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NUCLEON-RESONANCE DECAY BY THE $K^0\Sigma^+$ CHANNEL NEAR THRESHOLD*

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For the combined setup of the Crystal Barrel and TAPS at ELSA in Bonn we have proposed to study the reaction $\gamma p \to K^0\Sigma^+$. The reaction is characterised by the final state of 6 photons and a forward emitted proton. Here we report on results of simulations to demonstrate the feasibility of the experiment. From the threshold behaviour of the cross section and angular distributions we aim to search for a $3^{\rm rd}$ S_{11} resonance just above the $K\Sigma$ threshold, which may mix with the two lower lying S_{11} resonances and thus provide an explanation for the unusually strong η branching of the $S_{11}(1535)$ resonance. The hyperon polarisation can be studied as a sensitive tool to determine the various resonance admixtures.

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1. Introduction

The spectrum of baryon excitations is not yet well described on basis of QCD. Theoretical studies of baryon resonances take into account the internal degrees of freedom of the flavour triplet of light u, d and s quarks. Models differ, however, in the treatment of the spatial dynamics which provides different modes of excitation. A stringent test of hadron models requires a systematic study of baryon excitations and their respective decay modes into the mass region of 1 GeV above the nucleon mass and beyond. Recent predictions in a quark-pair creation model [1] or a collective string-like three-quark model [2] revealed substantial decay branches into $K\Lambda$ and $K\Sigma$ final states. Kaon production experiments will be an important tool to establish or disprove "missing" resonances and thus to determine the relevant degrees of freedom of quark models. The observed η decay branches of S_{11} baryon resonances seem to find an explanation in mixing with other exotic

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resonances of pentaquark nature or with quasi-bound S_{11} states near the $K\Lambda$ or $K\Sigma$ threshold. The precise threshold behaviour of the $K^0\Sigma^+$ decay, accessible via the multiphoton-proton decay channel, in photoexcitation of the proton may provide a signature of an additional S_{11} resonance.

2. Photoproduction of η-mesons

The photoproduction of η-mesons in the second resonance region is completely dominated by the excitation of the $S_{11}(1535)$ nucleon resonance [3] which so far is the only known nucleon resonance with a strong branching into the $N\eta$-channel. The structure of the $S_{11}(1535)$ in terms of the quark model is still poorly understood. Alternatively, the $S_{11}(1535)$ resonance was treated as a quasi-bound $K\Sigma$-state [4] which may explain the large ηN branching, or as a quasi-bound $N\eta$ (penta-quark) state [2].

Of particular interest is the Q^2-dependence of the electromagnetic helicity coupling $A^p_{1/2}$. For an extended, molecular-like object one expects a much faster drop of the coupling with the momentum transfer than for a conventional three-quark resonance. The experimental values show a very flat Q^2-dependence [5] which is consistent with a three-quark nature. Therefore, if a quasibound $K\Sigma$-state exists, it should be strongly mixed with the three-quark configuration in order to explain the peculiar branching ratio. This requires a 3rd S_{11} resonance [6] near the two S_{11} resonances predicted by the quark model and near the $K\Sigma$ threshold. Although such a resonance has not been established, there is some evidence for an S_{11} resonance with mass 1712 MeV and width 184 MeV from a recent VPI analysis [7] of πN elastic scattering data. The partial wave analysis indicates [8] a much stronger coupling of this resonance to the $K\Sigma$ final state as compared to the nearby $S_{11}(1650)$ resonance, which only couples strongly to the πN final state. Similar to the $S_{11}(1535)$ resonance which lies just above the ηN threshold, the postulated $S_{11}(1710)$ resonance lies just above the $K\Sigma$ threshold (see Fig. 1).

The contribution from the 3rd S_{11} resonance is further enhanced by threshold effects. The leading Born terms are dominated by the contact term which is proportional to the charge of the photoproduced meson and thus vanishes in the $K^0\Sigma^+$ channel. Therefore the S-wave determines the threshold behaviour, similar to the η photoproduction in case of the $S_{11}(1535)$. Thus the $S_{11}(1710)$ resonance should be enhanced in $K^0\Sigma^+$ photoproduction. Systematic data in the threshold region are needed in order to establish such a resonance and can be achieved with the combination of Crystal Barrel and TAPS at ELSA [9]. In the future studies of the threshold behaviour may also become possible with the upgraded MAMI and the combination of Crystal Ball and TAPS [10].

