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Proposal Title

High-Resolution Electroproduction of Light Hypernuclei

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CEBAF PROPOSAL

High-Resolution Electroproduction of Light Hypernuclei

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I. Abstract

We propose high resolution measurements of kaon electroproduction to investigate hypernuclear states for the ^{4}He and ^{12}C targets. The proposed experiments will provide information on the ΛN spin-orbit interaction, bound Σ hypernuclei and short range correlation. Excitation of unnatural parity states will rapidly expand hypernuclear spectroscopy. The establishment of the experimental technique for light hypernuclei production will be extremely useful for the study of the deep hole states in heavy nuclei.

II. Introduction

Hypernuclear states have been studied by the (K^-, π^-), (π^+, K^+) and stopped K reactions. Each reaction has different characteristics. The (K^-, π^-) reaction at small angles is a process with small momentum transfer. In this case it preferentially populates substitutional hypernuclear states in which a nucleon is replaced by a Λ particle. This transition is characterized by an orbital angular momentum transfer of ΔL=0. The (π^+, K^+) reaction favors the formation of high spin states due to large momentum transfer. The stopped K reaction is a special case of the (K^-, π^-) reaction where the kaon is captured at rest. In this reaction variety of hypernuclear states is populated by a sizable momentum transfer.

For the Λ hypernuclei up to ^{89}Y , the binding energies of the single particle state of the Λ were obtained by the (π^+, K^+) experiments at BNL[1]. On the other hand for the Σ hypernuclei, many candidates for narrow Σ states in the continuum in light nuclei have been found, but not confirmed as the Σ hypernuclei[2]. Recently evidence of a bound Σ state for A=4 was reported[3]. However the hypernuclear production so far reported have been done with a poor energy resolution of ~3MeV. Thus, it is highly desirable to study the hypernuclear states by another probe with much higher resolution.

The (e, e' K^+) and (γ, K^+) reactions are expected to provide a useful alternative to the (π^+, K^+) and (K^-, π^-) reactions. The (e, e' K^+) reaction is similar to (π^+, K^+) reaction in regard to variable momentum transfer, but the former has some advantages for studying deeply-bound Λ orbits. The electrons are very weakly absorbed in compared with the pions. In addition the (e, e' K^+) reaction excites both natural and unnatural parity hypernuclear states with comparable strength. Although many theoretical predictions have been carried out for hypernuclear production by the (e, e' K^+) and (γ, K^+) reactions, no experimental data have been reported up to the present. Recently ^{12}C(γ, K^+)^{12}B measurements have been successfully performed at INS[4].

We emphasize that the high resolution measurement of hypernuclear states produced in (e, e' K^+) reaction on ^{4}He and ^{12}C targets is a promising experiment as the first hypernuclear experiment. It will provide information on the ΛN spin-orbit interaction, the bound Σ hypernuclei and the short range correlation. It will also provide a test of the capabilities of study of the deeply bound state in heavy nuclei. The (e, e' K^+) measurements are not feasible anywhere but CEBAF.

III. Physics Motivation

A. ^{4}He

i) Λ hypernuclei

The ^{4}He nucleus is one of the simplest nuclei whose wave function is obtained with the realistic interactions. In order to obtain Λ–nucleon interaction exactly, it is necessary to carry out experiments with such a nucleus for which the wave function is well known.

Experiments on Λ hypernuclear state of ^{4}H have been studied by the stopped K reaction[5]. The life time of the 1^+ states has been measured[6]. In the ^{4}He(e, e' K^+) reaction , the 0^+ state with the configuration of ($s_{1/2}{}^{\Lambda}$, $s_{1/2}{}^{-1}$) should be excited as well as the 1^+ state. The *l-s* interaction of Λ optical potential can be deduced from the split width between these states.

ii) Σ hypernuclei

The Σ hypernuclear state is quite interesting, since the narrow Σ states is unanticipated because of the strong ΣN – ΛN conversion. Recently evidence of the bound Σ hypernuclear state of ^{4}He has been found at a binding energy of 3.2 MeV with respect to the Σ^+ emission threshold, with a width of 4.6 MeV, via the stopped K reaction (Fig. 1)[3]. It is very important to conform the Σ hypernuclear state with other reactions, especially with the electromagnetic reaction. The electro-production is superior to the (K^- , π^-) reaction in low background and relatively reliable analysis.

