frac{e\vec r}{r^3}\right)\times \frac{g(\vec r-\vec R)}{(\vec r-\vec R)^3}\right]$$

$$= \frac{eg}{c}\hat R$$ by sym. (integral can only supply a numerical factor)

Semiclassical quantization:

$$\vec J\cdot\hat R = \frac{eg}{c} = n\frac{\hbar}{2}$$

$$\boxed{eg = \frac{n}{2}\hbar c}$$

Dirac (1931) showed that QM consistent with the existence of magnetic monopole provided the quantization condition holds,

$$eg = \frac{n}{2}\hbar c$$

(Explains Quantization of Charge)

This was generalized by Schwinger to dyons (a term he coined in 1969) (e_1, g_1) (e_2, g_2)

$$e_1 g_2 - e_2 g_1 = \frac{n}{2}\hbar c$$

[Schwinger sometimes argued that n = even integer, or even 4 × integer.]

One can see where this comes from by considering QM scattering. To define the Hamiltonian one must introduce a vector potential, which must be singular because

$$\vec{B} \neq \vec{\nabla}\times\vec{A}$$

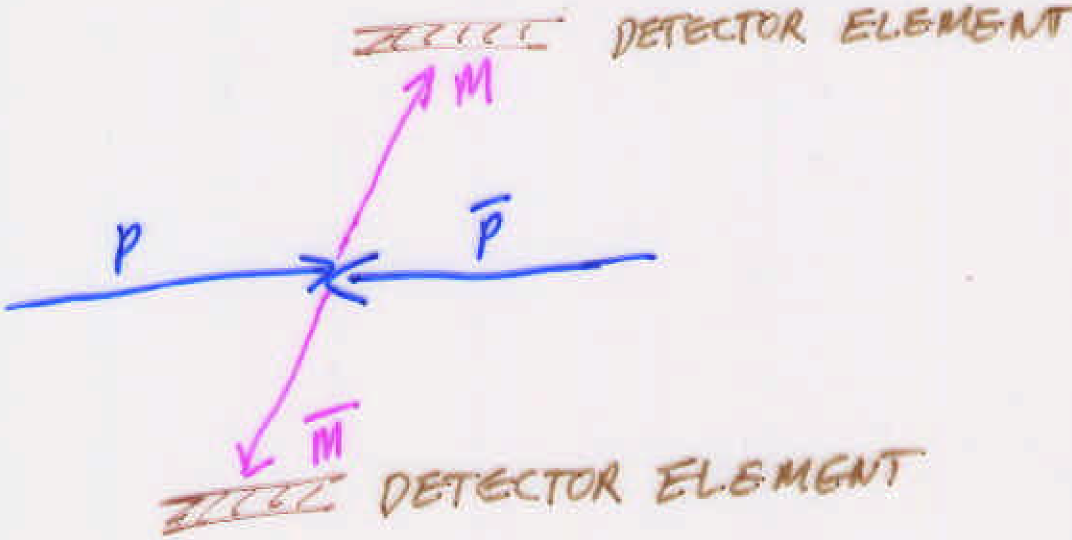
For example, a potential singular along the entire line $\hat{n}$ is

$$\vec{A}(\vec{r}) = -\frac{g}{r}\frac{1}{2}\left[\frac{\hat{n}\times\vec{r}}{r-\hat{n}\cdot\vec{r}} - \frac{\hat{n}\times\vec{r}}{r+\hat{n}\cdot\vec{r}}\right]$$

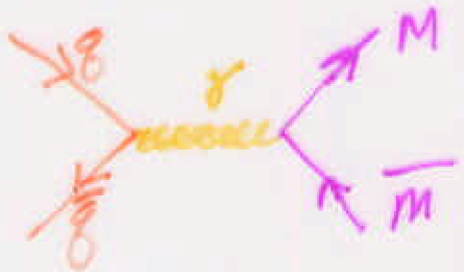
$$= -\frac{g}{r}\cot\theta\,\hat{\varphi} \quad \text{if } \hat{n} = \hat{z}$$

corresponds to $\vec{B}(\vec{r}) = g\frac{\vec{r}}{r^3}$

Invariance of the theory (wavefunctions single valued) under string reorientation $\Rightarrow$ charge quantization condition. < NP



The idea is that $M\bar{M}$ pairs are created in a DY process



(model dep.)
β^3: phase space + velocity suppression of mag. coupling.

