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Spectroscopy of Light Quark Systems

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Spectroscopy of Light Quark Systems

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SPEKTROSKOPIE LEICHTER QUARK-SYSTEME

Der vorliegende Artikel ist Teil eines Vorschlags zum Bau eines Hochstrom-Protonen-Beschleunigers in Europa (EHF, Proposal for a European Hadron Facility, herausgegeben von J.F.Crawford (SIN), unterstützt von BMFT (Deutschland) und INFN (Italien)). Er beschäftigt sich mit der Frage, welche Experimente auf dem Gebiet der Spektroskopie leichter Quark-Systeme mit den dort verfügbaren Kaonen-Strahlen von hoher Intensität und Reinheit ausgeführt werden können. Es wird zunächst ein kurzer Überblick über den derzeitigen Stand der Mesonen- und Baryonen-Spektroskopie gegeben und danach weiterführende Experimente zusammen mit einem dafür optimierten Detektorsystem vorgestellt. Zwei dieser Experimente (Erzeugung von Glue-Balls mit K^--Strahlen; radiative Zerfälle der $\Lambda(1405)$-Resonanz) werden herausgegriffen und in einer Monte-Carlo-Simulation in dem vorgeschlagenen Detektor näher diskutiert. Es zeigt sich, daß bereits in kurzen Meßzeiten bisher nicht meßbare Reaktionen zu deutlichen Signalen führen und so für die weitere Untersuchung der Hadronen-Spektroskopie und damit auch für die Quantenchromodynamik wichtige neue Erkenntnisse gewonnen werden können.

ABSTRACT

This article is part of a proposal for the construction of a high intensity proton accelerator in Europe (EHF, Proposal for a European Hadron Facility, edited by J.F.Crawford (SIN), supported by BMFT (Germany) and INFN (Italy)). Experiments concerning the spectroscopy of light Quark systems are discussed, which can be performed with Kaon beams of high intensity and high purity at EHF. After a brief review of the status of Meson- and Baryon- spectroscopy an optimized detection system is presented, and two specific experiments (Glue-Ball production with K^- beams; radiative decays of the $\Lambda(1405)$-resonance) are discussed in detail. A Monte-Carlo-simulation shows, that clear signals for these processes can be obtained in short measuring times. These examples demonstrate, that with high quality K^- beams new and important information on Hadron-spectroscopy can be obtained, which is important for a further understanding of Quantum-Chromo-Dynamics.

Spectroscopy of Light Quark-Systems

1 Introduction

Hadron spectroscopy of u, d, and s quarks is a necessary ingredient for all attempts at a detailed understanding of the strong interaction. All theoretical approaches in non-perturbative QCD have to be checked against the measurable properties of hadronic states, such as masses, decay rates and production mechanisms. Their knowledge is as relevant for the development of QCD as were the atomic spectra for the understanding of atomic physics. Of special importance is the question whether s quarks behave dynamically the same as u and d quarks, a problem for which the K^{-} beams of EHF are ideally suited.

In the following the experimental and theoretical status of Hadron Spectroscopy is shortly reviewed and a survey on possible experiments with the excellent EHF-beams and an optimized detector system is given. A few of the experiments are highlighted and the results of Monte-Carlo simulations are given.

2 Hadron Spectroscopy

2.1 Experimental Status

Mesons

Candidates for the most low-energy $\bar{q}q$-states are known [1], as well as some candidates for exotic states like glueballs (gg or ggg) or hybrids ($\bar{q}qg$). Most desired is the appearance of states with exotic quantum numbers ($J^{PC} = 0^{--}, 1^{-+}, 2^{+-}, 3^{-+}, \ldots$), unallowed for $\bar{q}q$-states, which unambiguously identify an exotic state. The first evidence for such states has occurred recently in $\pi^- p \to (\eta\pi^o)n$ and $\gamma p \to (b^{\pm}(1235)\pi^{\mp})p$ reactions [2], but needs further confirmation. Also uncertain is in many cases the quark content of the experimentally identified $\bar{q}q$ states and their mixing with glueball/hybrid states. Most data come from old-fashioned bubble-chamber experiments with low statistics, and it is only recently that more modern detectors have been used [3] or are under construction [4] for $\pi, \bar{p}, \gamma$ induced reactions or radiative ψ decays. Such detectors have never been used in combination with high quality K^{-} beams.

Baryons

Most of the information on $S = 0$ Baryons comes from sophisticated energy independent partial-wave-analyses (PWA) of $\pi^{\pm}p$ reactions, using dispersion relations (DPR) as constraints [5]. Here, little improvement seems possible. In $K^{-}p$ reactions the situation looks different. Compared to πN data the statistics is generally lower by one order of magnitude (low intensity and high π, e contamination of the Kaon-beams) allowing only energy dependent PWA ("Poor man's solution"). Data on polarization parameters and inelastic channels are missing which are needed for an unambiguous analysis [6]. Exotic baryonic states ($qqqg$) are predicted but have not yet been found[7].