Observed narrow width has been interpreted as follows by Akaishi and his collaborators[7]. A potential between Σ and the core nucleus is expressed by a central potential and the Lane term, which has isospin operators. In $^4{}_{\Sigma}$He nucleus, h+Σ^0 and t+Σ^+ channel components exist as shown in Fig. 2, the channel potentials are repulsive at short distances, while the coupling potential between the two channels is very attractive. The Lane term produces attractive potential to make a bound state. In Fig. 3 the same nucleus -Σ potential is plotted for the isospin T=1/2 and T=3/2. As seen, the potential for the T=1/2 state is attractive with slight repulsive part in the central region. On the other hand the potential for the T=3/2 state is strongly repulsive in the real part; no bound state can be realized. The energy and width predicted with the calculation are in agreement with the experimental data[3] obtained from the stopped K reaction on ^{4}He. Since the isospin of $^4{}_\Sigma$H can be T=1/2, it is expected to be bound. Then we want to search a bound Σ hypernuclear state through the ^{4}He(e, e' K^+) reaction.

iii) Momentum transfer dependence of the cross section

Since positive kaons weakly interact with the nucleus, it is suitable to investigate the short range correlation (SRC). Recently Shinmura et al.[8] have examined the effects of the short range correlation on the hypernuclear production cross section. Most of the reactions producing the hypernuclei, except the (K^-, π^-) reaction, accompany with the large momentum transfer. In such reactions, the hypernucleus production cross section seems to strongly depend on the high momentum components of the wave functions. Fig. 4 shows the angular distributions of the kaons from ^{4}He(π^+, K^+)$^4{}_\Lambda$He reaction for the incident π^+ momenta 1.097 and 1.334 GeV/c. The solid lines are the results with the Hamada-Jonston potential and phenomenological ΛN potential. The dashed lines are the those without SRC. For non-forward angles, SRC becomes important and makes a dip structure in the angular distribution. The SRC gives no effect for q<300 MeV/c, destructive effect for 300 MeV/c< q<600 MeV/c and dominant effect for q>600 MeV/c. In the ^{4}He(e, e' K^+) reaction we can study SCR instead of the (π^+, K^+) reaction.

B. ^{12}C

i) Λ hypernuclei

Λ hypernuclear states in $^{12}{}_\Lambda$C have been extensively studied by hadronic reactions. Recently the measurement of the ^{12}C (γ, K^+) reaction has been carried out by using tagged photon and a preliminary cross section has been obtained[4]. Also many theoretical works on the electromagnetic production have been done. Bernstein et al.[9] have discussed photo- and electro-production of kaons on nuclei. They have estimated cross section for photo-production of hypernuclei from ^{4}He and ^{12}C using single -particle single -hole configurations with harmonic oscillator single-particle wave functions for the proton and lambda. Cotanch and Hsiao[10] have calculated the production cross section for hypernuclear formation from ^{12}C using the single virtual photon exchange approximation and density matrix formalism. The cross section shows similar strength as that calculated by Bernstein et al. Rosenthal et al.[11] have calculated the ^{12}C(γ, K^+) cross section using a distorted wave impulse approximation including the full Coulomb plus kaon-nucleus interaction. Calculated differential cross sections for the ($p_{3/2}^{-1}$, $p_{3/2\Lambda}$) multiplet are shown in Fig. 5. Recently Sotona et al.[12] have calculated the polarization phenomena in hypernuclear phtoproduction. Fig. 6 shows their result of the strength function for the $^{12}C(\gamma, K^+)^{12}{}_{\Lambda}B$ reaction.