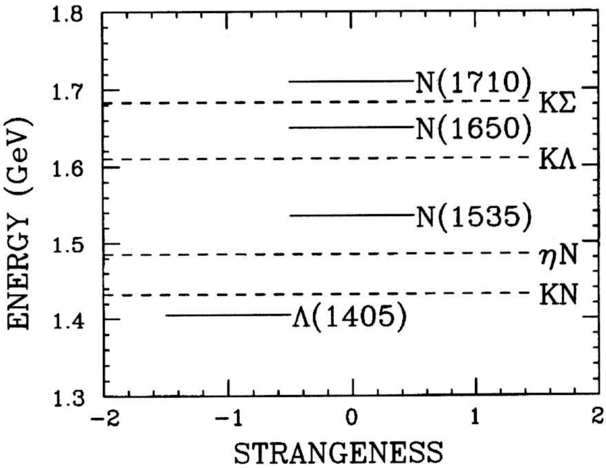

Fig. 1. Position of the S-wave nucleon resonances and the threshold energies for KN, ηN, $K\Lambda$ and $K\Sigma$ production. Figure from Ref. [6].

3. $K^0\Sigma^+$ photoproduction

The reaction $\gamma p \to K^0\Sigma^+$ was measured [11] with the SAPHIR detector at ELSA. A total of 405 events was accumulated in the photon energy range from threshold up to 1.55 GeV, which corresponds to ca. 200 MeV in center-of-mass energy (W) above threshold. In SAPHIR the decay modes $K_s^0 \to \pi^+\pi^-$ and $\Sigma^+ \to n\pi^+$ and $\Sigma^+ \to p\pi^0$ were studied. Events were completely reconstructed from the incident photon energy and the three charged particles in the final state. The data are shown in the lower left part of Fig. 2 (from Ref. [11] and [12]) and are a good basis for the event-rate estimate. This experiment improved considerably the quality of older data [13] which are indicated in the figure by the open circles. Fig. 2 also shows the data for the much better determined $K^+\Sigma^0$ channel and indicates the required quality for a study of the threshold behaviour. The data are compared with a tree-level approximation [12, 14] of the kaon photoproduction process. Earlier calculations included an overall hadronic form factor multiplied to the entire amplitude, which leads to violation of gauge invariance. The solid and dashed lines include the contact diagram in the Born terms in order to restore gauge invariance. Violation of unitarity is partly recovered by absorbing rescattering contributions in effective coupling constants. Guided by coupled channels results, a tree-level amplitude was constructed that simultaneously reproduces $K^+\Lambda$, $K^+\Sigma^0$ and $K^0\Sigma^+$ data. The model includes resonances that were found to give important contributions in coupled channels calculations. It is found that the reaction mechanism is resonance dominated in all isospin channels. The curves in Fig. 2 show