2.2 Theoretical Description

The most advanced theoretical description of bound hadronic states is based on a quark model inspired by QCD ideas [8]. It explains well the masses of most of the lighter hadrons and makes predictions on higher mass states and their coupling to 2-body channels like $\pi N, \bar{K}N, \pi\Sigma, \ldots$ An essential point in the $SU(6) \times O(3)$ model for excited baryonic states is the existence of the $[56, 2^{+}], [56, 0^{+}], [70, 0^{+}], [70, 2^{+}]$ and $[20, 1^{+}]$ multiplets (2-quanta excitations of the ground state). So far, few or no candidates have been found as members of the $[70, 0^{+}], [70, 2^{+}]$ and $[20, 1^{+}]$ multiplets. This fact was explained by weak coupling of these states to the πN and $\bar{K}N$ channels [8], a prediction which is essential for the model and should be checked experimentally in detail. Beyond the $\bar{q}q$ and qqq states exotic systems like glueballs (gg/ggg), mesonic ($\bar{q}qg$) and hadronic ($qqqg$) hybrids are predicted, some with exotic quantum numbers[7].

3 Spectroscopy experiments at EHF

3.1 Meson spectroscopy

The field is presently developing rapidly, using $e^{+}e^{-}$ machines (radiative ψ decay) and π, γ induced reactions (BNL, CERN). LEAR will contribute significantly in the next few years using $\bar{p}p$ annihilation as a source of exotic/non-exotic mesons. The main impact of EHF in this field will be the use of high quality π^{-}, K^{-} beams together with an optimized detector. Emphasis will be on the search for exotic states, particularly those with exotic quantum numbers, which should show up in reactions like

$$\pi^{-}p \rightarrow (\eta\pi^{0})n, (\eta\phi)n, (\eta\eta')n \qquad (10.1)$$

and similarly in K^- induced reactions like

$$K^- p \rightarrow (\eta\pi^0)\Lambda, (\phi\phi)\Lambda, \ldots \tag{10.2}$$

There is no obvious reason why such elusive states should be produced more frequently in strangeness induced reactions, but the comparison between 10.1 and 10.2 will yield information on the quark content of the states produced. The detection of a Λ, decaying to $p\pi^-$ (64%), is experimentally much easier than an efficient n-detection, so that 10.2 has an experimental advantage as compared to 10.1 . Furthermore, the Λ is produced in a second vertex different from the interaction vertex, which facilitates the setting up of a fast trigger on the reaction (Λ tag). Of particular importance here is a high performance detector allowing the simultaneous identification of many-particle final states in a nearly 4π solid angle. Hybrids, for example, are predicted to decay preferentially to mesons with $L > 0$, giving rise to a complicated final state. An example would be [8]:
hybrid$^+ \rightarrow f_1^0(1285)\pi^+$; $f_1^0(1285) \rightarrow a_0(980)\pi^0$;$a_0(980) \rightarrow \eta\pi^0$; $\eta, \pi^0 \rightarrow \gamma\gamma$ leading to the final state $\pi^+ 6\gamma$.

3.2 Baryon spectroscopy

In the first round of experiments the emphasis will be on the improvement of $S = -1, -2$ baryonic resonance states. Only 9(6) states of the already observed 18(26) $\Lambda^*(\Sigma^*)$ states are four star [1] and thus more confirmation is needed. Many of the predicted states are still missing and the quark content of some long-established resonances is in serious doubt. For example, the $\Lambda(1405)$ fits very badly into the Isgur-Karl-model and there is lively discussion whether it is a $(uds)-$ or a bound $K^- N-$ state [9] The aim of all measurements on K^- induced reactions is to reach a quality similar to the already existing πN data, allowing an energy independent PWA using DPR. Typical experiments would be

$K^- p \rightarrow K^- p$ (Elastic)

$K^- p \rightarrow K_S^0 n$ (CEX)

$K^- p \rightarrow K_S^0 \pi^- p$ (Example of inelastic channel)

. . .

. . .

$K^- n \rightarrow K^- n$ (Deuterium target)

Of particular importance is here the measurement of polarization parameters using polarized Hydrogen (Deuterium) targets [6]. The comparison between reactions on protons and neutrons will allow the disentangling of $I = 0, 1$ amplitudes, which is very important for a proper distinction of Λ^* and Σ^* states. In that respect also the reaction

$$K_{L}^{0}p \rightarrow K_{S}^{0}p$$

is of interest because of its interference between $I = 0, 1$ amplitudes [6]. According to the Isgur-Karl model many of the baryon resonances with two quanta of excitation do not couple to πN and $K^{-}N$ and therefore can not be found in formation experiments of the type $\pi(K)N \rightarrow \pi(K)N$. Thus, for the production of a weakly coupling Y^{*} resonance, experiments of the type

$$K^{-}p \rightarrow \Sigma^{*}\pi \text{ (prominent resonance)}; \ \Sigma^{*} \rightarrow Y^{*}\pi$$

are necessary. The mass spectrum of baryonic states can be easily distorted by threshold effects, so that the measurement of decay branching ratios (dependent on the eigen-vector) is often more useful for the determination of the nature of a state than its mass (eigenvalue). For example, the radiative decay rate is a sensitive tool to decide to which multiplet a given state belongs. As an example the radiative decay of the $\Lambda^{*}(1405)$ resonance is discussed later in greater detail.