[This elementary process cannot be calculated at present, because the QFT of magnetic charge has not been perfected.] (Gamberg + Milton, PRD 61, 075013 '99)

Any monopoles produced at Fermilab are trapped in detector elements with 100% probability due to interaction with magnetic moments of nuclei.

- $\int \mathcal{L} = 10^4 \times$ that of previous accelerator search (Bertani et al., 1990).
  $= 172 \pm 8\ pb^{-1}$ (DØ)

$\hat{\gamma} = \gamma \frac{A}{Z}$

[There may also be deeply bound rel. bd states for spin 1/2, $\underline{E = C}$ — see [5]]

$E_b = .5$ MeV

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

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Remarks on Binding

- Dyons always bind to charges of the appropriate sign.
- Monopoles bind to magnetic moments if certain conditions on the magnetic moments are satisfied.
  - ⋆ Binding in the lowest angular momentum state requires for the anomalous magnetic moment of the nucleus ($\hat{}$ signifies nuclear units)

    $$\hat{\kappa} > \frac{1}{2nZ}.$$

    Example: $^{27}_{13}$Al (spin 5/2) binds.
  - ⋆ Binding can occur for negative κ in higher angular momentum states if certain inequalities are satisfied. For example, for spin 1/2, binding will occur if

    $$|\hat{\kappa}| > \frac{2}{nZ}\left|J^2 + J - \left(\frac{nZ}{2}\right)^2\right|.$$

    Example: $^{9}_{4}$Be (spin 3/2) does not bind. (However, nuclear rearrangement may occur.)
- The binding energies are highly model dependent, depending, in general, on additional interactions since the $1/r^2$ potential is so singular. Typical values range from 10–1000 keV. (One estimate for Al is 2.6 MeV.)
- I am working on refining these estimates and models, particularly relativistically.

• Binding of monopoles to matter is permanent!
11/95

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,

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

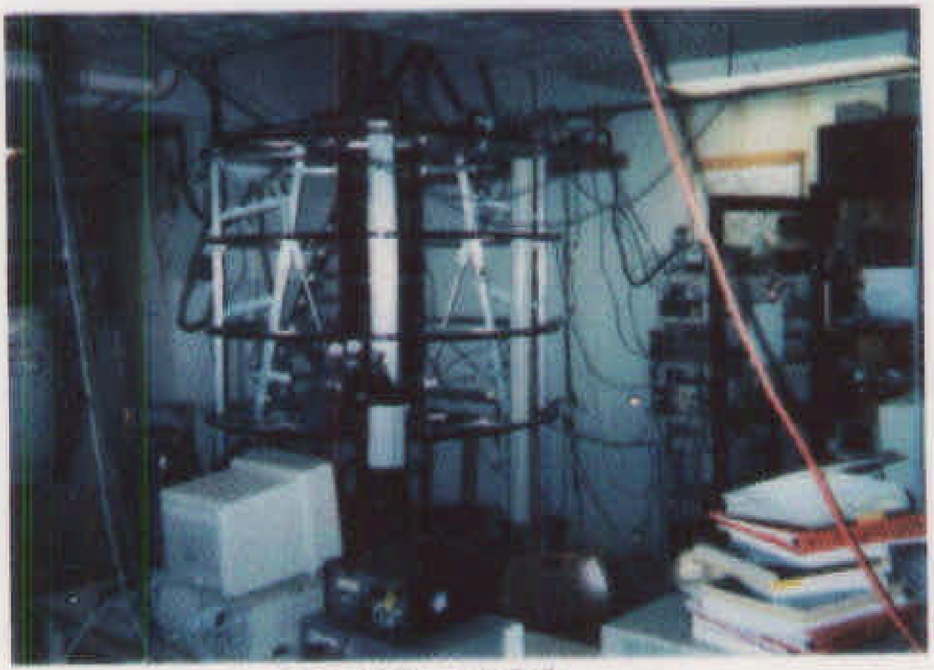
which should be very well satisfied, since the right hand side equals $10^{-20} n^3$ MeV^3, we can write the decay rate as

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

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.

