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THE FIRST MEASUREMENT OF THE Ξ^{o} MAGNETIC MOMENT

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ABSTRACT

In the neutral hyperon beam at FNAL, we have identified 42000 Λ daughters from $\Xi^o \to \Lambda\pi^o$ decays, produced in the reaction $p + Be \to \Xi^o + X$ at a 7.2 milliradian production angle. A magnet precessed the spin of the Ξ^o hyperons and a spectrometer observed $\Lambda \to p\ \pi^-$ decays. The π^o from Ξ^o decay was not seen. We found the average Ξ^o polarization to be -0.09 ± 0.02 perpendicular to the production plane at $\langle p_T \rangle = 0.73$ GeV/c, and $\mu_{\Xi o} = -1.20 \pm 0.06$ nuclear magnetons. The moment disagrees with broken SU(6) predictions by 21 ± 5%.

It has been known for a long time that the baryons cannot be point-like spin-1/2 particles like the electron and the muon. In the lowest mass baryon octet, containing p, n, Σ^+, Σ^o, Σ^-, Λ, Ξ^o, and Ξ^-, the charged baryon magnetic moments differ considerably from their "natural" values, $q_B e\hbar/2m_B c$, and, where they have been measured, the magnetic moments of the neutrals are of the same order of magnitude as the charged moments. The quark model predicts the baryon magnetic moments by a vector addition of the moments of three constituent quarks (u, d, s), thus giving 9 observables (all of the static μ's plus the transition moment responsible for the decay $\Sigma^o \to \Lambda\gamma$) in terms of only three parameters: μ_u, μ_d, and μ_s.[1] These three parameters can be calculated from measured values of μ_p, μ_n, and μ_Λ.[2] Accurate measurements of the magnetic moments of the other baryons then furnish constraints to test the model. This letter reports the first measurement of the magnetic moment of the Ξ^o hyperon.

A precision measurement of the magnetic moment of the Λ hyperon has been previously reported.[2] This measurement exploited the fact that Λ hyperons in the inclusive process $p + A \to \Lambda + X$ are produced with a net spin polarization perpendicular to the production plane formed by the momentum vectors $\vec{k}_{in}$ and $\vec{k}_{out}$.[3,4] In the Fermilab neutral hyperon beam, the polarized Λ's have a mean decay length of several meters in the laboratory. A conventional magnet with a field $\sim$ 2 T oriented perpendicular to the Λ spin could be made long enough (actually 5.3 m) to precess the hyperon magnetic moment through a large angle. This precession angle in turn was measured from the proton asymmetry in the decay $\Lambda \to p\pi^-$.

The neutral hyperon beam contained Ξ^o hyperons in the ratio $\Xi^o/\Lambda \sim 1.5\%$. A small fraction of the 3×10^6 Λ's observed in the Λ moment experiment were therefore daughters from $\Xi^o \to \Lambda\pi$ decay. These events, which represented

a background in the Λ moment measurement and were eliminated from that data sample, offered the opportunity of measuring the Ξ^0 magnetic moment for the first time. The measurement required that the daughter Λ's from Ξ^0 decay could be cleanly separated from the beam Λ sample, that the polarization of the daughter Λ tag the Ξ^0 polarization, and that the Ξ^0's were polarized.

The experimental geometry is shown in Fig. 1. A 400 GeV proton beam incident at ± 7.2 mrad in a vertical plane produced hyperons in a 6 mm diameter beryllium target, T in the inset in Fig. 1. A neutral beam was defined by a 4 mm diameter collimator 3 meters from the target. The collimator was embedded in a 5.3 meter long magnet which swept charged products out of the neutral beam and precessed the hyperon spin for the moment measurements. Λ's and Ξ^0's produced in the target and emerging from the magnet were highly collimated. When the Ξ^0 decays downstream from the magnet, it typically gives a Λ which does not point back through the collimator. For example, at the Jacobian peak of the decay, an 80 GeV/c Λ emitted from a 100 GeV/c Ξ^0 decay 8 meters from the collimator points back to r = 14 mm from the neutral beam axis. The only cut to select daughter Λ's was to choose off-axis Λ's, those with $9 \text{ mm} < r < 18 \text{ mm}$, which gave a sample of 42,000 events.