substitutional state

The substitutional states have been studied by the (K^-, π^-) reaction[13]. The dominant peak at $B_{\Lambda}=0$ was observed and was assumed to have the $J^{\pi}=0^+$ assightnment that belongs to the $(1p_{3/2},1p_{3/2}^{-1})_{\Lambda n}$. The states of $0^+$and 2^+ were not resolved. The (K^-, π^-) reaction studied for momentum transfers up to 260 MeV/c[14] excited a peak corresponding the $(1p_{3/2},1p_{3/2}^{-1})$ and $(1p_{1/2},1p_{3/2}^{-1})$ configurations at the same energy . From the angular distribution they show the existence of at least one 2^+ state degenerated with the 0^+ state. In the electro- or photo- production, the unnatural parity 3^+ state of the substitutional states is predicted to be excited strongly. The energy difference of the 3^+ state and 2^+ state coreeesponding the $(1p_{1/2},1p_{3/2}^{-1})$ configuration is predicted to be of ~500 keV[12]. These states can be separated with the high resolution $(e, e' K^+)$ measurements proposed, which will provide important information about the Λ spin -orbit interaction.

ground state

The ground state transition corresponding to the $(1s_{1/2},1p_{3/2}^{-1})_{\Lambda n}$ configuration is strongly excited by the (K^-,π^-) reaction and the angular distribution for this state shows 1^- excitation. In the electromagnetic interaction the unnatural parity 2^- member of the ground state doublet is predicted to be excited most strongly, but the separation of the doublet(~0.14 MeV[12]) will be difficult.

hole state

The hole states are not observed by hadronic production. However in electroproduction the 1^+state corresponding to $(1s_{1/2}, 1s_{1/2}^{-1})$is predicted to be strongly exited. The 0^+ state is predicted to be weakly excited.

Observable states by electroproduction is summarized in table 1. The states observed by hadronic probes are surrounded by circles and the states with unnatural parity are surrounded by triangles. Excitation of those many unnatural parity states will make progress in hypernuclear spectroscopy if combined with results by hadronic proves.

IV. Summary of proposed measurements

We propose to measure the angular distribution of kaons produced by the $(e, e' K^+)$ reaction on ^4He and ^{12}C. Also we propose to measure momentum transfer dependence of the production cross section on ^4He. Virtual photon energies and the angles will be 2.0 and 1.84 GeV and θ=7°, 10°, 13°, and 16°. The $(e, e' K^+)$ measurements are not feasible anywhere but CEBAF. The data obtained will provide a test of the capabilities of the study of deeply bound states in heavy nuclei.

V. Experimental technique

The basic experimental requirement is to use two spectrometers. Of particular importance is the possibility to set the pair spectrometer at minimum achievable scattering angle. The experiment is designed so as to be run in A hall with HRS electron arm and the Multi Purpose Spectrometer (MPS) proposed by Frullani et al[15].

The MPS is composed of the septum, quadrupole, dipole and quadrupole magnets. Principal characteristics of the MPS are as follows. The maximum central momentum is 1.3GeV/c. The solid angle acceptance is 10msr in the small forward angles set up. The resolution is better than 10^{-4}. The momentum acceptance is $\pm$ 7.5%. The optical length is 10.6m. By using the septum magnets to the HRS and MPS, the smallest angles of the kaon and the electron arms will be 7° and 6°, respectively. An overview of the MPS is shown in Fig. 7.

The focal plane detector for the MPS includes two wire chambers near the focal plane, Cerenkov counters and several planes of scintillators to define the trigger. For the identification of kaons a combination of TOF, dE/dx, aerogel Cerenkov detectors, lucite detectors will be used. For π-K discrimination, the dE/dx technique is used to discriminate kaons from pions up to 0.6 GeV and an aerogel Cerenkov detector with n=1.025 from ~0.6 GeV/c to ~2 GeV/c. In order to separate kaons from protons, the dE/dx technique allows to separate them over the entire momentum range interest.