An experimental program as outlined above will allow quantitative checks of the predictions of the Isgur-Karl-model. It is to be expected that the missing four states of the $[70, 1^{-}]$ multiplet (one quantum excitation) will be found ($\Lambda^{*}(3/2^{-}); \Sigma_{1}^{*}(1/2^{-}); \Sigma_{2}^{*}(1/2^{-}); \Sigma^{*}(3/2^{-})$) and the existence of the elusive $[70, 0^{+}]$, $[70, 2^{+}]$ and $[20, 1^{+}]$ will be settled.

Of highest importance is of course the question whether the predicted [7] baryonic hybrid states ($qqqg, \ldots$) exist. Their ground states should have masses below 2 GeV, a region which can be ideally investigated with the π/K beams of EHF. Here again, high intensity beams and a good detector enabling the reconstruction of complicated final states will be of importance.

The same is true for the study of the predicted Dibaryon resonances consisting of u, d and s quarks [10]. In contrast to multi-quark systems consisting only of u and d quarks, the addition of s quarks enhances the chance to form a dibaryon system because of the reduced Pauli blocking. A high quality experiment could even try to find states as exotic as $K^{*}\Delta$ and others of this kind [11].

4 π/K Beams

For hadron-spectroscopy experiments π^{-}/K^{-} beams in the momentum range 0.5 - 15 GeV/c are needed. The spectroscopy of non-exotic states would be mainly performed in the momentum region up to 4 GeV/c, while the production of exotic states might be favoured at higher energies (central collisions). The usable intensities of the beams are dictated by the tolerable rates in the detectors. For a 4π arrangement of high modularity using detectors with fast decay times (e.g. $BGO, BaF_{2}, \ldots$) and very fast triggers, an interaction rate in the target of 10^{6}/s, corresponding to about 10^{8} particles impinging on the target, appears to be an upper limit. In setups with smaller solid angles correspondingly higher rates could be digested. With the EHF π^{-} beams the maximum acceptable interaction rate can be easily achieved. For K^- beams, not only is intensity essential, but π or e contamination also matters. With double separation, K/π ratios of 1:1 can be reached with K^- intensities of about 10^6/s ($\sim 10^4$/s interactions in the target), thus easily allowing the use of sophisticated 4π detectors. In order to use the full performance of the detector, the π/K separation can be relaxed a little, so that $10^7 K^-$ together with $10^8 \pi^-$ impinge on the target, giving rise to about 10^6 interactions/s in total. The beams at EHF adapted to hadron-spectroscopy would be S6 and S20, offering good intensities and good particle separation in the relevant momentum region.

5 Detection system

Figure 1 outlines a sophisticated detection system for hadron-spectroscopy experiments to be used on EHF $\pi/K(\bar{p})$ beams. In order to make it as compact (i.e. cheap) as possible, a vertex detector with very high spatial resolution is used in a magnetic field of 1.5 Tesla, produced by a superconducting coil. When multiple scattering does not matter, a set of microstrip detectors ($\sigma_\perp \sim 5\mu$m) ($\sigma_\parallel \sim 50\mu$m) detectors can be used, in other cases a TPC. The relative momentum resolution at 200 MeV/c is assumed to be $\Delta p_\perp / p_\perp = 0.01$.

The identification of particle masses will be performed in Cherenkov counters, either of threshold or RICH-type, and by ToF in the forward hemisphere. The electromagnetic showers are detected in BGO modules (1200 total) with an energy resolution of $\Delta E/E(FWHM) = 2.5\%/\sqrt{E[GeV]}$ and an angular modularity of 3° (forward) and 6° (backward hemisphere), respectively. The (polarized) hydrogen/deuterium target has a length of 15 cm and a diameter of 5 cm. This detector arrangement fulfills the needs of a sophisticated spectroscopy experiment, i.e.:

- simultaneous detection of charged and neutral particles with $\Omega \approx 4\pi$
- good vertex resolution (important for K_S^0, Λ decays)
- mass identification of the particles via Cherenkov counters, ToF and dE/dx
- fast triggers for event selection using ToF, Cherenkov and multiplicity (BGO detector) information

K_L^0 and neutrons are not detected explicitly. They can easily be reconstructed by missing momentum analysis and can be verified by using the amply available kinematical constraints. This detector scheme is optimized for high energy beams. For lower momenta, a transverse magnetic field seems more appropriate. With similar but differently arranged detectors, the same performance can be achieved.