Are the off-axis Λ's from Ξ^0 decay? Daughter Λ's from Ξ^0 decay have several characteristics which can distinguish them from directly produced Λ's. Daughter Λ's would have a lower average momentum than direct Λ's, because the Ξ^0 spectrum is not expected to be more energetic than the direct Λ and the π^0 in the Ξ^0 decay carries off energy. In this experiment, the average momentum of all Λ's was 114 GeV/c, while the average momentum for off-axis Λ's was 86 GeV/c. Daughter Λ's also should decay much later than direct Λ's,

being the product of a two-stage decay. The distributions of the Λ decay vertex along the neutral beam axis are shown in Fig. 2 for the two event samples. The experimental decay vertex distribution for all Λ's is consistent with the Λ lifetime. The late vertex distribution for the off-axis events marks this sample as predominantly Λ's from Ξ^o decay in contrast to any Λ's (scattered or direct) whose source is upstream of the decay vacuum region. A comparison of this decay vertex distribution with a Monte Carlo simulation of Ξ^o decay gave an estimated background in this sample of 16 ± 5%. The distribution of r^2 of the daughter Λ at the collimator was also reproduced by the Monte Carlo as shown in Fig. 1.

An independent check on the nature of the off-axis Λ's came from comparing the ratio of observed $K_s \to \pi^+\pi^-$ decays to Λ's for all events, and for off-axis events. There are no particles whose decay would give rise to an off-axis K_s, while both Λ's and K_s's would be roughly equally likely to scatter out of the neutral beam. We found a 45% K_s/Λ ratio for all events and a 3.5% ratio for off-axis events. Thus, this technique implies an 8% background of non-Ξ^o events in the off-axis Λ's.

Since we did not observe the π^o in the Ξ^o decay, we must relate the Λ polarization to the Ξ^o polarization without knowledge of the decay vectors in the Ξ^o center-of-mass. In Ξ^o decay the Λ polarization, neglecting the time-reversal-violating β term, is

$$\vec{P}_\Lambda = \frac{\alpha_\Xi \hat{\Lambda} + (1 - \gamma_\Xi)(\vec{P}_\Xi \cdot \hat{\Lambda})\hat{\Lambda} + \gamma_\Xi \vec{P}_\Xi}{1 + \alpha_\Xi \vec{P}_\Xi \cdot \hat{\Lambda}} \qquad (1)$$

where $\vec{P}_\Xi$ is the Ξ^o polarization, α_Ξ is the parity-violating asymmetry parameter of the Ξ^o weak decay, γ_Ξ is the parity-conserving decay parameter, and $\hat{\Lambda}$ is the unit direction of the Λ emitted in the Ξ^o rest frame.[5] The Λ distribution from polarized Ξ^o's is

$$\frac{dN_\Lambda}{d\Omega_\Lambda} = \frac{N_o}{4\pi} (1 + \alpha_\Xi \vec{P}_\Xi \cdot \hat{\Lambda}) \tag{2}$$

and the proton distribution from polarized Λ's is

$$\frac{dN_p}{d\Omega_p} = \frac{N_o}{4\pi} (1 + \alpha_\Lambda \vec{P}_\Lambda \cdot \hat{p}) \tag{3}$$

where N_o is the number of Ξ^o events, α_Λ is the asymmetry parameter for Λ decay, and $\hat{p}$ is the unit proton direction in the Λ rest frame. We do not know the direction $\hat{\Lambda}$ for our events, so we integrate over $\hat{\Lambda}$ in the proton distribution from the Λ decay

$$\left\langle \frac{dN_p}{d\Omega_p} \right\rangle = \frac{1}{N_o} \int \frac{dN_\Lambda}{d\Omega_\Lambda} \frac{dN_p}{d\Omega_p} d\Omega_\Lambda \quad . \tag{4}$$

The result of the integration over the full solid angle $d\Omega_\Lambda$ in the Ξ^o rest frame gives

$$\left\langle \frac{dN_p}{d\Omega_p} \right\rangle = \frac{N_o}{4\pi} \left(1 + \alpha_\Lambda \left(\frac{1 + 2\gamma_\Xi}{3} \right) \vec{P}_{\Xi o} \hat{p} \right) \tag{5}$$