We expect to use cryogenic helium and solid carbon targets.

VI. Beam time request

The cross section for the ^{4}He(e, e' K$^+$)$^4{}_\Lambda$H and ^{12}C(e, e' K)$^{12}{}_\Lambda$B reactions are estimated from the ^{4}He(γ, K$^+$)$^4{}_\Lambda$H (ref. 9) and ^{12}C(γ, K$^+$)$^{12}{}_\Lambda$B (ref. 11) cross sections using the method proposed by Donnelly et al[16]. The parameters used for the estimate of the coincidence rate are as follows. The beam current is 30 μA; the target thicknesses of liquid helium and carbon are 75 and 50 mg/cm^2, respectively, the solid angles of the HRS and MPS are 1.8 and 10 msr, respectively; the momentum acceptance of the HRS is 10 %. The kaon detection efficiency of 0.2 is also included. The resulting count-rate estimates are shown in Table 2.

In order to study the hypernuclear state with high resolution for two targets nuclei, we request a total of 1000 hrs of beam time. This includes 100 hrs of running for calibration and checkout.

VII. Commitment of collaboration

The collaborators listed on the cover page have all great interest in this program. Several members of this collaboration are those of the MPS. Some are those having taken the initiative of the $^{12}C(\gamma, K^{+})$ reaction at INS[4].

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Table 1. Observable hypernuclear states by electroproduction.

○ obseved states by hadronic probes △ unnatural parity states

$p_{3/2}$	proton hole	$s_{1/2}$ Λ particle	○ 1^- △ 2^-
		$p_{3/2}$	△ 3^+ ○ 2^+ 1^+ ○ 0^+
		$p_{1/2}$	△ 1^+ ○ 2^+
$s_{1/2}$	proton hole	$s_{1/2}$	△ 1^+
		$p_{3/2}$	1^- △ 2^-
		$p_{1/2}$	1^-

Table 2. Count Rate Estimates.

Target	E_e (GeV)	$E_{e'}$ (GeV)	$\vartheta_{e'}$	ϑ_K	Rate /hr
^{4}He	3.0	1.0	6°	7°	20
^{4}He	3.0	1.0	6°	10°	14
^{4}He	3.0	1.0	6°	13°	6.6
^{4}He	3.0	1.0	6°	16°	3.3
^{12}C	3.0	1.16	6°	7°	2.7
^{12}C	3.0	1.16	6°	10°	1.9
^{12}C	3.0	1.16	6°	13°	0.71