6 Monte Carlo Simulations of selected Reactions

To demonstrate the sensitivity for rare events on EHF K^- beams achievable with the detector discussed above, two elusive reactions have been selected:

(I) K^- (10 GeV/c) $p \rightarrow g_t(2300, 270)\Lambda;$
$g_t \rightarrow \phi\phi;$
$\Lambda \rightarrow p\pi^-;$
$\phi \rightarrow K^+K^-$

This reaction serves as an example of the search for glueball/hybrid states with exotic/non-exotic quantum numbers.

(II) K^- (4.2 GeV/c) $p \rightarrow \Sigma^+(1660)\pi^-;$
$\Sigma^+(1660) \rightarrow \Lambda(1405)\pi^+;$
$\Lambda(1405) \rightarrow \Lambda^o\gamma, \Sigma^o\gamma$

This reaction belongs to the field of Baryon spectroscopy. It aims at the investigation of the nature of the $\Lambda^*(1405)$ resonance. The rate of this rare radiative $\Lambda(1405)$ decay is essential for the determination of the quark content of the $\Lambda(1405)$ state, presently an open question.

For both simulations the properties of the detection system as described in Section 5 were taken. The rate estimates are based on $10^7 K^-$/s hitting the target (15 cm length). In all computer simulations shown, a 4C kinematical fit of measured energies and momenta was applied to optimize the resolution.

6.1 Meson-Spectroscopy: Search for rare exotic States

The process (I) $K^-p \rightarrow g_t(2300)\Lambda$ is very similar to the reaction $\pi^-(23\ \mathrm{GeV/c})p \rightarrow g_t n$ which was first investigated at BNL (MPS) [12]. Three broad states at masses of 2120, 2220 and 2360 MeV were found with a cross section of about 1 μbarn. The same cross section was assumed for (I) yielding a production and detection (4π) rate of 1 $g_t(2300)$ events/sec. The total K^-p cross section at 10 GeV/c is 30 mbarn, giving rise to 3×10^4 general background events/s. They can be easily reduced *via* a fast hardware trigger [12] by 2-3 orders of magnitude, so that all relevant events can be dumped on magnetic tapes or disc drives. In contrast to the π induced reaction, the off-set of the Λ vertex can be used as additional trigger condition here, thus cleaning up the spectra further. The most annoying background comes from the channel $K^-p \rightarrow \phi K^+K^-\Lambda$ (10 μbarn) which was also simulated and explicitly taken into account, giving rise to the small background in the Monte-Carlo-spectra.

The detector performance results in invariant $\phi(\rightarrow K^+K^-)$ mass resolutions as good as 5 MeV (FWHM). The invariant $\phi\phi$ mass distribution is shown in Figure 2. It is based on $3 \times 10^4 g_t$ events plus 3×10^5 background events, and thus corresponds to a measuring time of several hours. The broad $g_t(2300)$ peak is clearly seen above a small background. This case study clearly demonstrates the sensitivity of the setup for rare events. As the detector is equally powerful in the detection of charged and neutral particles, other decay channels of eventual resonant states X, like

$$X \rightarrow \eta\eta, \eta\eta', \eta\phi, \eta\omega$$

can be simultaneously detected. All these channels couple to exotic quantum number states, and are thus very well suited for their investigation.

The high statistics in Figure 2 demonstrates that processes with cross sections considerably smaller than 1 μbarn are detectable. In special cases cross sections smaller than 1 nbarn seem measurable in a reasonable time and with reasonable background.

Needless to say, that the corresponding measurements with π^- would be easily feasible at EHF under ideal conditions, the only limitation being given by the rate capability of the detector system. Thus, even lower values for the detection limits of rare events are realistic using π^- induced reactions.

6.2 Baryon Spectroscopy: Search for rare decay modes of baryon resonances

The study of decay rates of baryonic resonances will allow very clear statements about the question to which $SU(6) \times O(3)$ multiplets the resonance belongs, or even more generally about its quark content. As example the $\Lambda(1405) \rightarrow \Lambda^o(\Sigma^o)\gamma$ radiative decay has been chosen. As shown in a recently published bubble chamber experiment [9], the $\Lambda(1405)$ state can be very clearly produced in the reaction $K^-p \rightarrow \Sigma^+(1660)\pi^-$ (4.2 GeV/c) restricting the data sample to small momentum transfers ($t < 1$ (GeV/c)^2) between K^- and π^-. Thus with nearly 100% efficiency, $\Lambda(1405)$ states are produced via the decay $\Sigma^+(1660) \rightarrow \Lambda(1405)\pi^+$. For this production mechanism a cross-section of 100 μbarn was assumed. The radiative decay branching ratio was assumed to be 1%, resulting in $\sigma \times BR = 1\mu$barn for the process $K^-p \rightarrow \Sigma^+(1660)\pi^-; \Sigma^+(1660) \rightarrow \Lambda(1405)\pi^+; \Lambda(1405) \rightarrow \Lambda^o(\Sigma^o)\gamma$

With Λ^o decaying to $p\pi^-$ and Σ^o decaying to $\Lambda\gamma(\Lambda \rightarrow p\pi^-)$, respectively, the final states $p\pi^-\pi^+\pi^-\pi^o$ and $p\pi^-\pi^+\pi^-\pi^o\gamma$ have to be measured. With a detection efficiency of nearly 100% as discussed in Section 5, and for $10^7 K^-/s$ impinging on the target, 1 event/s would be produced. The total K^-p reaction rate ($\sigma_{tot} \sim 30$ mbarn) is again 3×10^4 events/s, which can easily be reduced to a manageable level.