A comparison of Eq.(5) with Eq.(3) gives the Λ polarization vector in terms of $\vec{P}_\Xi$:

$$\vec{P}_\Lambda = \frac{1 + 2\gamma_\Xi}{3} \vec{P}_\Xi \quad . \tag{6}$$

The decay parameters are related by the equation $\alpha_\Xi^2 + \gamma_\Xi^2 = 1$, and γ_Ξ is known to be positive.[6] Using $\alpha_{\Xi o} = -0.490 \pm 0.042$[7] gives $\gamma_\Xi = 0.872 \pm 0.047$ and $\vec{P}_\Lambda = (0.91 \pm 0.03)\ \vec{P}_\Xi$. The sample of daughter Λ's used in this experiment did not populate the solid angle $d\Omega_\Lambda$ uniformly, principally because of the selection criterion which required that the Λ have finite transverse momentum. The integration performed in Eq.(4) to give Eq.(5) is therefore not valid. The relation given in Eq.(6) is nevertheless accurate to a few percent for two reasons. The first is that data were taken with both signs of $\vec{P}_\Xi$ and asymmetries were subtracted from each other, cancelling the $\alpha_\Xi \hat{\Lambda}$ term in Eq.(1) which does not change sign. The second is that $(1 - \gamma_\Xi)$, which multiplies the other correction terms, is a small number.

If parity is conserved in the production process $p + Be \rightarrow \Xi^o + X$, the vector $\vec{P}_\Xi$ must be normal to the plane formed by $\vec{k}_{in}$ and $\vec{k}_{out}$, the incident proton and produced hyperon momentum respectively. The positive direction was chosen along $\hat{n} = (\vec{k}_{in} \times \vec{k}_{out})/\left|\vec{k}_{in} \times \vec{k}_{out}\right|$. The magnetic field, perpendicular to the polarization, precessed the Ξ^o spin through an angle $\phi = \mu_{\Xi o} \frac{e}{m_p \beta c} \int Bdl$, where $\int Bdl$ is the integral of the field over the Ξ^o path, and $\mu_{\Xi o}$ is the Ξ^o magnetic moment in nuclear magnetons, $\mu_N = e\hbar/2\ m_p c$, m_p = proton mass. In this experiment, the velocity of the Ξ^o, βc, equals c to 0.1%, and the off-axis requirement for the Λ guaranteed that the Ξ^o did not decay in the magnetic field. Thus, the Ξ^o's in the sample emerged from the magnet with a unique polarization direction, the Ξ^o decay left the Λ polarized in this direction (Eq.(5)) and the Λ decay analyzed the Λ polarization (Eq.(3) and Ref. 2).

Systematic biases in the polarization measurements were eliminated by two methods. Six precession field integrals were used for different runs, which gave both clockwise and counterwise precession of the spins

of up to 300^{o} (Fig. 3a). Runs with the field off measured the initial spin direction at the target. Then, for each value of precession field, the initial polarization direction was reversed for half the data. This was done by producing Ξ^{o}'s by a proton beam incident from above onto the target ($\hat{n} = -\hat{x}$ in Fig. 3a), or from below ($\hat{n} = +\hat{x}$). Thus, the polarization was reversed but apparatus-induced asymmetries were not.

Two horizontal polarization components along $\hat{x}$ and $\hat{z}$ in Fig. 3a were measured for each of 14 combinations of magnetic field and polarization sign, giving 28 data points which must depend on the known run conditions in a prescribed way, if the signal is real. The polarization and magnetic moment were obtained by a least-squares technique[2] which fit the 28 data points with four free parameters - two biases, P_{Λ}, and $\mu_{\Xi o}$, which had $\chi^2 = 17$, an 85% confidence level. The fit gave $\alpha_{\Lambda}P_{\Lambda} = -0.051 \pm 0.011$ and $\mu_{\Xi o} = -1.20 \pm 0.05\ \mu_N$, with no background correction. Near the minimum value of χ^2 the two parameters were not correlated.

Figure 3b shows the measured polarization projected onto the axis defined by the fitted value of the magnetic moment, for each magnetic field value. The polarization can be positive or negative and the sign is relative to the direction $\hat{n}$. If the data were unpolarized, the polarization measurements would scatter about $\alpha P_{\Lambda} = 0$ in the figure; a real polarization signal should be independent of the field integral. The 4.6 σ polarization signal we observe represents a 10^{-5} probability that the events have no polarization. A possible background in the events would be polarized Λ's which precess with the Λ moment ($\mu_{\Lambda} = -0.61\ \mu_N$) and which, for some reason, do not point back to the target. If we test the hypothesis that the polarization and moment be the same as for Λ's produced in the target, the fit gives $\chi^2 = 73$.

