Measurement of the Σ^- Magnetic Moment*

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We have observed x rays produced in atoms formed by Σ^- hyperons with both lead and uranium nuclei. The fine-structure splitting of the x rays can be used to determine the magnetic moment of the Σ^- particle by a method similar to that used in a recent measurement of the $\bar{p}$ magnetic moment. Although the fine-structure splitting for the Σ^- atom was not distinctly resolved, our measurement can place an upper limit on the fine-structure splitting and hence the magnetic moment. We find that the magnetic moment lies in the range $-1.6<\mu<0.8$ in nuclear magneton units.

Magnetic moments of hyperons have typically been measured by observing their angle of precession in a magnetic field.[1,2] However, the Σ^- hyperon has a decay asymmetry parameter of 0.06, which is too small for this method to be practical. The magnetic moment can also be measured by observing x rays emitted from Σ-atomic transitions. Groups at Lawrence Berkeley Laboratory and CERN have observed Σ^- x rays in low-Z nuclei for which the fine-structure splitting is extremely small.[3,4] Since the fine-structure splitting varies as Z^4, we have looked for x rays in high-Z atoms such as lead and uranium in which the predicted splittings are appreciable.

The experimental setup for a similar experiment on the alternating-gradient synchrotron at Brookhaven National Laboratory is described by Fox *et al.*[5] We stopped about 4000 K^- per 2×10^{12} protons on the production target. The Σ^- particles are formed by kaons which are captured into an outer atomic orbit and cascade down through the atomic levels, emitting x rays until a level is reached from which they are captured by the nucleus. In the nuclear capture process, a Σ^- can be produced in the reaction

$$K+N\rightarrow\Sigma+\pi.$$

In some cases the Σ^- is ejected from the nucleus, forms an atom with another nucleus in the target, and cascades through the atomic levels, emitting x rays until it reaches a level from which it is captured by the nucleus. Since the process from K^--atomic capture to Σ^--nuclear capture takes less than 1 nsec, both Σ x rays and K x rays appear in the prompt x-ray spectra. In the lead spectra, we find that the ratio of Σ^- x rays in the 12-11 transition to K^- x rays in the 9-8 transition is about 0.06. This number can be compared to Zieminska's prediction of 0.05 for the number of Σ^- stopped per K^- stopped.[6] If the yield of x rays per stopping particle is the same for K's and Σ's, the two numbers are in good agreement.

The data obtained by stopping K^- in lead and uranium are shown in Fig. 1. Peaks are observed at positions corresponding to the 13-12 and the 12-11 Σ transitions. The 11-10 transition, observed for $\bar{p}$ atoms in lead and uranium,[5] is not seen for Σ's in uranium, but may be pres-