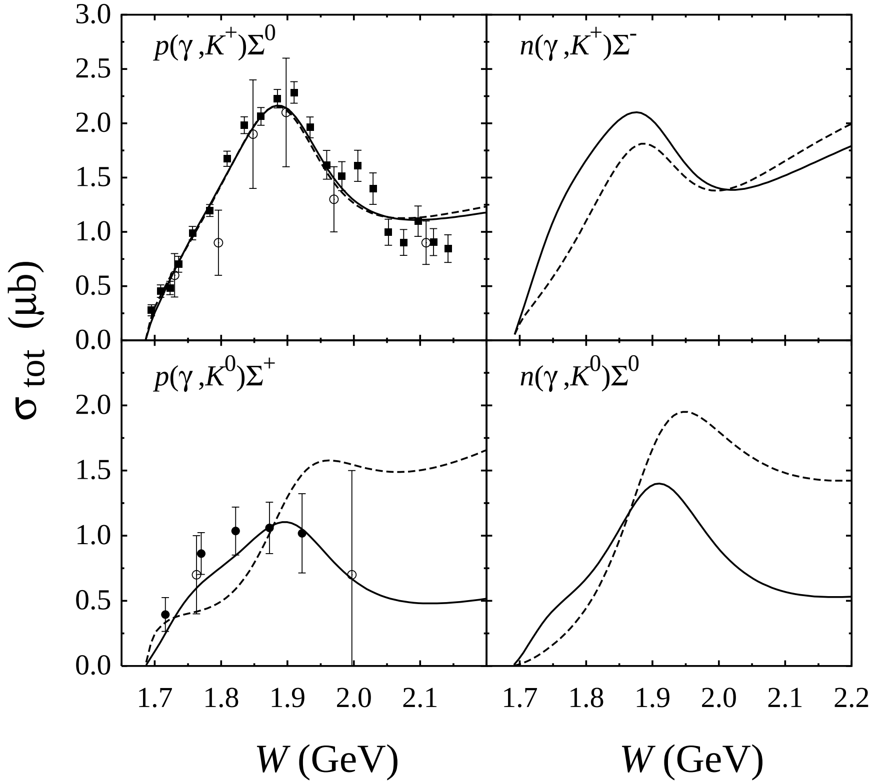

Fig. 2. Total cross section for $K\Sigma$ photoproduction (with the SAPHIR data [11] for $\gamma p \to K^0\Sigma^+$ on the lower right) as function of W. The curves show results from an isobar calculation with (solid) and without (dashed) inclusion of the $P_{13}(1720)$ resonance. Older data [13] are displayed by the open circles.

the calculations with (solid) and without (dashed) inclusion of the $P_{13}(1720)$ resonance. However, for a precise determination of the resonance contribution in the $K^0\Sigma^+$ channel, *e.g.*, to indicate a strong S-wave contribution by a steep rise at threshold, the data are not precise enough. For this purpose an excitation function is required with W-bins around 20 MeV and error bars below 5%, and corresponding angular distributions. This is the goal of the proposed experiment exploiting neutral decay modes. The K_s^0 decays with a BR of 31.4% into $\pi^0\pi^0$ and the Σ^+ decays with a BR of 51.6% into $\pi^0 p$. The reaction is thus characterized by the final state of 6 photons and a forward emitted proton with a total branching ratio of 15.6%.

4. Crystal Barrel and TAPS setup at ELSA

The combination of the Crystal Barrel detector (CB), consisting of 1380 CsI_2 crystals, and the TAPS photon spectrometer, consisting of 528 BaF_2 crystals, offers almost 4π acceptance (see Fig. 3) and excellent energy and position resolution for the final-state photons in the proposed reaction. TAPS will be placed in a wall configuration with hexagonal boundaries at forward angles covering the polar angle region from 5° to 30° at a distance of 1.2 m from the target center. The target, a 5 cm long liquid hydrogen cell, is surrounded by the SCIntillating FIbre inner detector (SCIFI), covering the solid angle of the CB. The SCIFI allows to correlate the measured position of charged particles with the corresponding cluster of detectors in the CB and it acts as veto counter for neutral particles.

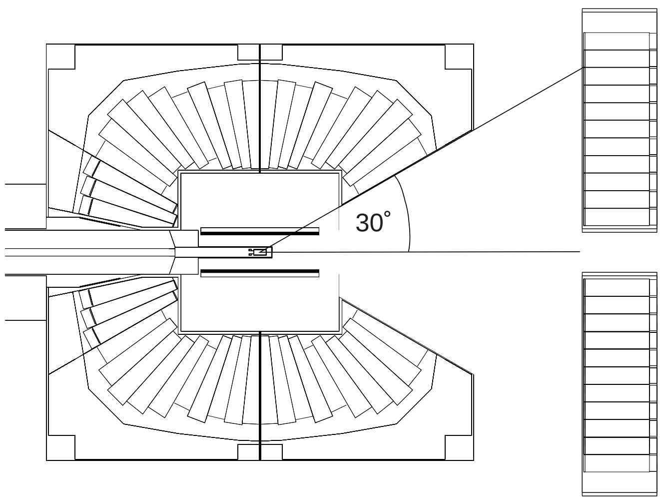

Fig. 3. Side view of Crystal Barrel and TAPS setup at ELSA. The Crystal Barrel is modified to leave on opening cone of 30° for the forward region to be covered by TAPS consisting out of 528 BaF_2 crystals in a wall at a distance of 1.2 m from the target center.