Figure 3c shows the precession angle ϕ for each field integral. ϕ was calculated from the measured polarization components using values for the initial polarization direction and precession direction from the fit. ϕ should depend linearly on the magnetic field, with the slope of ϕ giving the Ξ^o magnetic moment. Thus, the data fit a polarization signal with a magnetic moment twice the Λ magnetic moment, and the consistency of the results for runs taken with polarization reversals and with different precession fields provided a strong test of the data.

The most likely source of background in the daughter Λ sample is ordinary beam Λ's produced at the beryllium target and scattered out to larger angles. An unpolarized background would affect P_Ξ, but not μ_Ξ. A polarized background with a different magnetic moment could be searched for in the experimental data by fitting the results to two polarizations P_1 and P_2 and two magnetic moments μ_1 and μ_2. When a 16% background with the Λ polarization[4] and the Λ moment[2] were assumed for (P_2, μ_2), the fitted value of $\mu_{\Xi o}$ increased by 0.03, but with no improvement in χ^2. To account for possible systematic errors due to background contamination, an error of 0.03 has been added quadratically to the statistical error for the moment, giving $\mu_{\Xi o} = -1.20 \pm 0.06\ \mu_N$, and a background error of $\Delta P/P = 0.16$ to the statistical error for the polarization, giving $P_{\Xi o} = -0.086 \pm 0.023$. The conversion from P_Λ to $P_{\Xi o}$ used Eq.(6) and $\alpha_\Lambda = 0.647$[8] and the sign of the polarization is relative to the direction $\vec{k}_{in} \times \vec{k}_{out}$.

In the broken -SU(6) model of baryon structure, the magnetic moment of the Ξ^o is

$$\mu_{\Xi o} = \frac{4}{3}\mu_s - \frac{1}{3}\mu_u \ . \qquad (7)$$

The moment of the s-quark is the same as that of the Λ, since the u and d quarks in the Λ are in a singlet spin state. Thus, $\mu_s = -\phi.6138\ \mu_N$.[2] For

the u-quark moment, we take the average from measurements of μ_n[9] and μ_p[10], assuming $\mu_d = -\mu_u/2$, or $\mu_u = 1.8875\ \mu_N$ and $\mu_d = -0.9438\ \mu_N$. The formula (7) then predicts $\mu_{\Xi^o} = -1.45\ \mu_N$. The discrepancy between this prediction and the result of this experiment is μ_{Ξ^o} (predicted) - μ_{Ξ^o} (measured) = -0.25 ± 0.06, a four standard deviation difference. Constituent quark,[1] current quark,[11] and bag models[12] predict the same sum rules between baryon moments, so the violation is common for the three models. Historically, the fact that the experimental ratio $\mu_p/\mu_n = -1.46$ was close to the quark model prediction[13] of -3/2 was a cornerstone of the model. Later, baryon mass differences were used to predict[14] $\mu_\Lambda = -0.6$, which was also confirmed by experiment. The Ξ^o discrepancy implies, however, that the simplest picture of baryon structure in terms of (u,d,s) quarks is incomplete. The disagreement is basically between μ_{Ξ^o} and μ_Λ, each of which measures predominantly the s-quark moment. It is important to note that μ_Λ and μ_{Ξ^o} were measured simultaneously in the same experiment with the same precession field integrals, pattern recognition, and polarization analysis.

The result that Ξ^o's are produced polarized in high energy inclusive interactions as well as Λ's, but not $\bar{\Lambda}$'s,[4] is also interesting. The Ξ^o polarization is observed for $\langle p_T \rangle = 0.73$ GeV/c and $\langle x_F \rangle = 0.22$. The Λ polarization, -0.070 ± 0.003 at the same p_T and x_F,[4] is very close to the result for Ξ^o's, but the unknown $\Sigma^o \to \Lambda\gamma$ component in the Λ polarization makes a quantitative comparison difficult. The result that both Λ's and Ξ^o's are polarized indicates that strong spin-dependent forces are an important feature of particle production at high energy. Finally, other hyperons are likely to be produced polarized. If so, their magnetic moments can be measured precisely, further constraining models of hadron structure.