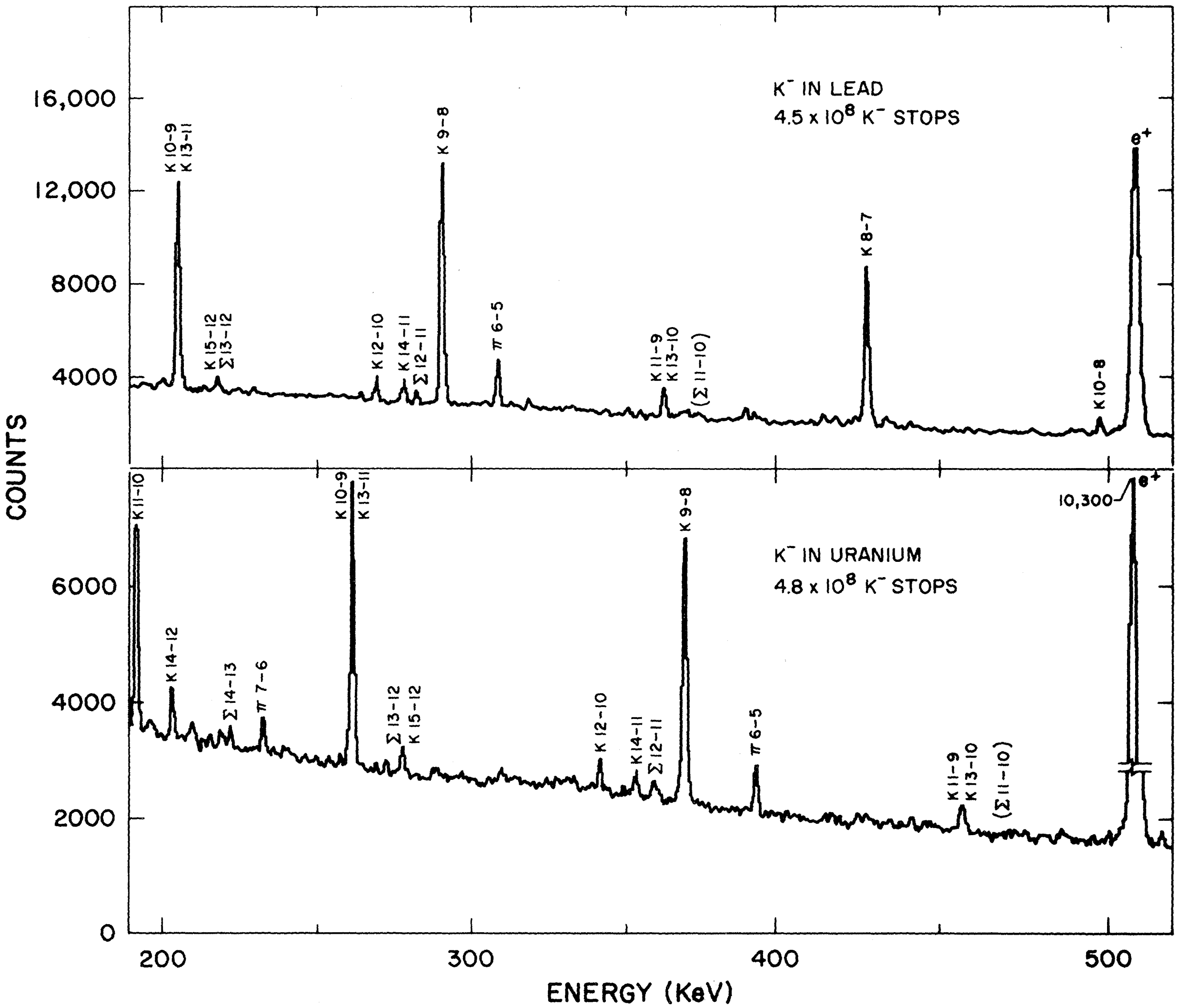

FIG. 1. X-ray spectra obtained by stopping K^- in lead and uranium. The expected positions of π^-, K^-, and Σ^- transitions are identified by the principal quantum numbers of the initial and final states of the transition. The energy resolution was 1.3 keV full width at half-maximum at 400 keV.

ent with a low yield in the lead data. Since the Σ has a larger mass than the $\bar{p}$, the Bohr radius of the Σ is closer to the nucleus, thereby increasing the nuclear capture rate from the $n = 11$ level and reducing the 11-10 x-ray yield. The 13-12 Σ transition is not resolved from the 15-12 K transition which is expected to have a comparable yield. The yield of the 15-12 K transition can be calculated by assuming that all K's are captured with a statistical distribution into a high atomic orbit, and then following the cascade process. Such a calculation predicts a yield of 2% for the 15-12 K transition, which is comparable in magnitude to the yield of Σ x rays predicted by Zieminska. As a result, the 13-12 Σ transition was not used for the analysis of the magnetic moment. The 12-11 Σ peak is identified by its energy and the fact that the line appears in both the lead and uranium data with approximately the same relative yield. However, the uranium line had a complicated structure as is discussed later. A search of tabulated nuclear γ rays and other kaonic and pionic transitions could not find any line near in energy to the 12-11 Σ lines. The predicted energies for the fine-structure splitting are given in Table I.

The region of the 12-11 Σ transition for the data of Fig. 1 is expanded in Fig. 2. As a preliminary analysis, the data were fitted assuming a fine structure corresponding to a magnetic mo-

TABLE I. Fine-structure splitting for Σ^- atoms, in keV, assuming a magnetic moment of 1 sigma magneton $(e\hbar/2m_\Sigma c)$ and neglecting the spin-down to spin-up transitions discussed in Ref. 5.

	Transition		
	13-12	12-11	11-10
Lead	0.112	0.187	0.327
Uranium	0.177	0.296	0.518

ment of 1 sigma magneton as given in Table I. We used the following assumptions:

(1) The fine-structure lines were represented by two Gaussians. We neglected the spin-down to spin-up transition in the fine-structure triplet as explained in Ref. 5.

(2) The relative peak height of the two Gaussians was calculated assuming all states are populated statistically, giving a ratio of 1.096. This ratio was held constant during the fitting process.

(3) The width of the Gaussian peaks was determined from an analysis of the width of the adjacent 9-8 K transition and radioactive sources.

(4) The background was represented by an expoential line.

(5) The effect of strong interactions was neglected since it is predicted to be small. A calculation of the natural width and shift of the 12-11 Σ transition assuming real and imaginary scattering lengths of 1 fm gives a width and shift less than 3 eV in both lead and uranium.[7]

(6) We assumed that all transitions were between atomic levels for which $n = l+1$.