TAPS can identify charged particles online by the thin plastic CPV counters in front of each crystal and in addition offline by the pulse-shape analysis of the BaF_2 signals and the time of flight. Protons with kinetic energy above 400 MeV will cause significant leakage of shower energy. With a time resolution of 0.2 ns (σ) the kinetic energy up to 600 MeV can be recovered from the TOF information. In the results of simulations presented here, the kinetic energy of protons was derived from the summed energy of all six photons in the desired reaction observing energy conservation. The direction of protons was determined from the measured position in TAPS or the CB. This method is applicable in the full energy range.

5. Results from simulations

For various reactions data sets of 100 k events were generated and analysed according to the experimental conditions. Since both TAPS and the CB have been used extensively in previous experiments, their response is well known and incorporated accordingly. The geometrical acceptance is limited to polar angles from 5° to 30° for TAPS and from 30° to 170° for CB. Absorption of particles in the scattering chamber and the SCIFI has been taken into account by energy thresholds of 10 MeV and 50 MeV for photons and protons, respectively.

5.1. Detection efficiency

The reaction $\gamma p \to K^0 \Sigma^+$ has been simulated for fixed photon energies of 1.2, 2.0 and 2.5 GeV. For the final state population the phase space distribution was assumed which appears to be the most appropriate assumption near threshold and expecting an S or P wave contribution. The energy and angle distribution for photons and protons show that the high energy photons are mostly found in TAPS and that the reaction can be triggered by the appearance of a proton in TAPS. In 68% (26%) of the accepted events the proton and at least one photon (at least 2 photons) are detected in TAPS. This signature allows to set up a very efficient trigger in order to select desired events.

From the 6 photon four-momenta and the proton four-momentum as detected by TAPS and CB the final-state particles were subsequently reconstructed by analysing the invariant mass spectra for $\gamma\gamma$, $\pi^0\pi^0$, and $p\pi^0$ combinations. The Σ^+ hyperon, *e.g.*, can be reconstructed with a signal : background ratio of ca. 10:1. After subtracting the residual smooth combinatorial background we recover 55% of all simulated reactions. This number is composed out of a geometrical acceptance of 91% and a survival probability of 64% for the subsequent cuts.

5.2. Background

The final state signature of the desired reaction can be produced by various competing reaction channels which might thus contribute to the combinatorial background below the K_s^0 and Σ^+ mass peak. We have simulated the following channels which are expected to give the strongest contribution

(a) $\gamma p \to \eta p \to \pi^0\pi^0\pi^0 p \to 6\gamma\ p$
with a cross section of ca. 2 μb at 2 GeV and a branching ratio of 32.1%,

(b) $\gamma p \to \eta' p \to \pi^0\pi^0\eta p \to 6\gamma\ p$
with a cross section of ca. 1.2 μb at 2 GeV and a branching ratio of 8%.

As a worst case scenario we assume the excitation of high lying resonances; these may decay via $2\pi^0$ decay into a lower lying resonance which subsequently decays by π^0 emission to the proton; since we deal with broad resonances these reactions can be reasonably well simulated by the phase-space distribution of 3 π^0 in the final state:

(c) $\gamma p \to \pi^0\pi^0\pi^0 p \to 6\gamma\ p$
with a cross section below 1 μb at 1 GeV, *i.e.*, a factor of 2 larger than the expected cross section for $K\Sigma$, and a branching ratio of 96%.

Two cross section estimates for (c) were studied. From MAMI data at 800 MeV the difference between the inclusive cross section and individually determined channels was considered and corrected for the charged pion contributions [15]. Another estimate is based on recent ELSA data for the $\pi^0\pi^0\pi^0$ channel at 2.6 GeV electron energy and uses the fraction of data not stemming from the η channel [16]. Both estimates give an upper limit for the cross section of about 0.5 to 0.8 μb.