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References

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Figure Captions

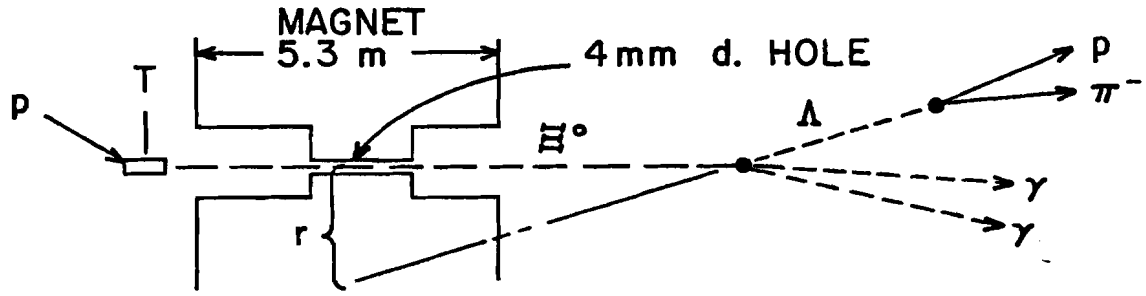
Figure 1: A schematic definition of r^2 for Λ at defining collimator and a histogram of its values. In the schematic, protons are incident from the left on the production target T and a Ξ^o is produced which passes through the 4 mm diameter defining collimator and decays to Λ-π^o. The Λ points back to a position r at the collimator. Λ's produced at T have small values of r, while Λ's from Ξ^o decay point away from the collimator. Λ's with 80 $mm^2 < r^2 < 340$ mm^2 made up the Ξ^o event sample. The dots in the figure are from a Monte Carlo simulation of Ξ^o production.

Figure 2. The Λ vertex position along the neutral beam axis for all r^2 and for the Ξ^o sample. The Λ vertices are further downstream for the off-axis events, which is expected for the two-stage Ξ^o decay. The dots are from a Monte Carlo simulation of Ξ^o decay, with 16% background of direct Λ's.

Figure 3. a) Shows the polarization vector of a Ξ^o at the production target T, and after passing through the precession field, having precessed by ϕ. The Λ in the decay retains the polarization direction of the Ξ^o, after averaging the unseen π^o direction.

