Fermi National Accelerator Laboratory

FERMILAB-Conf-90/238

Magnetic Moments of the Baryons An Experimental Review *

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November 1990

* Presented at the 9th International Symposium on High Energy Spin Physics, Bonn, Germany, September 10-15, 1990.

Magnetic Moments of the Baryons
An Experimental Review

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Measurements of baryon magnetic moments have provided important insights into the composition of baryons as well as important constraints for model builders. These measurements show that a simple quark model describes most of the salient features. However, the significant discrepancies have raised fundamental questions about baryon structure and produced a steady stream of theoretical papers. I would like to briefly review the technology for making these measurements, the current state of the measurements, and the near term prospects for improvements.

Measurement Techniques

Magnetic Resonance Techniques. The magnetic moments of the proton and neutron (Table 1) are known to great accuracy[1]. Highly developed magnetic resonance techniques[2,3] allow measurement uncertainties of 0.022 ppm for the proton and 0.235 ppm for the neutron. These uncertainties are orders of magnitude smaller than those for the other baryons.

Exotic Atoms. A method that has been used to measure the antiproton[4] and the Σ^- hyperon[5] magnetic moments utilizes stopping a beam of these particles and forming an "exotic" atom. This "exotic" atom consists of a negative baryon captured near rest by a nucleus. X-rays from the exotic atom transitions are detected with high resolution solid state detectors. From the hyperfine splitting the hyperon magnetic moment can be inferred. So far this technique has been applied to the measurement of the $\overline{p}$ and Σ^- magnetic moments. Complications occur because the captures are usually done in heavy elements. There are significant atomic physics corrections, and one is not able to resolve all the transition lines. This method has yielded a measurement of the Σ^-

magnetic moment which is consistent with the somewhat more precise measurement[6] done by the classical spin precession technique. The weighted mean of these results is given in Table 1.

Primakopff method. The electromagnetic decay, $\Sigma^{\circ} \rightarrow \Lambda^{\circ}\gamma$, is a magnetic dipole transition and has associated with it a transition magnetic moment. This transition moment is described by the same formalism as the static magnetic moments and amenable to the same quark model predictions. It has been measured[7] by the Primakopff[8] method.

Classical Spin Precession. The measurement of the spin precession in a magnetic field has been the most productive technique for yielding hyperon magnetic moments. Contributing to that success has been

1. The advent of high momentum (hundreds of GeV/c) hyperon beams has allowed hyperon decay lengths of a few to tens of meters. Thus hyperon path lengths sufficient to traverse significant magnetic fields are now at hand. Baryons with strong or electromagnetic decay modes still have decay lengths far too short for this technique to be useful.
2. Short ($\approx$10 meters) beams with very significant hyperon fluxes have made possible high statistics measurements.
3. The hyperon parity violating weak decays provide a simple method of identifying the hyperon spin direction.
4. An unpolarized proton beam impinging on an unpolarized target can produce hyperon beams of significant polarization. Many (but unfortunately not all) hyperons have significant polarization (10-25%) at P_t of $\approx$1 GeV/c.
5. The discovery by Fermilab E756 that the Ω^- is not produced with any significant polarization led this group to use a double targeting technique. Protons impinged on the first target to produce a polarized secondary neutral beam at a finite production angle. A subsequent magnet sweeps out the charged particles and the polarized neutral particles interacts with a second target. The spin of the neutral particles is then transferred to the tertiary Ω^- beam. This was used effectively to produce a beam of polarized Ω^-. See the talk of K. Heller for more details of this process.

New Developments

Developments reported at this meeting shed new insights - as well as confusion - on some of the above statements. Existing measurements[9] (at P_t of ≈ 1 GeV/c) showed that Λ° made by unpolarized incident protons were produced polarized, but $\overline{\Lambda}^\circ$ were not; Ω^- were not polarized but Σ^+, Σ^-, Ξ^-, and Ξ° were polarized. This (and other data) led to a simple picture indicating that the polarization was a leading particle effect. If the valence quarks that made up the hyperon came from the sea, the hyperon was not polarized. The surprising new measurement[10] from the Fermilab E756 group (reported at this meeting by K. B. Luk) showed that 800 GeV produced $\overline{\Xi}^+$ have the same polarization (~10% at P_t = 0.76 GeV/c as Ξ^-.