FNAL E882 — OUHEP : KALBFLEISCH, MILTON, STRAUSS
GAMBERG
LUO, SMITH



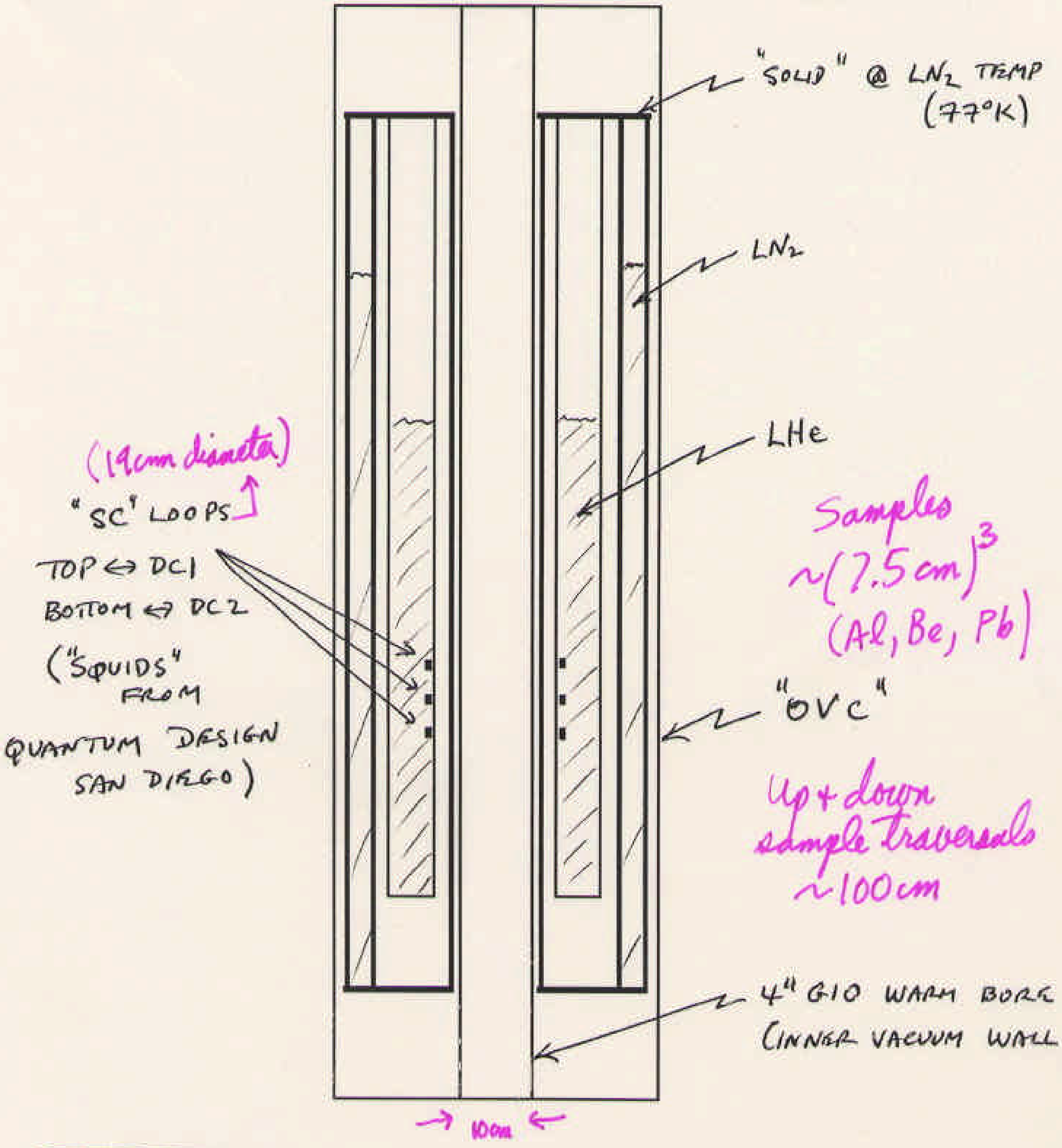
JUNE 1998

222 Al samples: Extension cylinders from DØ (150cm x 46cm x 1.26cm)
6 Be samples: Central section of Beam Pipe (46cm length)

GRK 11/16/98

"OU" MONOPOLE DETECTOR

(CYLINDER 18" ϕ x 60" HIGH)



NOT SHOWN

1. MAGNETIC SHIELDING (μ METAL + PB (SC AT ≤ 8°K)) & "SI"
2. SUPPORT AND FILL TUBES (OUT THRU TOP)
3. INSTRUMENTATION CONNECTIONS, ETC.