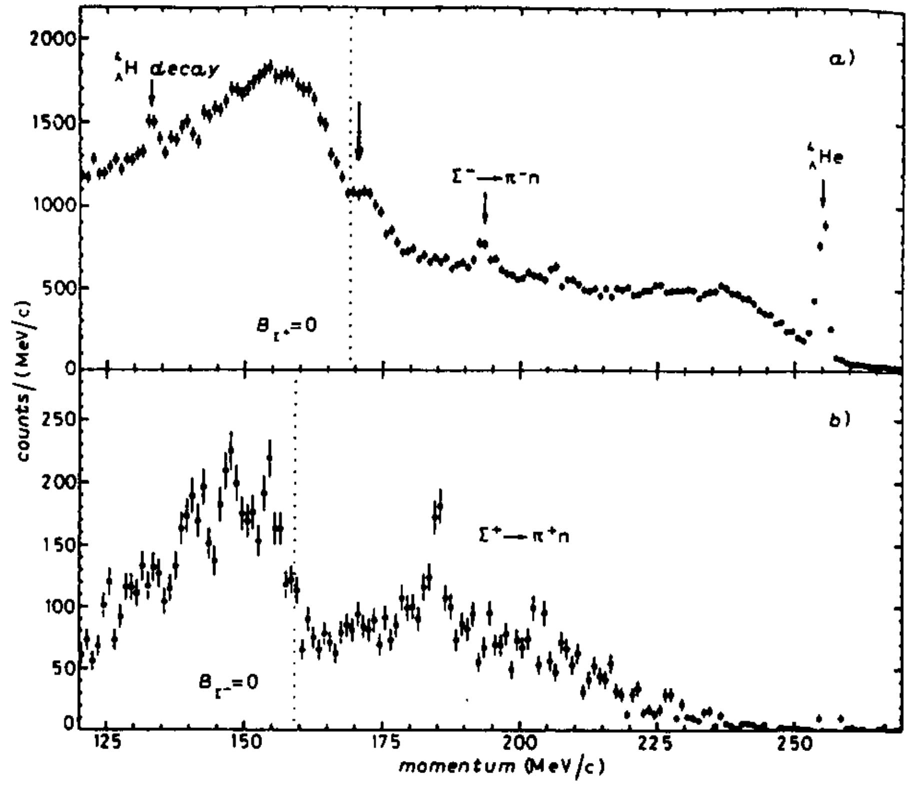

Fig.1 a) The π^- momentum spectrum observed in the $^4He(K^-,\pi^-)$ reaction at rest on a liquid helium. The shoulder indicated with the unlabeled arrow is interpreted as a Σ-nucleus bound state. b) The (K^-,π^+) spctrum (ref. 3).

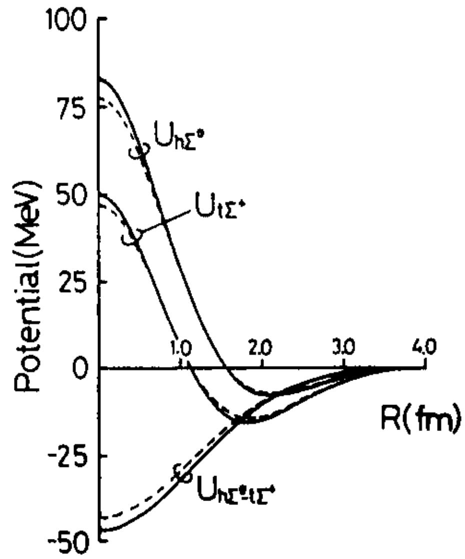

Fig.2 The real part of the nucleus-Σ channel and coupling potentials. The potentials of the $^3H+\Sigma^+$ and $^3He+\Sigma^0$ channels are denoted by $U_{t\Sigma^+}$ and $U_{h\Sigma^0}$ and the coupling potential by $U_{h\Sigma^0\text{-}t\Sigma^+}$. The solid and the dashed curves are for different sigma absorption potentials (ref. 7).