From reactions (a) and (b) only a few events survive the kinematical cuts so that at most 10 out of 100 k simulated events are detected. Considering the cross sections and branching ratios we estimate a background contribution of 0.2%. The worst contribution stems from reaction (c) where at 1.2 GeV photon energy still 16k events out of 100 k simulated events survive the selection criteria determined for the $K^0\Sigma^+$ case and give rise to a smooth combinatorial background. Considering the branching ratios and that the cross section for this reaction may be at most two times larger than for the desired reaction, we are left with a signal:background ratio of 1:2. The background due to reaction (c) decreases by a factor 2 with increasing photon energy from 1.2 to 2 GeV due to the wider phase space distribution. Thus at higher energy the signal:background ratio approaches 1:1.

The main trigger requires the tagger signal in coincidence with a charged particle either in TAPS or in the forward half of the SCIFI detector. We estimate an average trigger efficiency of 50% for selecting good events. The following results are determined on basis of 1000 hours of beam expected for this experiment during 2002 and applying realistic experimental and analysis conditions, *e.g.*, 50% analysis effeciency was used for the actual recovery of six photons in one event.

5.3. Cross sections and hyperon polarisation

The expected excitation function for $K\Sigma$ photoproduction is shown in Fig. 4 and compared to existing data. With a considerable improvement on the accuracy we can expect much higher sensitivity to resonance admixtures. The energy (W) dependence of the simulated data is taken according to the calculation shown in Fig. 2 by the solid curve.

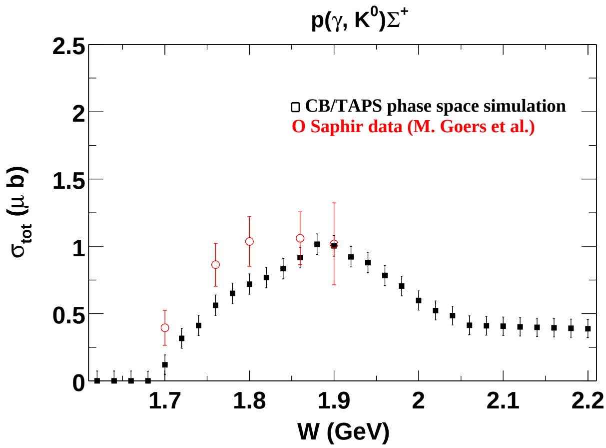

Fig. 4. Excitation function for $K\Sigma$ photoproduction with the SAPHIR data (open circles [11]) for $\gamma p \to K^0\Sigma^+$ as function of W. The filled squares indicate the results of this simulation with the expected accuracy.

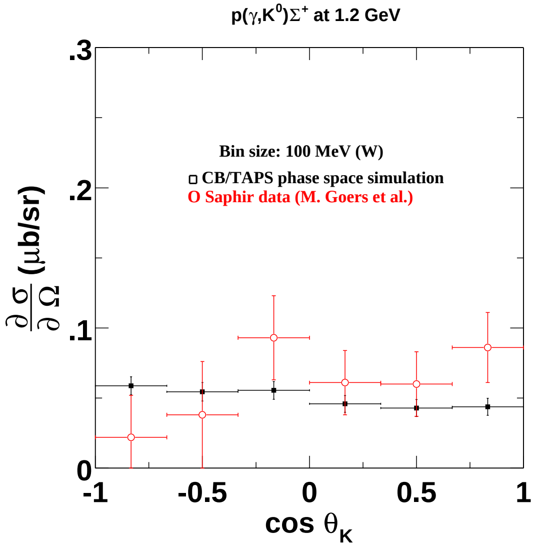

Fig. 5. Differential cross section for $K\Sigma$ photoproduction with the SAPHIR data (open circles) for $\gamma p \to K^0\Sigma^+$ as function of the cosine of the K^0 CM angle. The simulated data are shown by filled squares and calculated at similar energy and for the same W bin width of 100 MeV.

The results for the differential cross section are shown in Fig. 5. For the same binning in energy and kaon center-of-mass angle the error bars of the new data will be considerably smaller.