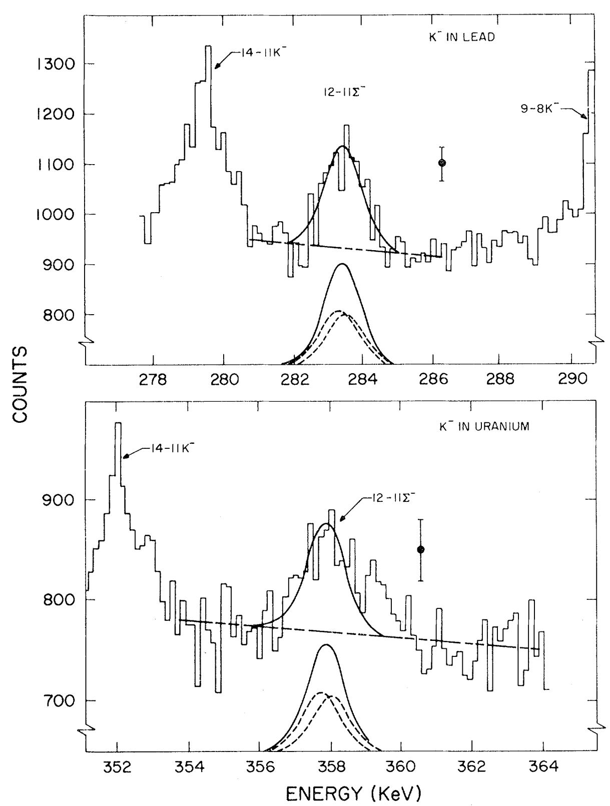

FIG. 2. X-ray energy spectrum in the region of the 12-11 Σ^- transition. The data are taken from those given in Fig. 1. The results of fitting two Gaussian lines with fine-structure separation corresponding to 1 sigma magneton are shown. The statistical error in the data is indicated by an error bar. The fit corresponds to a χ^2 of 50 for 34 degrees of freedom in the lead data and a χ^2 of 76 for 66 degrees of freedom in the uranium data.

The resulting fits are shown in Fig. 2. The fit to the lead data gives a peak centroid with an energy in agreement with the expected value of 283.44 keV. In the uranium data there appears to be a small peak to the right of the fitted peak. The small peak cannot result from a fine-structure splitting because the magnetic moment required for this splitting would be inconsistent with the lead data. It is likely that a nuclear level was excited by a K or Σ in their atomic cascade, or by a subsequent nuclear capture reaction which produced either a line splitting or a γ ray near in energy to the 12-11 Σ-uranium line. Since we do not understand the source of the small peak, we have considered only the lead line in our analysis of the magnetic moment.

The Σ-lead 12-11 line was analyzed by varying the separation of the two fine-structure lines and computing χ^2 for each separation. The fit was repeated for different widths of the Gaussian peak, for another peak shape which had a low-energy tail, and for different end points in the background fitting. A plot of the resultant χ^2 for different Gaussian widths is shown in Fig. 3. Plots for the other fitting shapes were similar. The double dip is due to the fact that our analysis is not sensitive to the sign of the magnetic moment. Another fit included peaks representing transitions between atomic levels for which $l = n-2$. An analysis of the cascade indicates that the yield of these transitions could be as high as 20% of the $l = n-1$ transitions. Limits for the magnetic moment μ were obtained by choosing as limits the values of μ which produced an increase in χ^2 by one unit over the minimum value. The range of μ which includes the values predicted by all of the different fitting procedures is

$$-2.0 < \mu < 1.0,$$

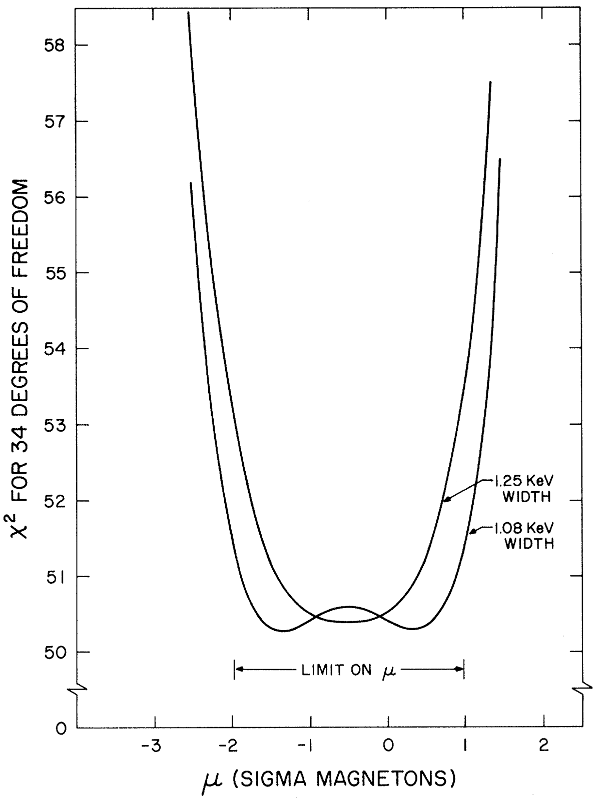

FIG. 3. χ^2 resulting from the fitting of two Gaussian-shaped peaks to the 12–11 Σ line of lead with separations corresponding to different values of the magnetic moment μ. The calculation was done twice. In one case the widths of the two Gaussian peaks were fixed at a value which was 2 standard deviations less than the expected value, and in the other case the widths were fixed at a value 2 standard deviations greater than the expected value.

in sigma magneton units ($e\hbar/2m_\Sigma c$). The value predicted by SU(3) theory is -1.12 sigma magnetons (-0.88 nuclear magneton).[8]

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