Figures 3 and 4 show the invariant $\Lambda\gamma(= p\pi^-\gamma)$ and $\Sigma^o\gamma(= p\pi^-\gamma\gamma)$ mass spectra resulting from the Monte-Carlo simulation. They contain about 100 radiative decays each, available after 1 minute of measuring time.

The background comes from the reactions

$$K^-p \rightarrow \Lambda^o\pi^+\pi^-\pi^o \text{and}$$
$$K^-p \rightarrow \Sigma^o\pi^+\pi^-\pi^o$$

which occur with about 1 mbarn cross sections and were explicitly taken into account in the simulation.

This example shows again that radiative or other rare decay channels with cross sections considerably lower than 1 μbarn can easily be seen.

7 Summary

Substantial progress in Hadron spectroscopy can be made by combining the highly intense and pure kaon (pion) beams of EHF with a powerful multipurpose detector (electronic bubble chamber). A survey on some reactions of particular interest is given in Table 1. The main impact of EHF on hadron spectroscopy will be in the investigation of baryon resonances with the high quality K^- beams, where today's limitations are directly connected to the poor performance of the beams. Pion-induced reactions, which are of extreme relevance for meson/exotics spectroscopy, will profit mainly from the development of powerful detectors, allowing very sensitive searches for rare and complicated final states. A proton beam of 100 μA produces reasonably well separated K^- beams with intensities up to 10^7/sec, giving rise to 10^5 interactions in a compact Hydrogen target. This rate can be mastered even in a 4π detector arrangement, if detectors with short decay constants and fast trigger systems are provided.

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Table 1: Survey of Hadron Spectroscopy experiments

Reactions	Observables	Physics
$\pi^-(K^-)p \to Xn(\Lambda)$ $X \to \phi\phi, \eta\pi^o, \eta\eta, \eta\eta'$ (Fixed momentum: 4-15 GeV/c)	Invariant mass spectra J^P analysis of decay channels	Exotic meson-like states (glueballs, hybrids) Emphasis on exotic quantum numbers
	Formation experiments:	
$K^-p \to K^-p$ $\to K^0_S n$ $\to K^0_S \pi^- p$ . . . $K^-n \to K^-n$ (momentum scan)	$d\sigma/d\Omega$ Polarization parameters, Λ Tag, Decay modes	Higher mass Baryon Resonances with $S=-1,-2$ Multiplet structure of the Baryon resonances Quark content of Baryon states
	Production experiments:	
$K^-p \to Y^*\pi$ $Y^* \to Y\pi$	Decay properties of resonances Y with weak coupling to the $\bar{K}N$ channel	Quantitative check of the Isgur-Karl Model Search for baryonic hybrid states
$K^-p \to K^+\Xi^{*-}$ (fixed momentum)	Double strange resonances	
$K^{-3}He \to K^+nH$		Search for double strange Dibaryon states (H)