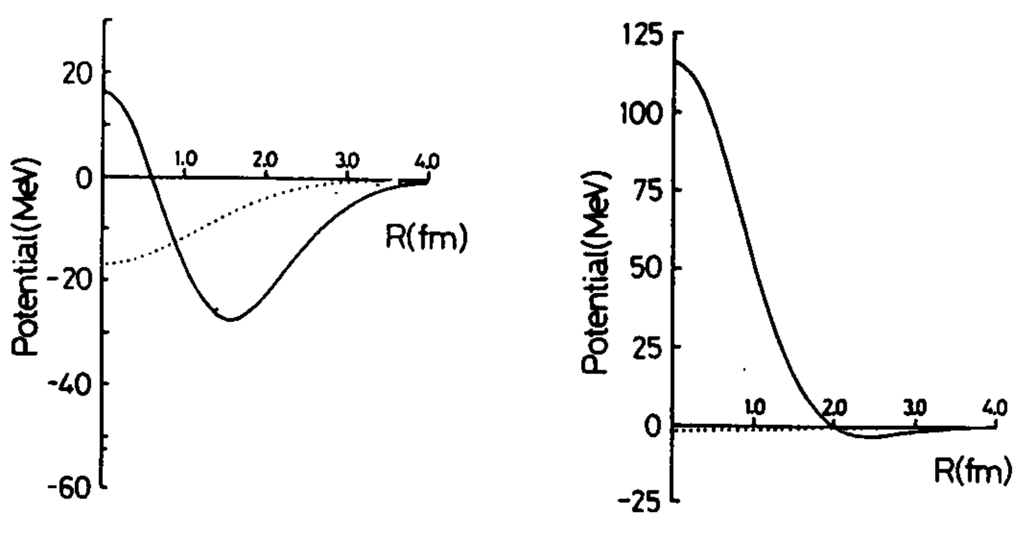

Fig. 3 The nucleus-Σ potentials for the isospin T=1/2 and T=3/2 states. The solid and the dotted lines are the real and the imaginary parts, respectively (ref. 7).

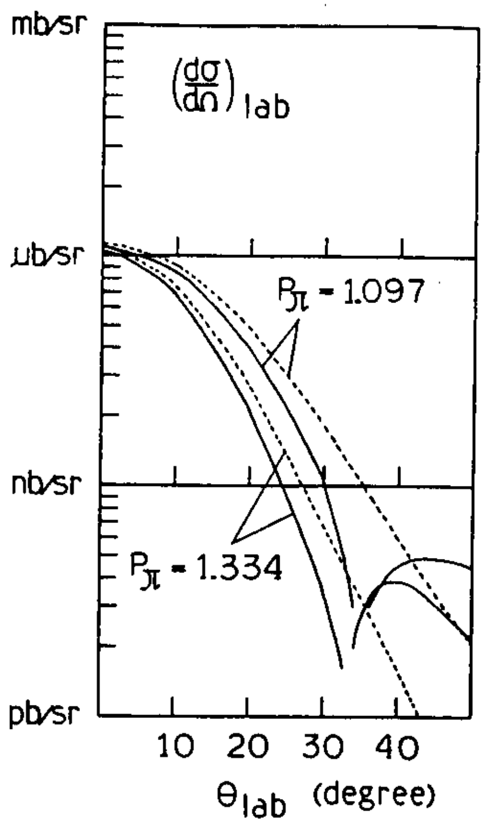

Fig. 4 The angular distributions of $^4He(\pi^+, K^+)^4{}_\Lambda He$ for the incident π^+ momenta 1.097 and 1.334 GeV/c. The solid lines are the results with the Hamada-Johnston potential and the phenomenological ΛN potential. The dashed lines are those without SRC (ref. 8).

