Hyperon physics in NA48

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During 89 days of data taking in 2002, NA48/I collected a large sample of hyperon beta decays. The status and the prospects for the study of Ξ^0 beta decay will be shown. NA48 is studying hyperon radiative decays and some results recently published analyzing the data collected in a 1999 special run will be shown.

1. Introduction

After the successful study of direct CP violation[1] in $K^0 \to \pi\pi$ (1997-1999 and 2001 runs) the NA48 collaboration has started a new research program on K^0_S rare decays and neutral hyperons physics (NA48/I) with two periods of data taking in 2000 and 2002. In fact, the "so called" K^0_S target is a good source of hyperon particles, with fluxes sufficient to study rare decays. The triggers and the beam for these runs (mainly for the 2002 run) were set-up after the study of the data collected during two short test runs taken in 1999 and 2001.

From 1999 data we have also measured the BR and the decay asymmetry for the radiative decay $\Xi^0 \to \Lambda\gamma$. The results have been recently published and they are included on this paper.

I will first focus on the data of the 2002 run. In that year, after 89 days of data taking, NA48 was able to collect the largest world sample of Ξ^0 beta decays.

2. Experimental set-up

This section describes the experimental set-up for the 2002 run.

2.1. The beam

NA48/I was performed at the CERN SPS accelerator and it used a 400 GeV/c proton beam impinging on a Beryllium target to produce a beam of neutral long-lived particles (K^0, Λ, Ξ^0, n and γ). The charged particles were deflected with a sweeping magnet positioned immediately after the target.

The beam is similar to the one used for the ϵ'/ϵ data, but the K_L beam was stopped and magnetic bending, rather than crystal channeling, was used to maximize the intensity.

The duty cycle was 4.8 s out of a 16.2 s cycle time. The proton intensity was fairly constant during the spill with a mean of 5×10^{10} particles per pulse.

To reduce the number of photons in the neutral beam, primarily from π^0 decays, a platinum absorber 24 mm thick was placed in the beam between the target and the sweeping magnet.

In order to minimize the interactions of the neutral beam with air, the beam collimator was immediately followed by a ~90 m long evacuated tank containing the fiducial decay region. The detector was located downstream of this tank.

2.2. The detector

The experimental layout is described in detail elsewhere[2]. To detect charged particles the detector included a spectrometer (4 drift chambers and a dipole magnet) with a momentum resolution that can be parameterized as $\sigma_p/p = 0.48\% \oplus 0.015\% \times p$ where p is in GeV/c. The time for charged decays was measured by a hodoscope of fast scintillators with a time resolution on the single track of ~250 ps.

The neutral particles were detected by a liquid krypton electromagnetic calorimeter (LKr) having an energy resolution $\Delta E/E = 3.2\%\sqrt{E(\mathrm{GeV})} \oplus 90MeV/E \oplus 0.42\%$.

Further downstream were an iron-scintillator sandwich hadron calorimeter and muon counters.

Seven ring of scintillation counters were used to veto photons and other particles outside the acceptance region of the experiment as defined by the LKr calorimeter and the spectrometer.

3. The hyperon trigger

Special triggers have been dedicated to hyperon decays. We only study hyperon decays with at least two out-going charged particles, then at trigger level the main difficulty comes from kaon decays. In particular the decay $K_S \rightarrow \pi^+\pi^-$ was a huge background to be rejected. In 2002 the charged $\pi^+\pi^-$ trigger (used in the ϵ'/ϵ measurement) was instead used in veto. The effect of such a trigger are shown in Fig. 1.

For decays with a secondary Λ a two tracks vertex with an invariant mass compatible with the Λ mass was required (Λ trigger). The reconstructed Λ must have a large transverse momentum with respect to the beam axis in order to veto Λ's coming directly from the target.

For all other hyperon decays (such as Ξ^0 semileptonic decays) the request was to have the same Λ trigger in veto.