IV. OU Exp.

Physics 5583. Electrodynamics II.
First Examination

Figure 1: Diagram of monopole detector

4. Obtain the following formula for the magnetic flux subtended by the loop:

$$\Phi = \int d\mathbf{S}\cdot\mathbf{B} = 4\pi g\Big[\eta(Z-z')$$
$$\underbrace{-\frac{2}{\pi}\frac{R}{a}\int_0^\infty dx\,\sin x\frac{Z}{a}\cos x\frac{z'}{a}\left\{K_1(xR/a) - I_1(xR/a)\frac{K_1(x)}{I_1(x)}\right\}\Big].}_{F(Z,z')}$$

$$LI(t) = \int_{\infty}^{t} dt'\,\mathcal{E}(t') = \frac{8g}{c}\frac{R}{a}F(Z,z(t))$$

$$\to \frac{4\pi g}{c}\left(1-\frac{R^2}{a^2}\right) \quad \text{if } \frac{Z}{a} \gg 1$$

$$\frac{Z-z'}{a} \gg 1$$

want $R/a \ll 1$, but...

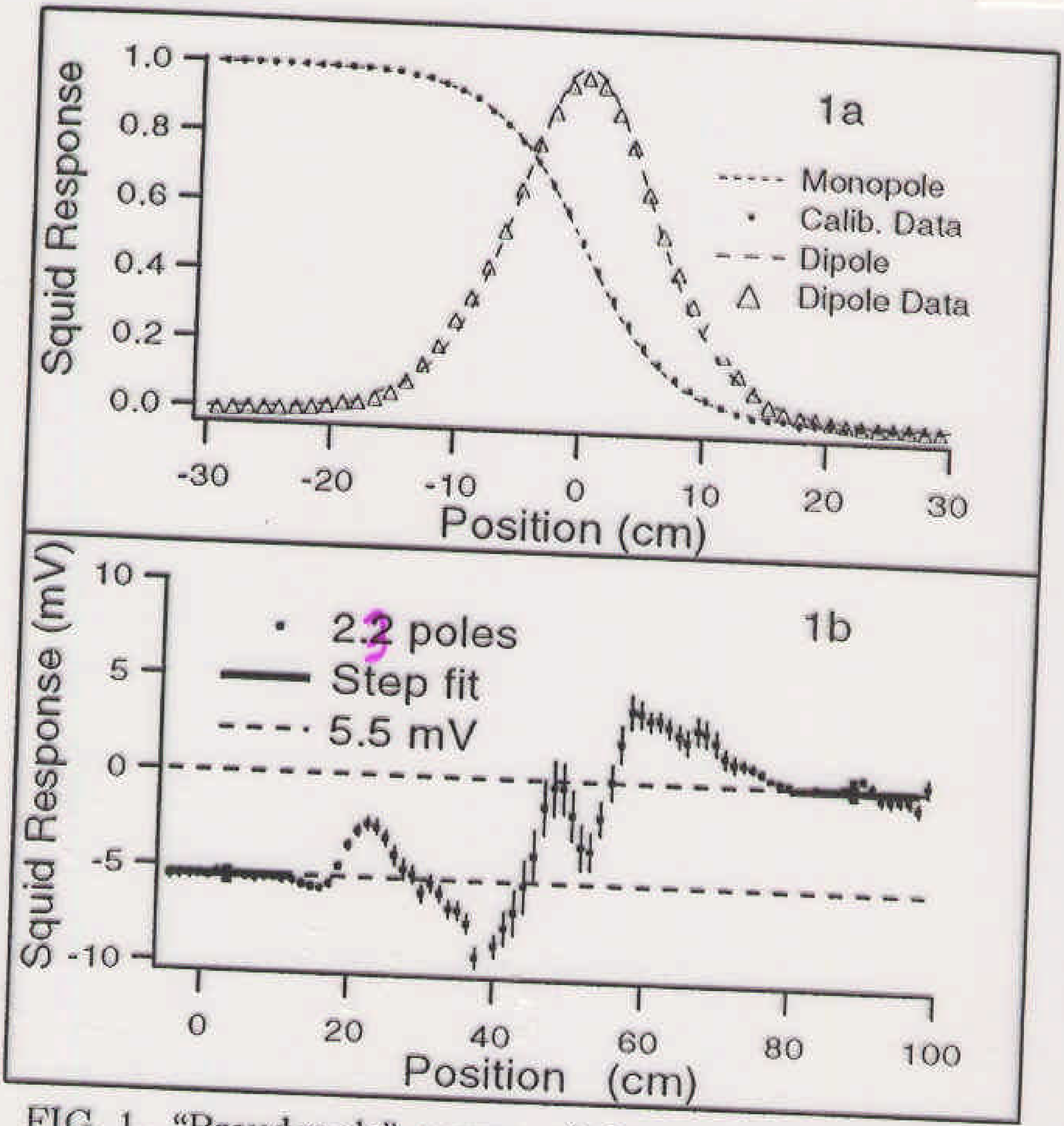


FIG. 1. "Pseudopole" curves. a) Comparison of theoretical monopole response to an experimental calibration and of a simple point dipole of one sample with that calculated from the theoretical response curve. b) The observed "step" for a pseudopole current, corresponding to 2.2 minimum Dirac poles, embedded in an Al sample.

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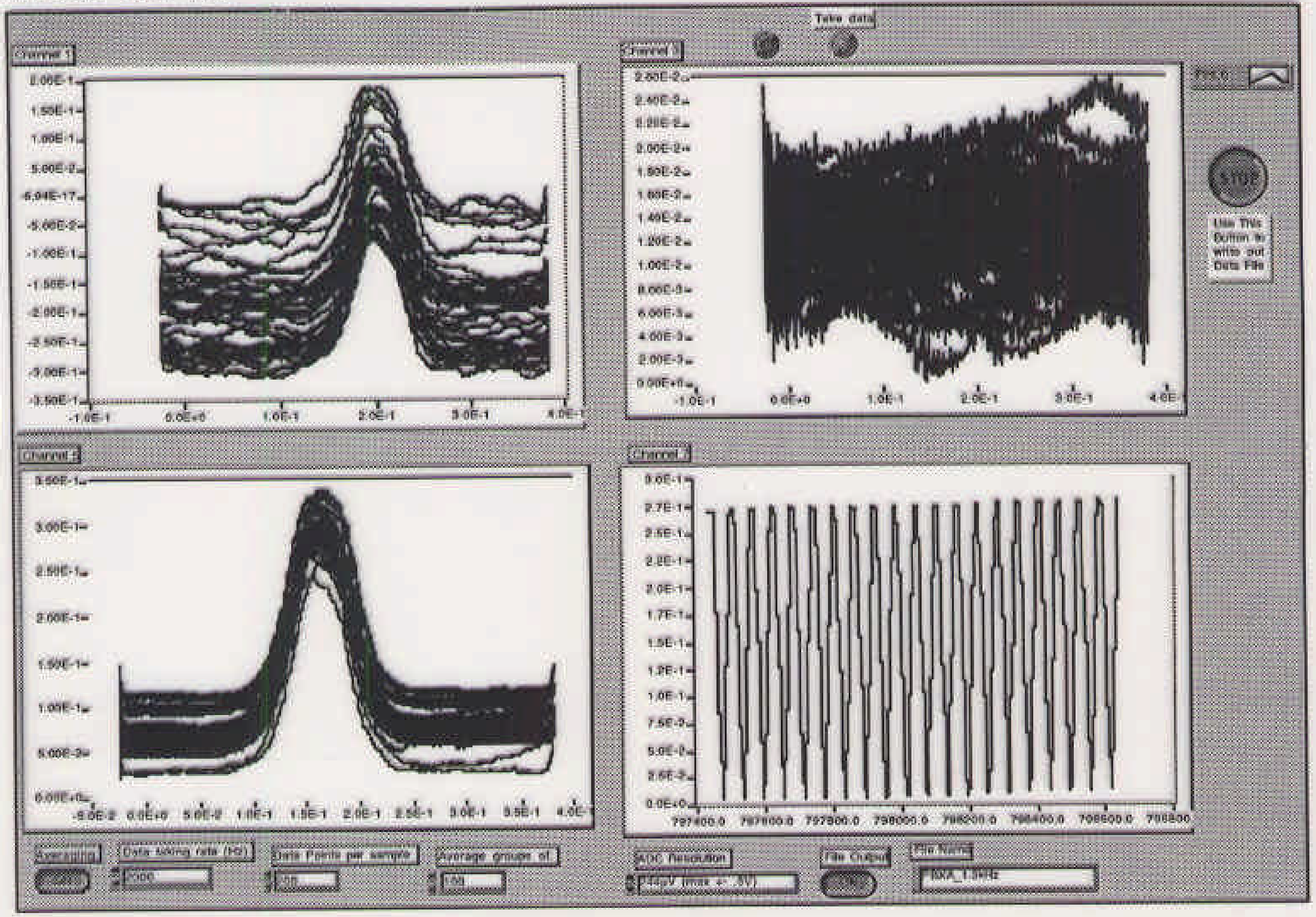