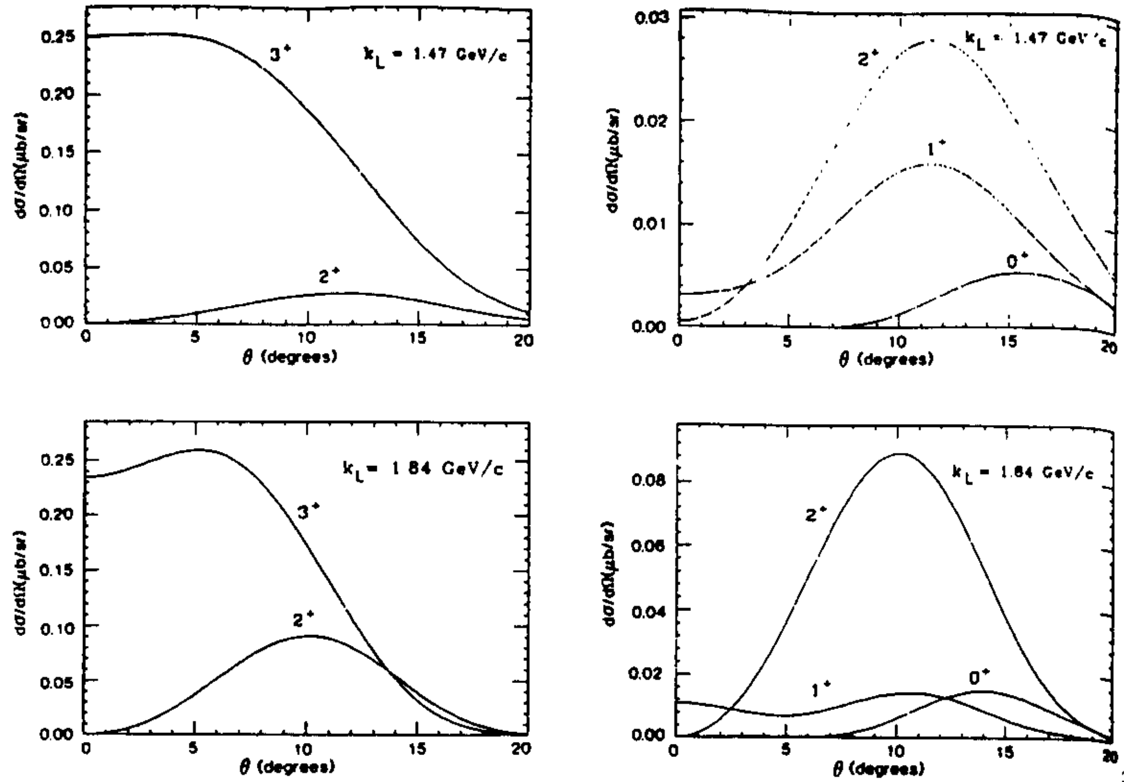

Fig. 5 The photoproduction differential cross sections for a pure ($p_{3/2}$, $p_{3/2}^{-1}$) multiplet, calculated with effects of full kaon distortion included (ref. 11).

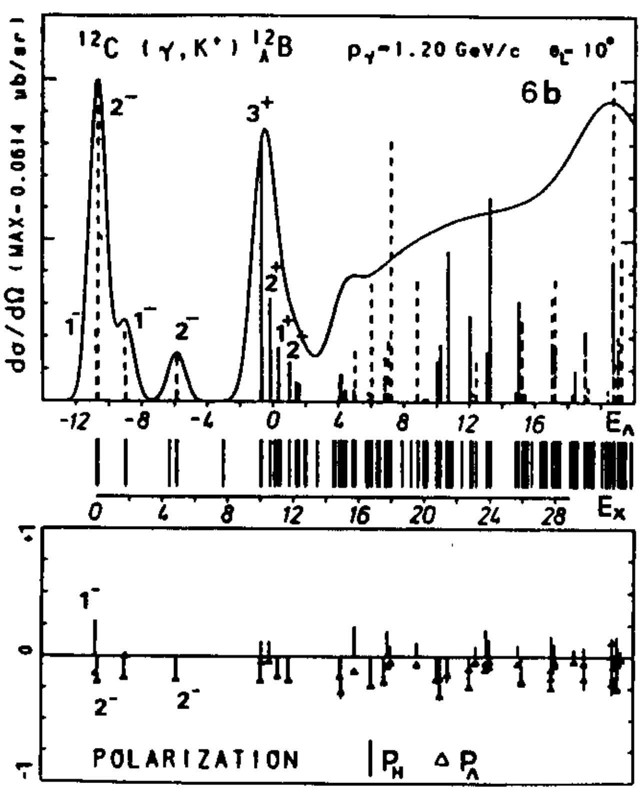

Fig. 6 Strength function, hypernuclear polarization P_H and Λ-spin polarization P_Λ for $^{12}C(\gamma, K^+)^{12}_{\Lambda}B$ (ref. 12).