This indicates that the nature of the process which produces the polarization are poorly understood. The report by K. Heller speaks at more length about the polarization question. However, this result does provide us with a source of polarized $\overline{\Xi}^+$ with which to measure its magnetic moment.

This summer Fermilab E761 has taken data on the polarization of a high energy $\overline{\Sigma}^+$ beam. It will be very interesting to see if they are unpolarized (like the $\overline{\Lambda}$) or polarized (like the $\overline{\Xi}^+$).

The phenomena of crystal channeling[11] has been of interest because of the very high effective magnetic fields that are involved. Figure 1a depicts a crystal oriented so that a positively charged particle entering almost parallel to the plane finds itself in a potential well formed by the positively charged arrays of nuclei. It is trapped -channeled- in this potential if the incident angle is near the crystal plane. If the angle is too large it passes through the crystal without being channeled as also indicated in the sketch.

If one now bends the crystal as depicted in Figure 1b, one finds that one also bends the channeled beam[11]. From the momentum of the particle and the bend angle one realizes that the effective magnetic fields inside the crystal can be very large. Can these same large fields be used to precess the spin direction of a polarized beam? Fermilab E761, whose

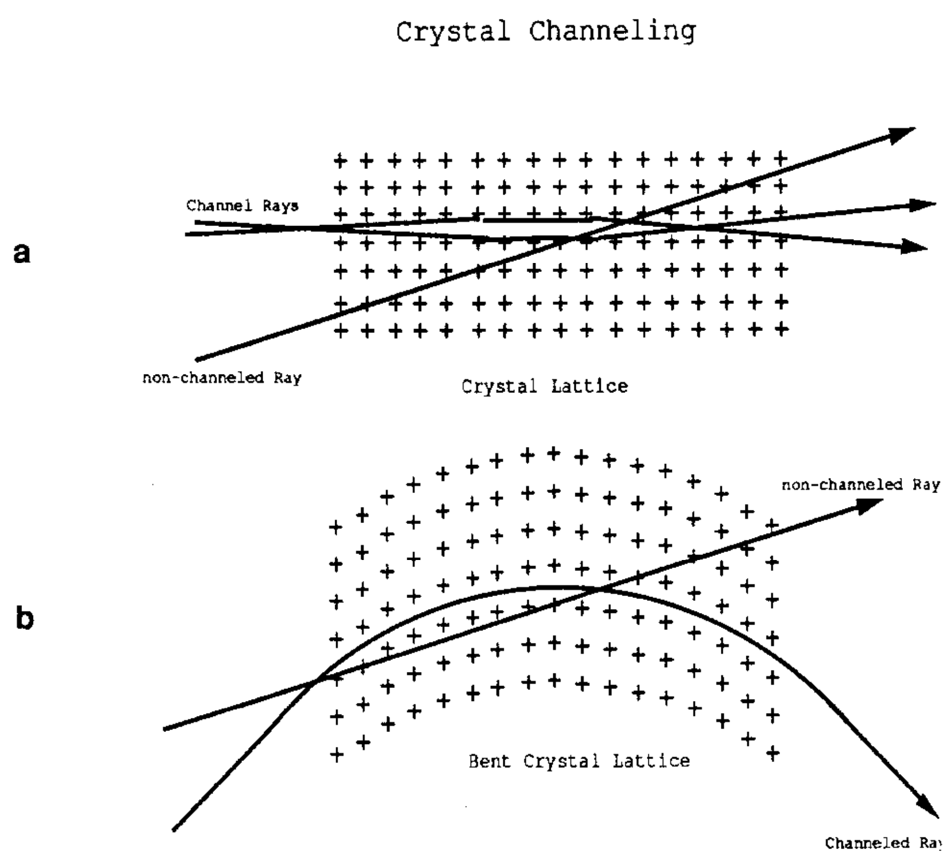

Figure 1. Sketch of crystal channeling in normal and bent crystal.

main goal was to look at hyperon radiative decays ($\Sigma^+ \to p\gamma$ and $\Xi^- \to \Sigma^- \gamma$), attempted to see this effect in a subsidiary experiment. A beam containing Σ^+ hyperons is a good candidate for investigating this effect since they can be produced polarized and have a large decay asymmetry parameter ($\alpha = -0.98$) for the major decay mode, $\Sigma^+ \to p\pi^0$. Hence one can readily measure their spin direction from the decay distribution.