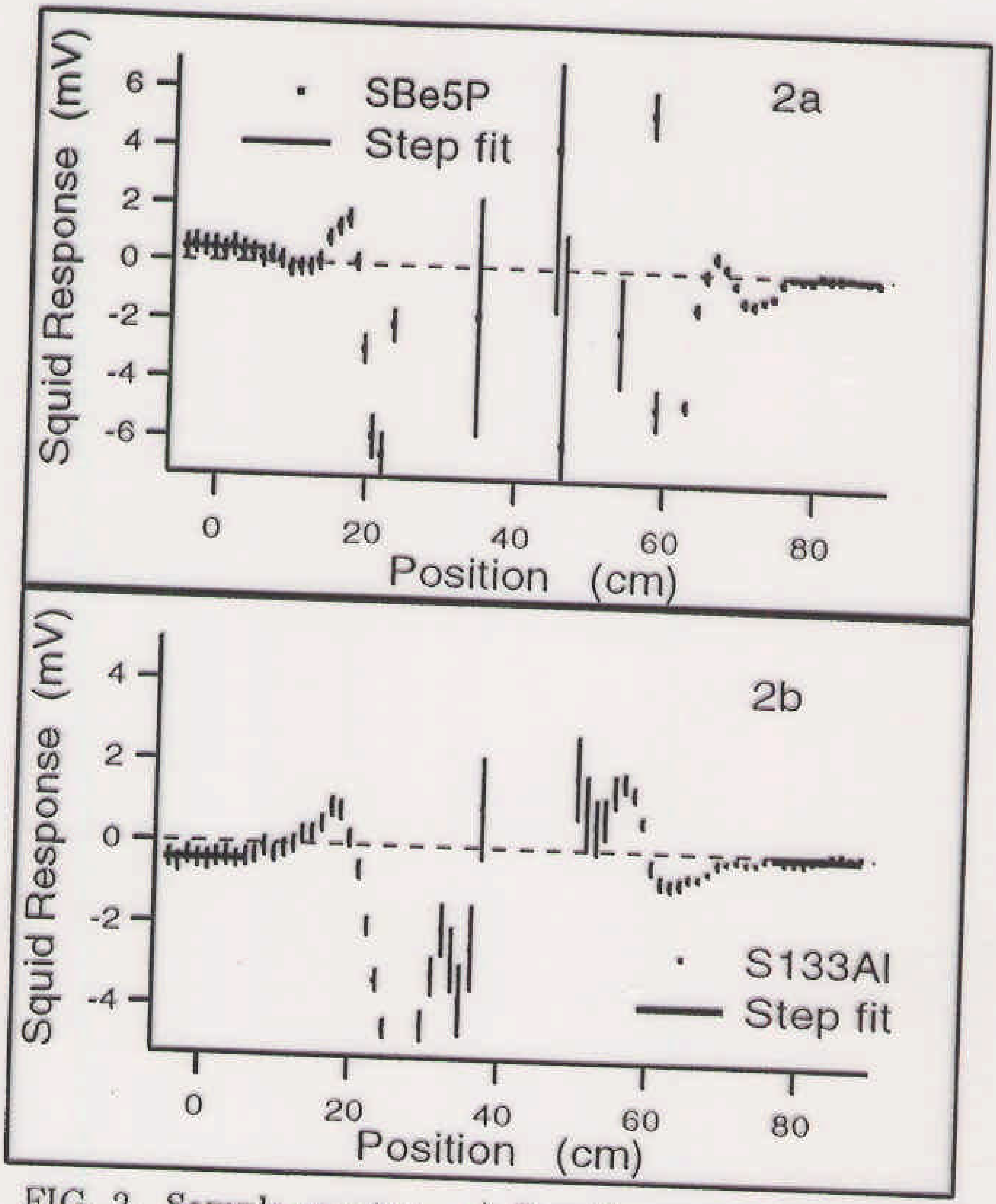


FIG. 2. Sample spectra. a) Beryllium sample "SBe5P," and b) aluminum sample "S133Al." The observed steps are -0.8 mV in a) and $+0.4$ mV in b). The dipole signals are off scale in the middle regions of the plot in this vertically expanded view.