A cut on the momentum ratio of the two charged particles was also applied. The decays studied always have an out-going proton carrying out a considerable fraction of the primary hyperon energy. In the 2002 run the track with higher energy was required to have at least a momentum 3.5 times bigger than the momentum of the lower energy track. No condition was applied on the charge of the two tracks in order to include in the trigger also the decays of $\bar{\Xi}^0$ and $\bar{\Lambda}$.

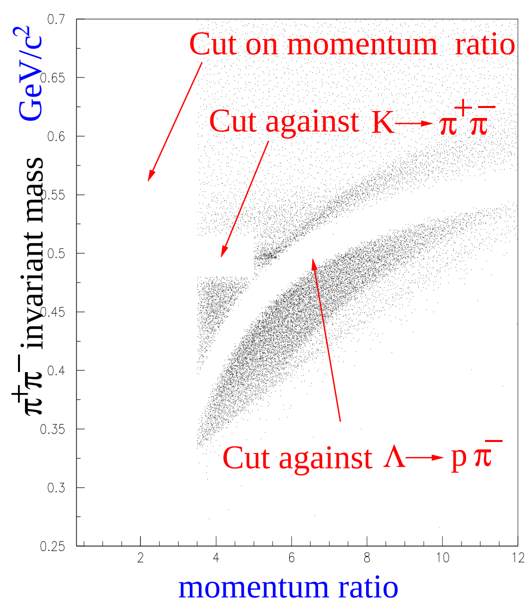

Figure 1. Momentum ratio between two tracks versus their invariant mass computed assuming the pion mass for the two tracks. The figure shows the effect of the 2002 charged hyperon trigger used for the events with two tracks.

4. Hyperon physics in NA48

Tab. 1 shows the rare hyperon decays that were accessible in the 2002 run and the present measurements of their branching ratios. About 5 millions events of the main decay mode $\Xi^0 \rightarrow \Lambda\pi^0$ have also been collected, with a trigger which was downscaled by a factor 4 during most of the run. Besides being useful for finding the number of Ξ^0 decaying in the fiducial region (normalization), they will allow measurements of mass, lifetime and of the production polarization.

Useful measurements can be also performed on $\bar{\Xi}^0$ and $\bar{\Lambda}$ in order to test CPT and to extract more informations on the polarization mechanism.

The measurements concerning Ξ^0 beta decay are described in more details below. Afterwards the new NA48 measurements on the decay $\Xi^0 \rightarrow \Lambda\gamma$ performed on the 1999 data will be described.

5. The Ξ^0 beta decay

From the experimental side, the Ξ^0 beta decay is interesting from many points of view. As other semileptonic hyperon decays it can provide information on the V_{us} element of the CKM matrix. The present measurements[3] are still limited by statistics, nevertheless this channel offers some experimental advantages. The possibility to reconstruct the mass of the outgoing Σ^+ hyperon via the decay $\Sigma^+ \to p\pi^0$ is enough to reduce the background substantially, since the 2 body decay with the same outgoing hyperon produced ($\Xi^0 \to \Sigma^+ \pi^-$) is kinetically forbidden.

Table 1
Rare hyperon decays accessible to NA48/I

Decay	BR	
$\Xi^0 \to \Sigma^+ e^- \bar{\nu}_e$	$(2.54 \pm 0.19) \times 10^{-4}$	[4]
$\Xi^0 \to \Sigma^+ \mu^- \bar{\nu}_\mu$	$(2.6^{+2.7}_{-1.7} \pm 0.6) \times 10^{-6}$	[5]
$\Lambda \to p e^- \bar{\nu}_e$	$(8.32 \pm 0.14) \times 10^{-4}$	[6]
$\Lambda \to p \mu^- \bar{\nu}_\mu$	$(1.57 \pm 0.35) \times 10^{-4}$	[6]
$\Xi^0 \to \Lambda e^+ e^-$		
$\Xi^0 \to \Lambda \gamma$	$(1.18 \pm 0.30) \times 10^{-3}$	[7]
$\Xi^0 \to \Sigma^0 \gamma$	$(3.33 \pm 0.10) \times 10^{-3}$	[7]
$\Xi^0 \to p\pi^-$ $(\Delta S = 2)$	$< 3.6 \times 10^{-5}$	[7]