A single crystal of silicon, 4.5 cm long, was placed in a 375 GeV/c beam which contained about 1% Σ^+ (the rest being mainly protons and π^+). This crystal was also implanted with eight solid state energy loss detectors so that the energy deposited in the crystal could be measured. Apparatus upstream of the crystal measured the incident particle momentum and angle (with a precision of $\approx$0.25% and $\approx$ 5μrad respectively). A downstream spectrometer measured the particle momentum and trajectory a second time. Figure 2 shows some preliminary results where no distinction is made between particle types.

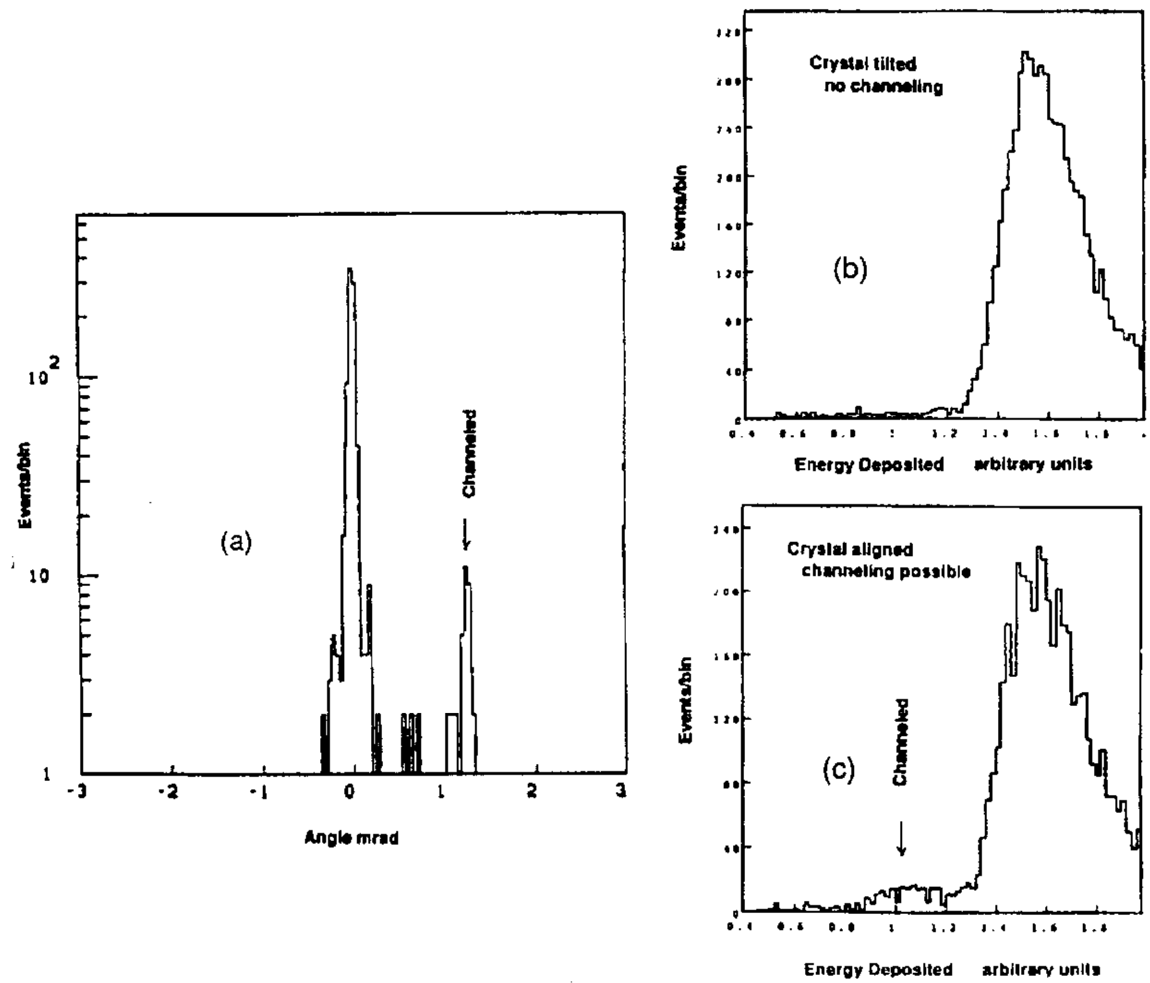

Figure 2. (a) Deflection by bent crystal showing channeling. (b) Energy deposition with no channeling. (c) Energy deposition in crystal with channeling.

Thus it contains mostly protons and π^+. Figure 2a shows the difference in the measured angle entering and exiting the crystal. One sees a peak at about 1.25 mradians which is the known bending angle of the crystal.

Another characteristic is that the channeled particles lose less energy due to ionization than their non-channeled counterparts. This is seen in Figure 2b and 2c which shows the energy deposition in the crystal aligned with the beam (so some beam will be channeled) and the energy loss for the same crystal not aligned with the beam (so there will be no channeling). One sees a clear signal of a smaller energy loss in the aligned case.