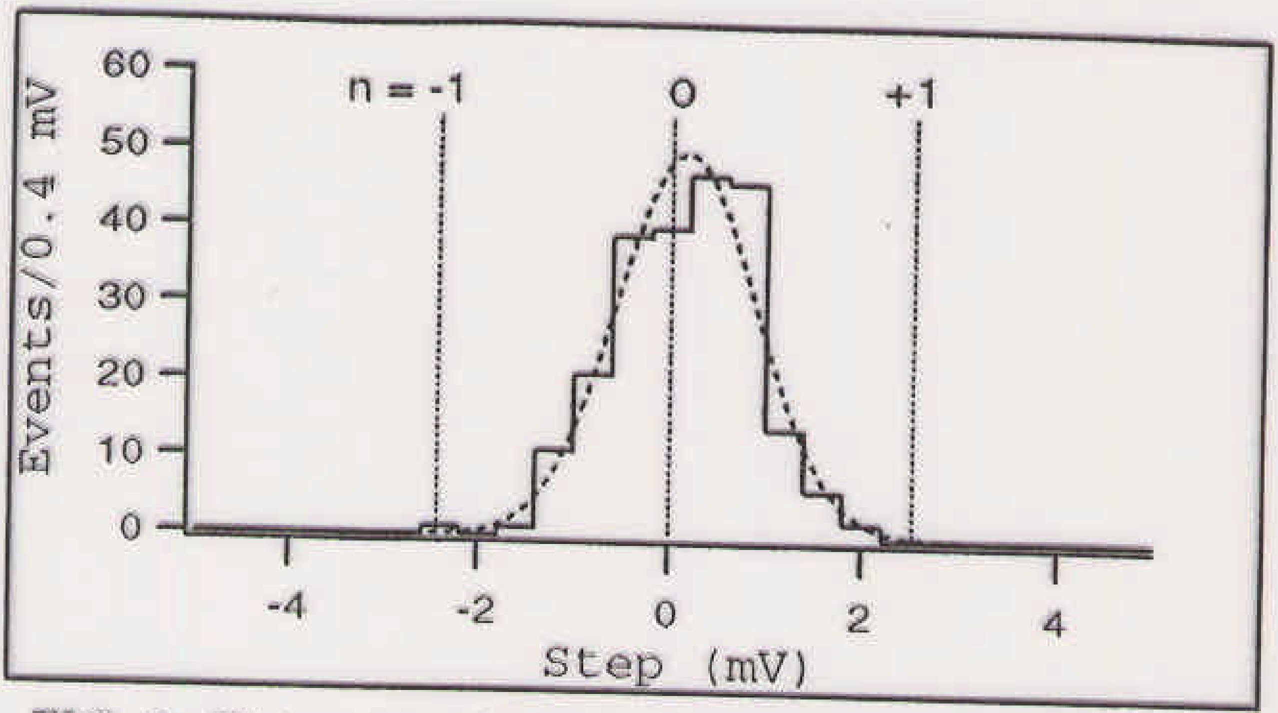


FIG. 3. Histogram of steps. Vertical lines (dashed) define the expected positions of signals for $n = -1$, 0 and 1. The Gaussian curve (dashed) corresponds to 228 measurements having an average value of 0.16 mV and an rms sigma of 0.73 mV. The eight samples in the tails were remeasured and fell within $\pm 1.4\cancel{5}7$ mV of $n = 0$.

Feldman-Cousins analysis:
8 samples within 1.28σ of $n = \pm 1$, when 10.4 expected.