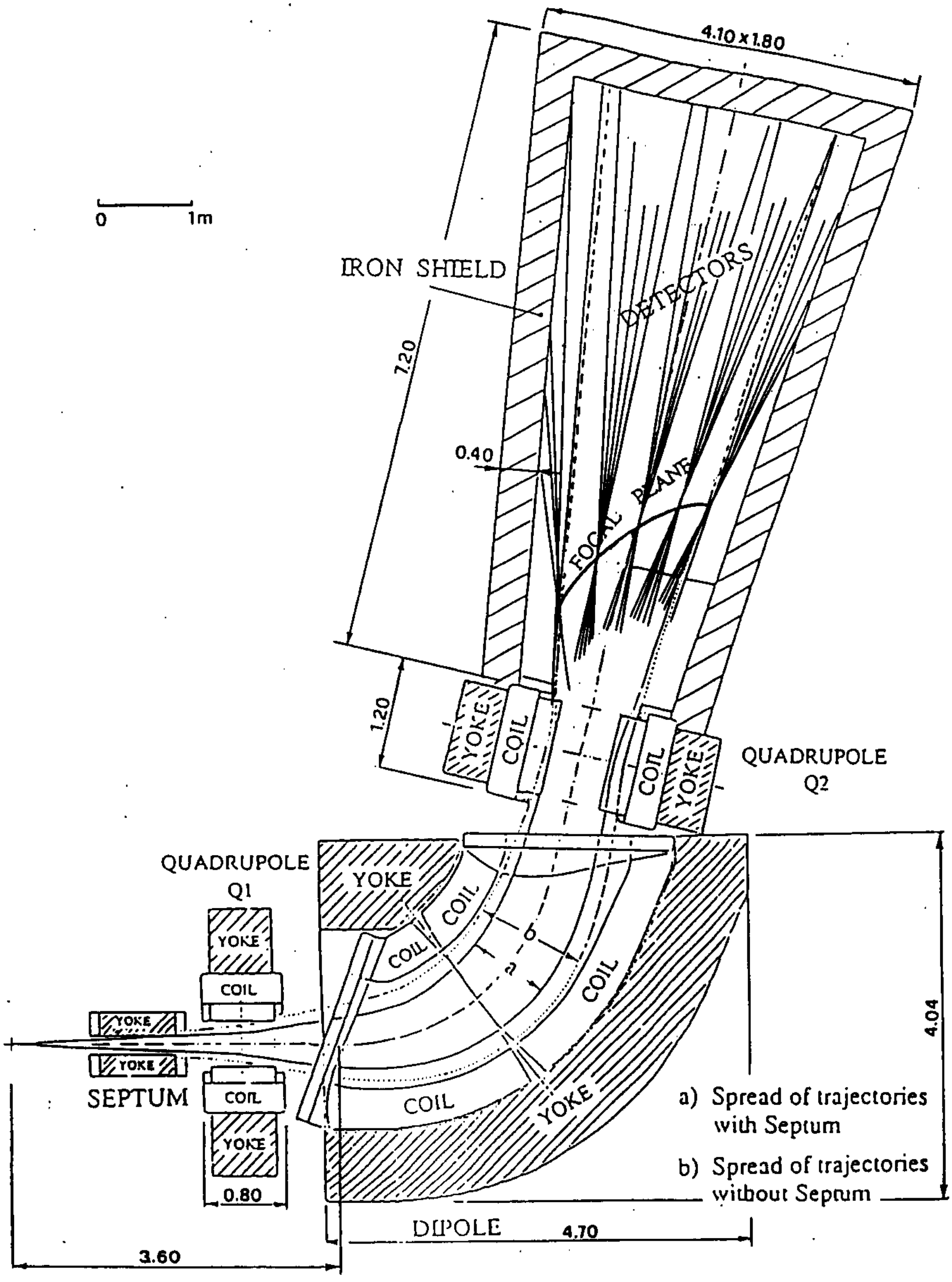

Fig. 7 Overview of 1.3 GeV Multi Purpose Spectrometer proposed(ref. 15).