Hadron-Spectroscopy-Detector

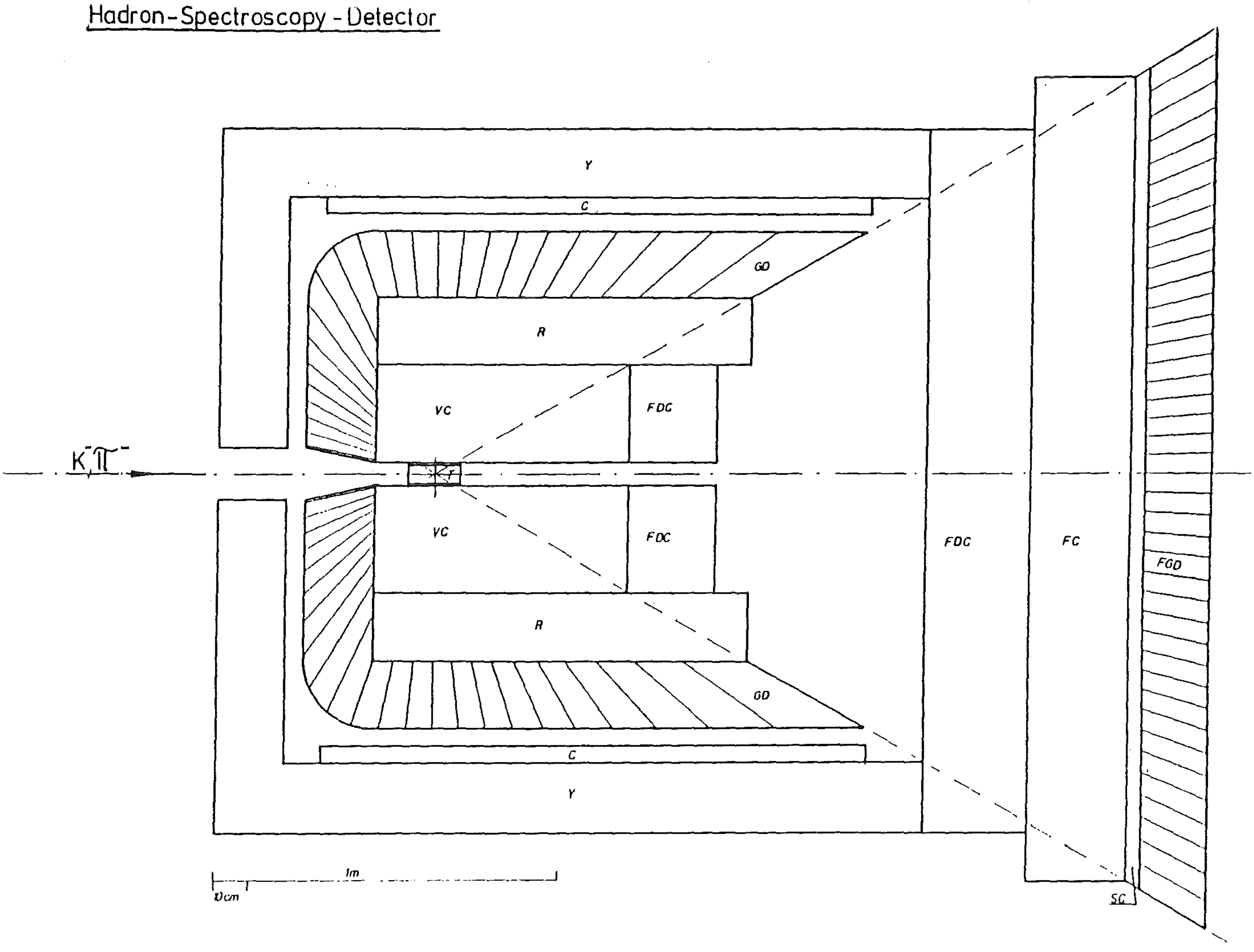

Figure 1: Sketch of a Hadron Spectroscopy Detector
T: Target; VC: Vertex chamber (Microstrip layers or TPC);
R: RICH Cherenkov; GD: Gamma detector (e.g. BGO);
FDC: Forward drift chamber; SC: Modular ToF scintillation counter;
C: Superconducting coil; Y: Fe Yoke;
FC: Forward Cherenkov; FGD: Forward γ detector.