b) Shows the Λ polarization for the off-axis events and,

c) the precession angle, each for different values of the precession field integral. The slope of the fit in c) gives the Ξ^o magnetic moment. The asymmetric error for the point at 10.6 T-m is caused by the small value of polarization measured at that point.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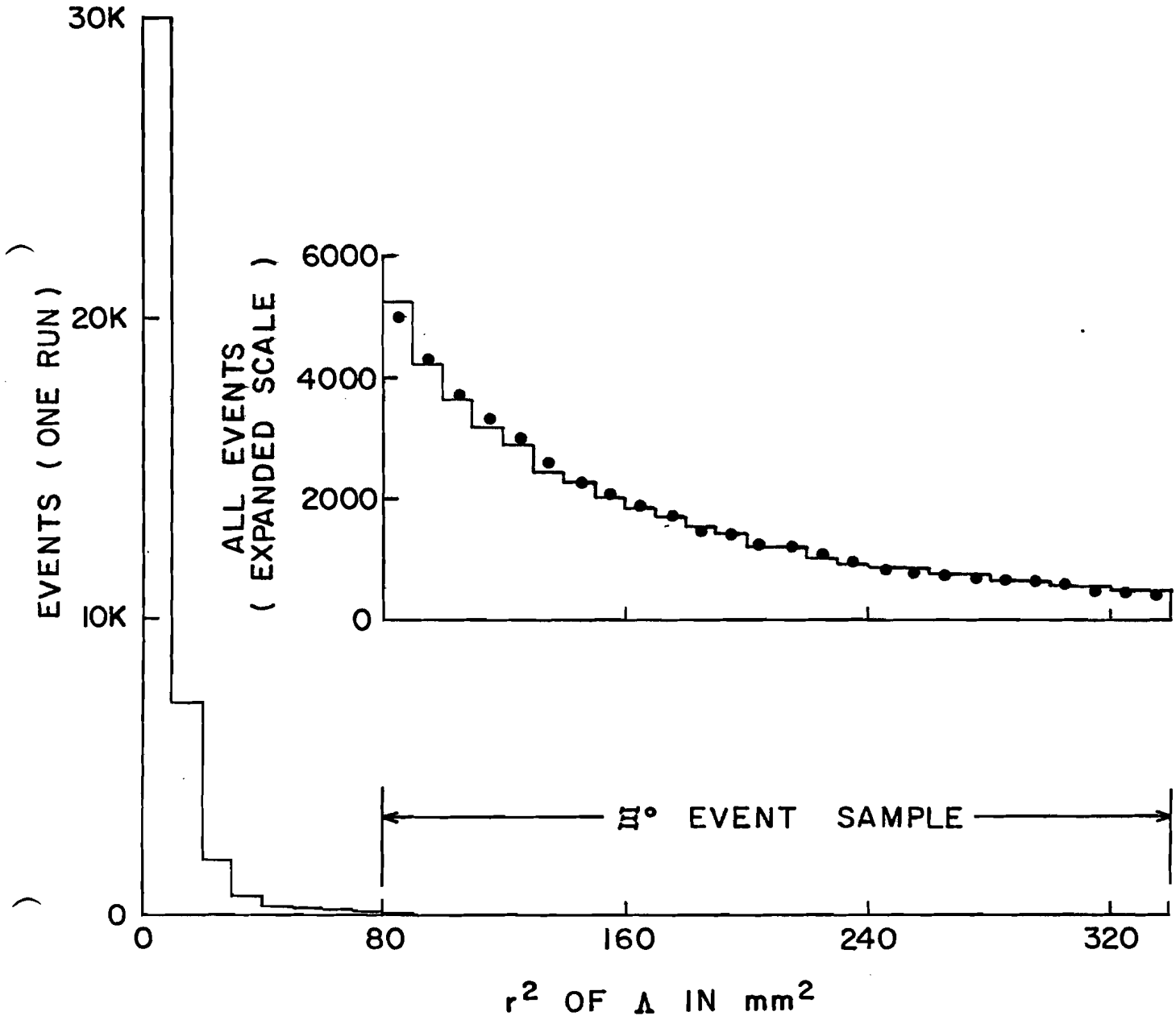