90% CL: 4.2 signal events: $|n| = 1$

just sufficient energy to reach sample

just sufficient energy to leave sample

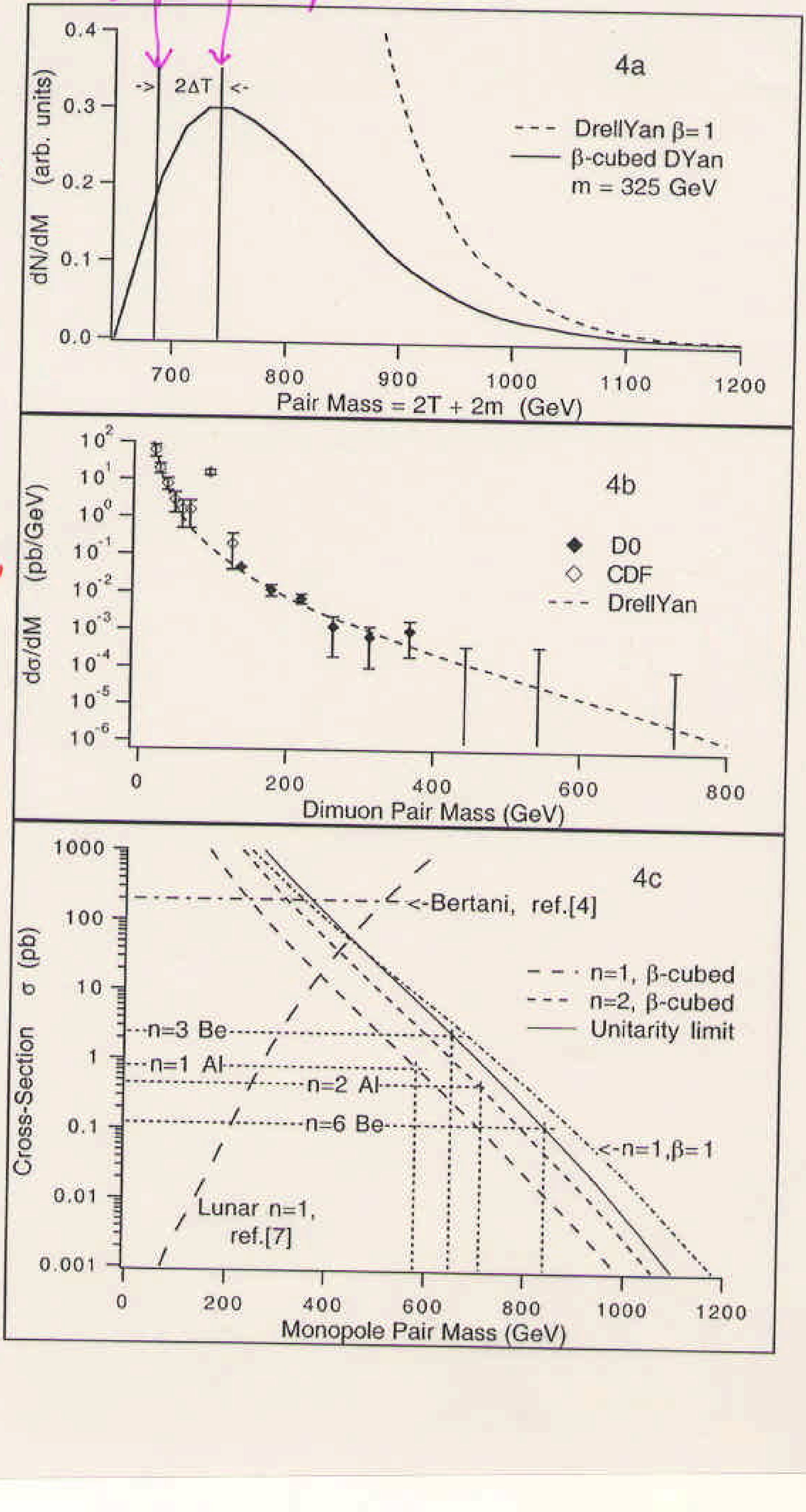
Acceptance (Model Dep.)
↓
σ-limits

Drell-Yan muon pair cross sections

$\times \beta^3$ gives MM cross section $\times n^2 \left(\frac{137}{2}\right)^2$

σ → mass limit

Uses CTEQ5m PDF



Magnetic Charge	$n = 1$	$n = 2$	$n = 3$	$n = 6$
Sample	Al	Al	Be	Be
$d\Omega/4\pi$	0.12	0.12	0.95	0.95
Mass Acceptance	0.23	0.28	0.0065	0.13
Number of Poles	$<$ ~~3.5~~ 4.2	< 2.4	< 2.4	< 2.4
Upper limit on cross section	~~0.79~~ pb .88	~~0.45~~ pb .42	23 ~~2.4~~ pb	~~0.11~~ pb
Monopole Mass Limit	$>$ ~~290~~ GeV 285	> 355 GeV	> 325 GeV	> 420 GeV

TABLE I. Acceptances, upper cross section limits, and lower mass limits, as determined in this work. Total luminosity a DØ is ~~160~~ 172 $\pm$ 8 pb^{-1}.

FUTURE PROSPECTS