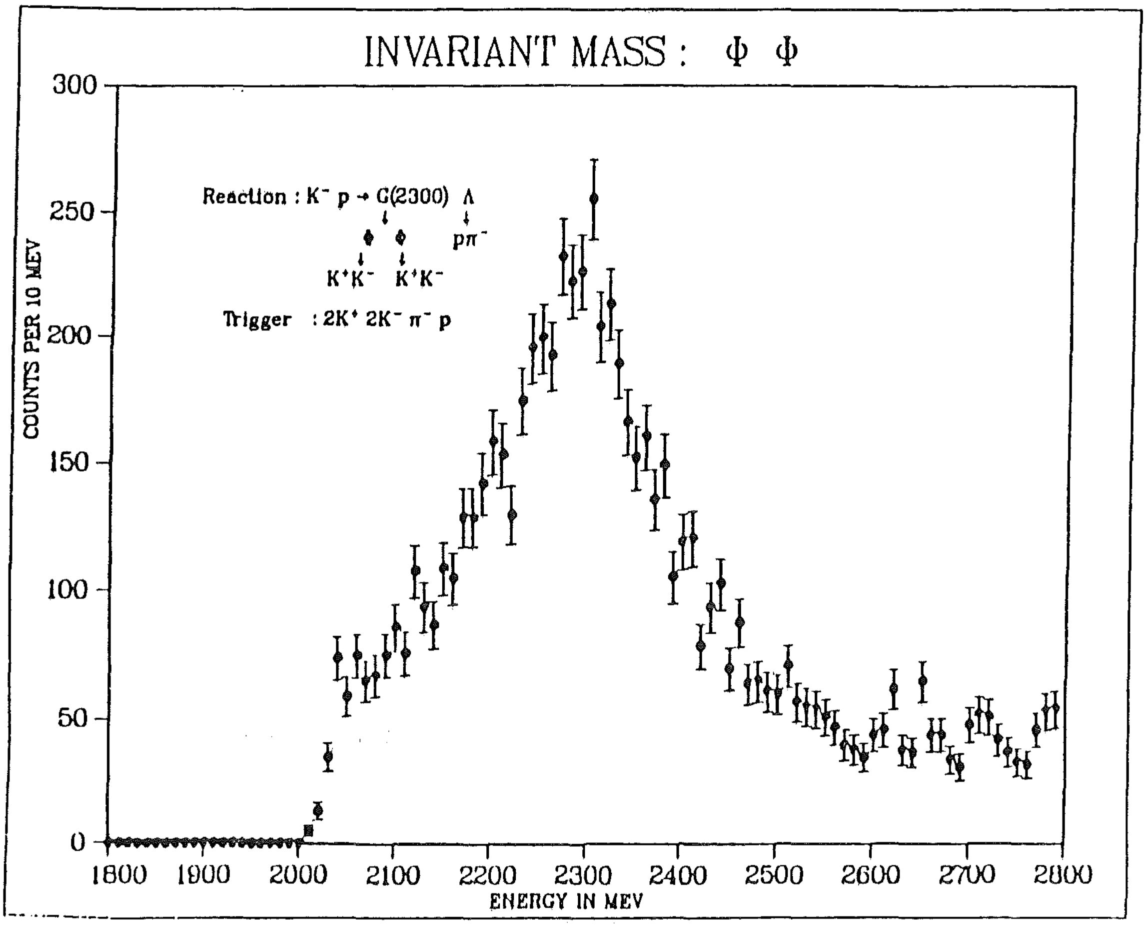

Figure 2: Monte-Carlo Simulation using the parameters of the detector in Figure 1.
Invariant mass plot of the resonant state $g_t(2300\ \mathrm{MeV})$ decaying into $\phi\phi(\phi \rightarrow K^+K^-)$. The state is produced via $K^-p \rightarrow g_t\Lambda$ at 10 GeV/c. As cross section 1 μ barn was assumed. The background is due to the process $K^-p \rightarrow \phi K^+K^-\Lambda(10\mu\mathrm{barn})$.

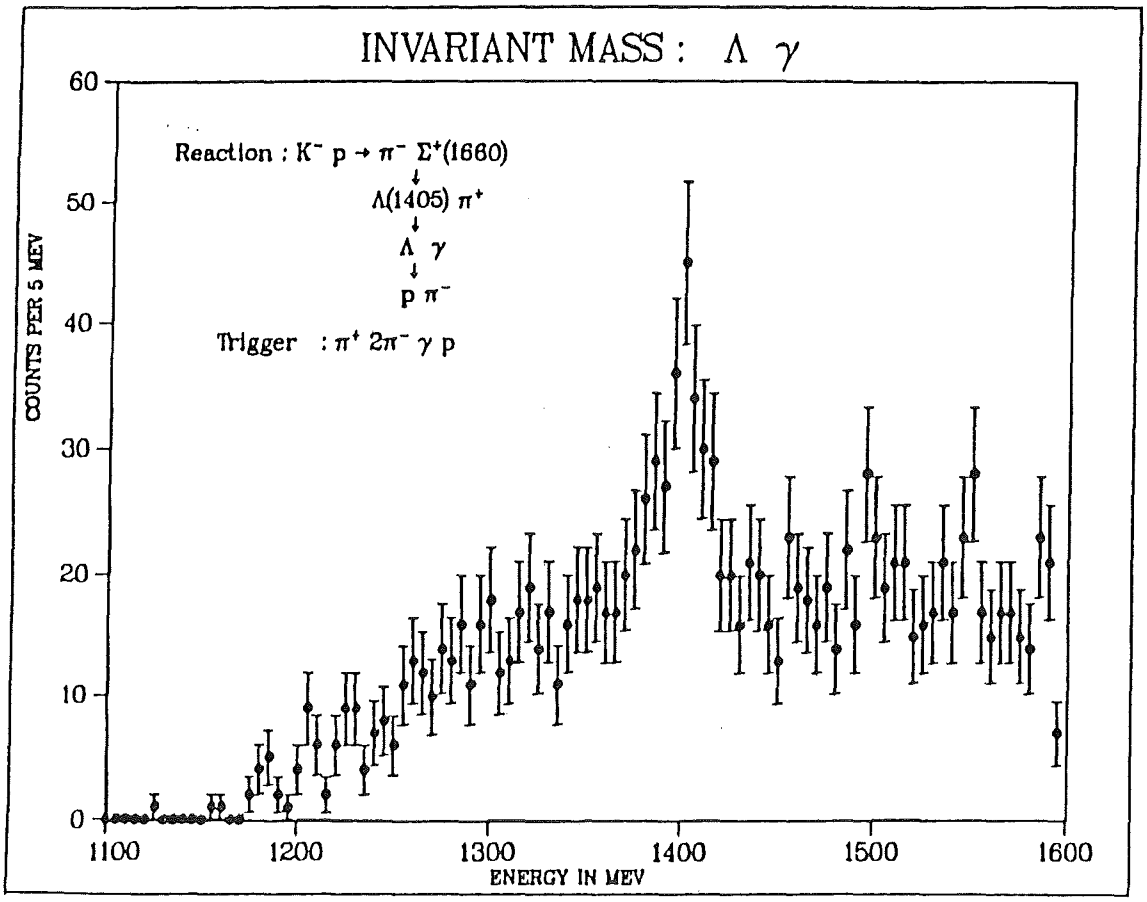

Figure 3: Monte-Carlo Simulation using the parameters of the detector in Figure 1.