The crystal bend angle of 1.25 mrad corresponds to an effective magnetic field of $\approx$35 T within the crystal. With the known Σ^+ magnetic moment one would expect a spin rotation of ≈42.5° in the crystal. About 5000 Σ^+ events have been recorded and assuming a beam polarization of 15%, this should lead to a measurement of the rotation angle to a precision of ≈12.5° which should be enough to see the effect. We look forward to the full analysis of this data.

The crystal bend angle of 1.25 mrad was chosen to match the acceptance of the downstream spectrometer. The crystal was bent to angles as large as 10 mrad (without breaking!) which would correspond to an effective magnetic field of 275 T.

In the longer range one may consider applying this technique to charmed baryons which have much shorter lifetimes[7] than Σ^+. Note that at 500 GeV/c the $\Lambda^+{}_c$ and $\Xi^+{}_c$ would have decay lengths of 1.18 and 2.64 cm respectively.

Recent Results and Near Term Prospects

The Ξ^- and $\overline{\Xi}^+$ system. Recent results from Fermilab E756 have yielded a new value of the Ξ^- magnetic moment and the first measurement of the $\overline{\Xi}^+$ magnetic moment[10]. Displayed in Figure 3 are measurements of the Ξ^- magnetic moment from three Fermilab experiments[10,12].

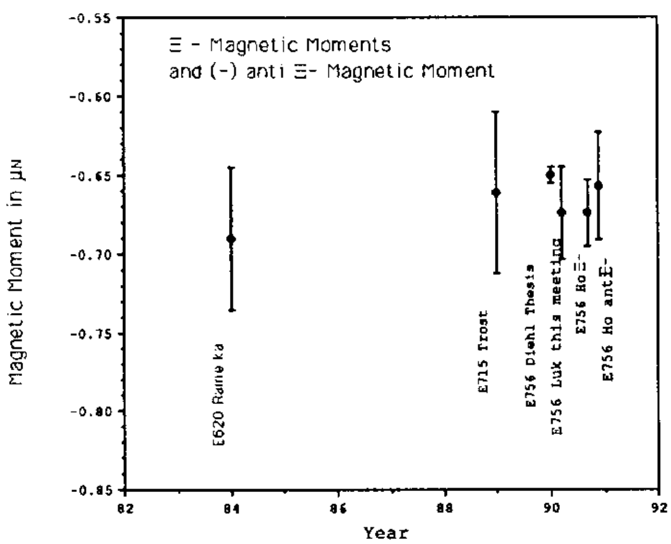

Figure 3. Ξ^- and anti Ξ^- magnetic moments.