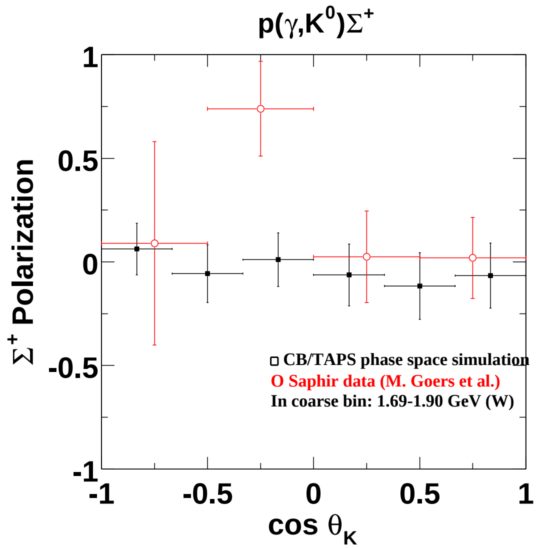

Fig. 6. Currently available Σ^+ polarisation data [11] (open sircles) as function of the cosine of the K^0 CM angle at an average CM energy of 1.8 GeV for an energy bin of 210 MeV. The filled squares show the simulated polarisation $P = 0$ of the Σ^+ as function of the cosine of the K^0 CM angle at the same energy and for the same W bin width of 210 MeV.

The expected accuracy of the results from the new measurement allows to shed a new light on the analysis of the recoil polarisation. Polarisation observables stem purely from resonance contributions and are therefore an important tool to study the resonance configuration. The presently available data in a coarse energy bin of 210 MeV are shown in Fig. 6 as a function of the K^0 CM angle. A comparison of these data with the model of [12] requires much higher accuracy in order to determine resonance contributions. Fig. 6 shows the quality of the data that can be achieved in the new experiment. A polarisation $P = 0$ was assumed and the error in 6 angle bins and for 60 MeV bins in W can be kept much below the presently available accuracy.

6. Conclusions

With the combined setup of the Crystal Barrel and TAPS at ELSA a number of neutral decay modes of nucleon resonances can be studied with high detection efficiency and precision. The analysis of the excitation function, differential cross sections and the hyperon polarisation of the $K^0\Sigma^+$ channel will provide valuable data for a coupled channels analysis of nucleon resonances above the $K\Sigma$ threshold. This investigation may lead to a better understanding of the properties of the $S_{11}(1535)$ resonance. First promising results on the detection of neutral decay modes have been obtained in commissioning experiments of the Crystal Barrel at ELSA. The clear identification of the $K^0\Sigma^+$ channel has been presented in another contribution [17] to this workshop.

REFERENCES

[1] S. Capstick, W. Roberts, *Phys. Rev.* **D58**, 074011 (1998).
[2] R. Bijker, F. Iachello, A. Leviatan, *Phys. Rev.* **D55**, 2862 (1997).
[3] B. Krusche *et al., Phys. Rev. Lett.* **74**, 3736 (1995).
[4] N. Kaiser, P.B. Siegel, W. Weise, *Phys. Lett.* **B362**, 23 (1995).
[5] P. Stoler, *Phys. Rev. Lett.* **66**, 1003 (1991).
[6] Z. Li, R. Workman, *Phys. Rev.* **C53**, R549 (1996).
[7] R.A. Arndt *et al., Phys. Rev.* **C52**, 2120 (1995).
[8] A. Waluyo *et al.*, `nucl-th/0008023.`
[9] H. Löhner *et al.*, accepted proposal ELSA/3-2001, 2001.
[10] R. Beck, H3-Treffen, Mainz, March 2000.
[11] S. Goers *et al., Phys. Lett.* **B464**, 331 (1999).
[12] T. Mart, *Phys. Rev.* **C62**, 038201 (2000).
[13] ABBHHM Collaboration, *Phys. Rev.* **188**, 2060 (1969).
[14] C. Bennhold *et al.*, `nucl-th/9901066.`
[15] B. Krusche, private communication.
[16] U. Thoma, private communication.
[17] J. Junkersfeld, *Acta Phys. Pol.* **B33**, 941 (2002).