Invariant mass plot of $\Lambda(1405)$ decaying radiatively into $\Lambda\gamma(\Lambda \rightarrow p\pi^-)$. $\Lambda(1405)$ is produced via $K^-p - \Sigma^+(1660)\pi^-$ at 4.2 GeV/c. For π^-/K^- momentum transfers smaller than 1 $(\mathrm{GeV/c})^2$, $\Sigma^+(1660)$ decays almost totally to $\Lambda(1405)\pi^+$. For the complete $\Lambda(1405)$ production process a cross section of 100 μbarn was assumed. The branching ratio for the radiative $\Lambda(1405)$ decay was assumed to be 1%. The background is due to the process $K^-p \rightarrow \Lambda^o(\Sigma^o)\pi^+\pi^-\pi^o$ (1 mbarn).

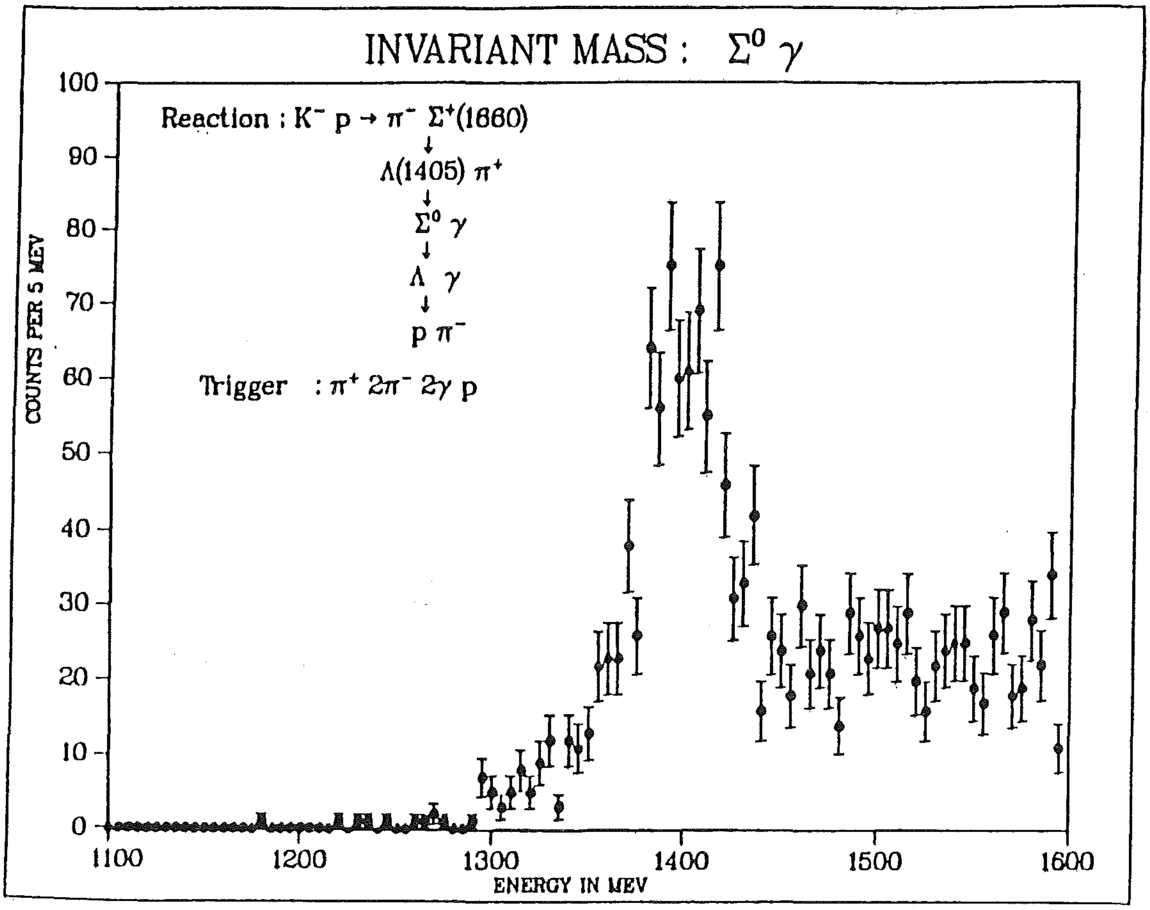

Figure 4: As Figure 3, but $\Lambda(1405) - \Sigma^o\gamma$