The result quoted in the thesis of H. Diehl[12] has a very small error ($-0.650 \pm 0.005 \pm 0.002\ \mu_N$ where the uncertainties are statistical and systematical respectively). The number presented at this meeting by K. B. Luk from the same experiment has a considerably larger uncertainty ($-0.674 \pm 0.021 \pm 0.020\ \mu_N$). It is preliminary and from a partial data sample. At this time it appears the E756 experimenters are not totally at ease with the Diehl result. In my composite result in Table 1, I use the Luk number. Hopefully, the Diehl number is representative of the final uncertainty that we may expect from this experiment.

Symmetry under the combined operation of charge conjugation, parity inversion, and time reversal (CPT) requires that magnetic moments of particle and antiparticle be identical in magnitude but opposite in sign. To compare the Ξ^- and $\overline{\Xi}^+$ magnetic moments on the same graph, I plot the negative of the $\overline{\Xi}^+$ moment in Figure 3. Note that the data of Ho et al[10] is a matched set of both the Ξ^- and $\overline{\Xi}^+$ magnetic moments which are both plotted (with the appropriate sign change for the $\overline{\Xi}^+$). As expected, the two measurements are in good agreement with the prediction of the CPT theorem.

If Fermilab E761 finds that their data sample of $\overline{\Sigma}^+$ is polarized, they should also have a measurement of its magnetic moment.

For completion we note that there is good agreement[7] between the magnitude of the antiproton magnetic moment ($-2.795 \pm 0.019\ \mu_N$) and the proton moment ($2.793\ \mu_N$).

The Σ^+ magnetic moment. There is poor agreement between measurements from two Fermilab experiments[13,14] as shown in Figure 6. These two nominally 1% measurements differ by 3.1σ indicating one or both of them probably have errors larger than the stated ones. This is a well known problem and it has been handled by increasing the error so that the mean is $2.419 \pm 0.022 \mu_N$. Although not crucial for the confrontation of existing models, it may soon be tidied up. Fermilab E761 has repeated this measurement with apparatus having considerably better angular and momentum resolution that either of the previous experiments. They have collected an order of magnitude more data. Hopefully, we will see a resolution of this discrepancy before the next meeting.

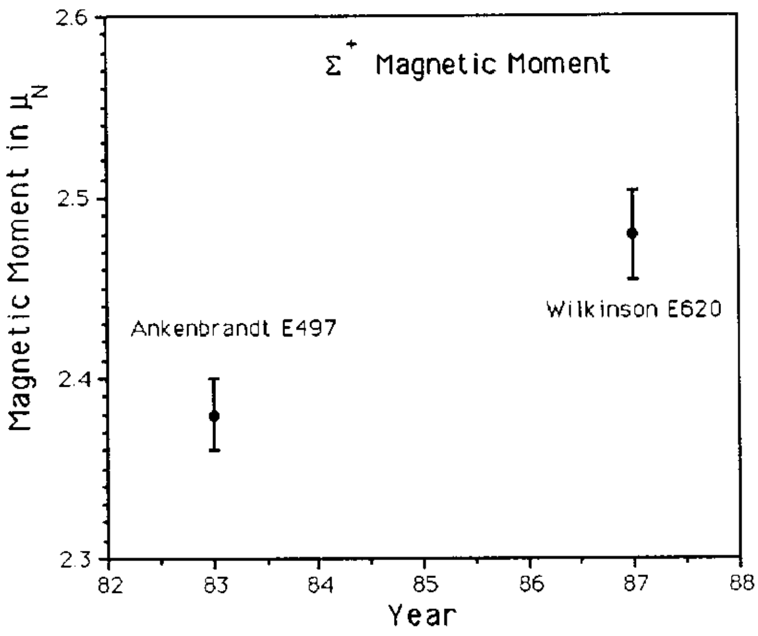

Figure 4. Σ^+ magnetic moment.

The Ω^- measurements. At this meeting K. B. Luk reported a revised preliminary value of the Ω^- magnetic moment of $-2.08 \pm 0.15\ \mu_N$ from Fermilab E756. Not included is an as yet unspecified systematic uncertainty. This experiment will run again early next year as Fermilab E800 and is expected to gather enough data to produce a measurement of precision $\pm 0.03\ \mu_N$.