4mm d. HOLE
T
p
Ξ°
Λ
p
π⁻
γ
γ
r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20K
10K
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EVENTS (ONE RUN)
ALL EVENTS
(EXPANDED SCALE)
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0
Ξ° EVENT SAMPLE
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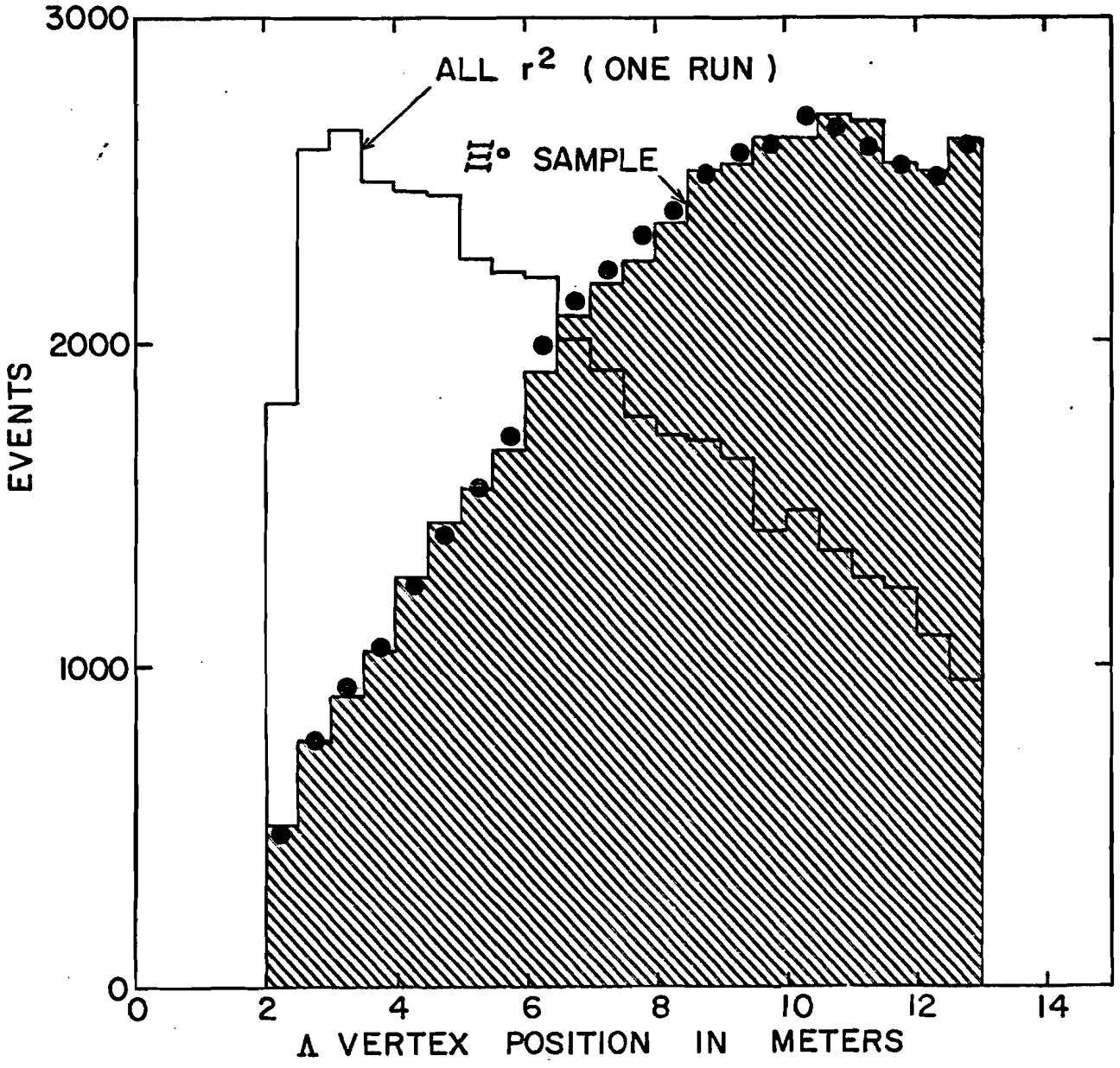
80
160
240
320
r² OF Λ IN mm²