SUMMARY

There are no new results on neutral hyperon magnetic moments or on the $\Sigma^0 \rightarrow \Lambda^0\gamma$ decay since the last review in this conference series. Table 1 summarizes the current status of the baryon magnetic moments. Also tabulated are the customary predictions from the simple quark model where we assume as input the p, n, and Λ^0 moments. The sign of the $\Sigma^0 \rightarrow \Lambda^0$ transition moment is taken from the quark model. The Ω^- moment prediction is taken as three times the Λ^0 moment. Table 1 also shows the differences from the moments predicted form the quark model.

Figure 5 is a plot of the differences. Here the error on the Λ^0 moment is plotted to illustrate the precision of the Λ^0 compared to the others.

Table 1

	Magnetic Moment μN	Quark Model μN	Difference μN	σ	%Dif
p	2.792847386 ± 0.000000063	input			
n	-1.91304275 ± 0.00000045	input			
Λ°	-0.613 ± 0.004	input			
$\Sigma+$	2.419 ± 0.022	2.67	-0.251 ± 0.022	-11.41	-9.40
$\Sigma-$	-1.156 ± 0.014	-1.09	-0.066 ± 0.014	-4.71	6.06
$\Sigma^\circ \to \Lambda^\circ$	-1.61 ± 0.08	-1.63	0.02 ± 0.08	0.25	-1.23
Ξ°	-1.253 ± 0.014	-1.43	0.177 ± 0.014	12.64	-12.38
$\Xi-$	-0.675 ± 0.022	-0.49	-0.185 ± 0.022	-8.41	37.76
$\Omega-$	-2.08 ± 0.15	-1.84	-0.24 ± 0.15	-1.60	13.04

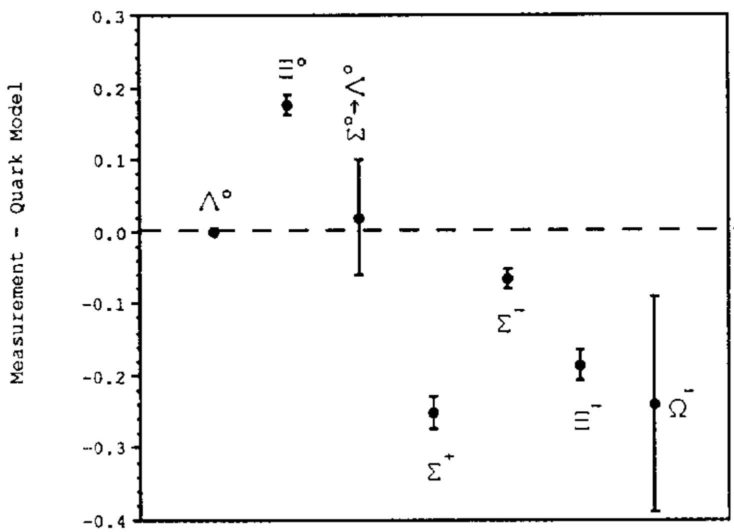

Figure 5. Comparison with Quark Mode.

The larger errors on the $\Sigma^\circ \to \Lambda^\circ$ transition moment and Ω^- moment distinguish them from the rest.

The quark model predictions reproduce all the signs correctly. In magnitude the worst disagreement is about 0.25 μ_N. This agreement makes you feel you are on the right track. However this is far from the complete story as a glance at the column showing the deviations in σ, or the % difference will attest. The Ξ^-, with a ≈37% deviation, is striking.

The quality of the hyperon magnetic moment measurements has not improved significantly since the last conference. However, considerably more data exists that has not been completely analyzed. Among the most important expected results are final values from E756 on the Ω^- and a much more precise value of the Ξ^- magnetic moment. E761 should be able to help resolve the discrepancy between the two existing measurements of the Σ^+ magnetic moment and, perhaps, demonstrate spin rotation by crystal channeling.

I thank my hyperon colleagues for many useful discussions and especially to K. B. Luk, T. Diehl, G. Rameika, and C. Newsom.

This work was supported by the U.S. DOE under contract #DE-AC02-76CH03000.

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