Fig. 1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2000
1000
0
EVENTS
ALL r^2 (ONE RUN)
Ξ^0 SAMPLE
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2
4
6
8
10
12
14
Λ VERTEX POSITION IN METERS

Fig. 2

Fig. 3a

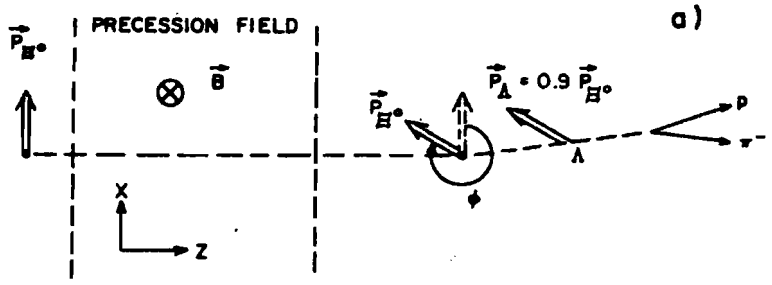

Fig. 3b

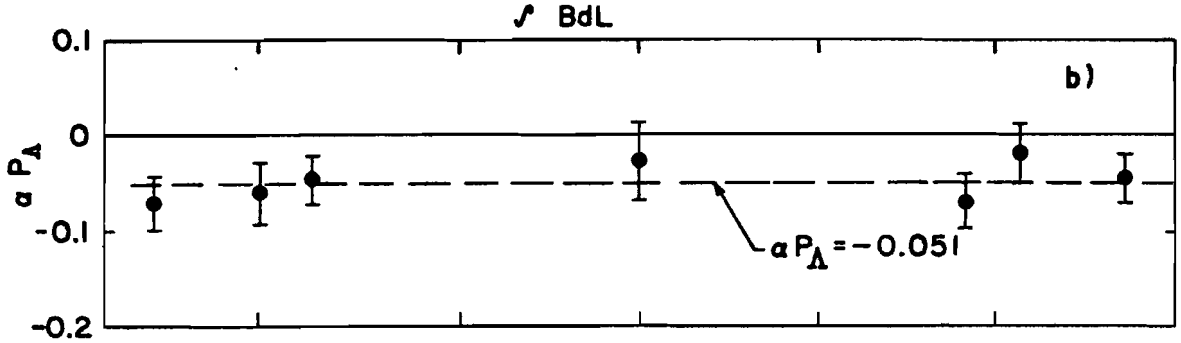
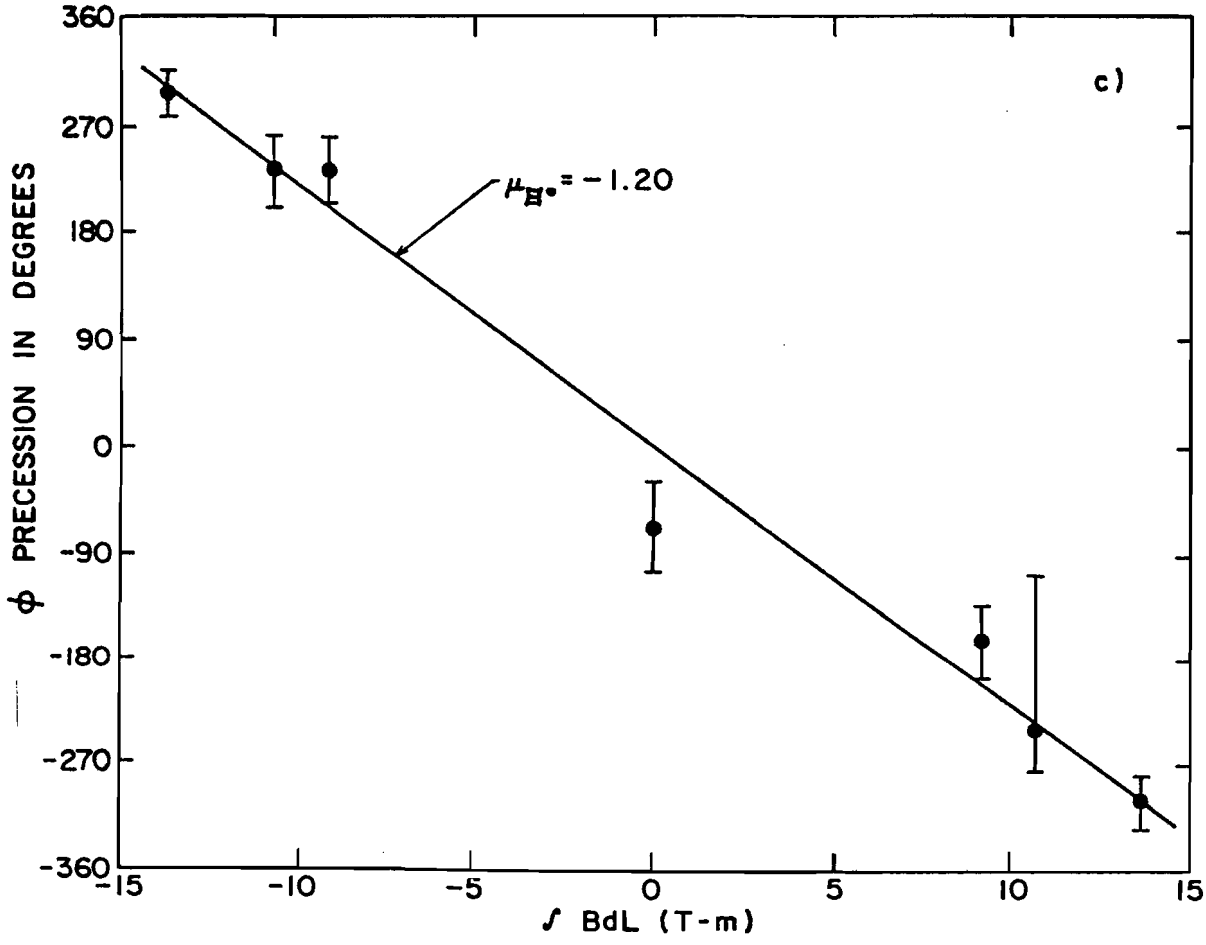
Fig. 3c