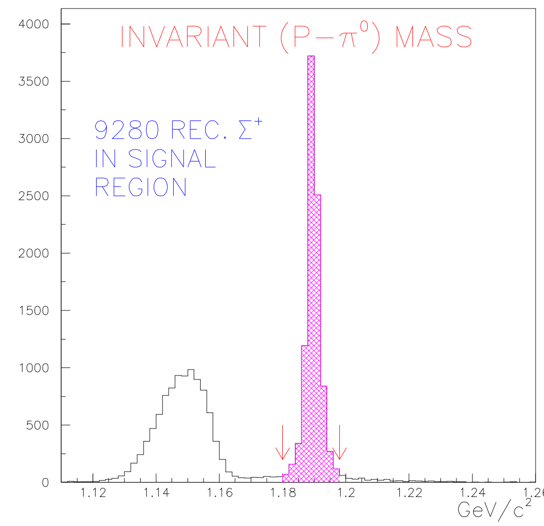

Figure 2. Distribution of π^0 invariant mass (preliminary). The peak in the region of Σ^+ mass (1.189 GeV/c^2) is the clear signature of Ξ^0 beta decay. The background on the left of the signal region is mainly due to the decay $\Xi^0 \to \Lambda\pi^0$ with a subsequent beta decay for the Λ.

From the theoretical point of view the Ξ^0 beta decay is important essentially for two reasons:

The first aspect is the fact that a more precise determination of the sine of the Cabibbo angle, the V_{us} element of CKM matrix, allows tighter constraints on the CKM unitarity.

One of the unitarity relations to be satisfied is the following:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \simeq |V_{ud}|^2 + |V_{us}|^2 = 1 \quad (1)$$

where the last approximation is explained by the current value measured for V_{ub}[8,9]: $|V_{ub}|^2 \sim 10^{-5}$.

Up to now V_{us} is measured from charged and neutral kaon beta decays, giving the following value[10]:

$$(V_{us})_{ke3} = 0.2200 \pm 0.0026$$

Asking for CKM unitarity we extract the following expected value for V_{ud}:

$$V_{ud}^U = 0.9755 \pm 0.0006$$

where the U indicates the unitarity hypothesis.

This is in disagreement, at the level of 2.2 standard deviation, with the value precisely measured from free neutron decay and nuclear decays[8,11]:

$$V_{ud} = 0.9738 \pm 0.0005$$

At this point the picture requires some clarification both from the theoretical and experimental point of view.

The agreement is slightly better if V_{us} is determined only from hyperon beta decays. Here averaging the main experimental results we obtain[12]:

$$(V_{us})_{Hyp} = 0.2250 \pm 0.0027$$

This value is substantially in agreement with both the set of measurements on kaon beta decays and on neutron beta decay, but the experimental and theoretical uncertainties are larger. In this context new data would be desirable.

The second aspect is the study of the form factors appearing in the decay amplitudes of the decay. Here a search for SU(3) breaking effects can be made and useful information on the mechanism of the possible breaking can be extracted.

Up to now there is only one result on the form factors for the Ξ^0 beta decay [13]. That measurement gives the value of the ratio between g_1, the axial-vector form factor and f_1, the vector form factor. The result doesn't show SU(3) breaking effects, since the ratio is compatible with the one measured in neutron beta decay. Indeed here more precise results are also useful.

In the 2002 run NA48 has collected the largest world sample of Ξ^0 beta decay events.

The photons coming from the π^0 decay are detected by the LKr calorimeter; after coupling this information with the tracks detected in the the Σ^+ decay vertex (position and 4-momentum) can be fully reconstructed and the position of the primary vertex corresponding to the Ξ^0 beta decay can also be determined.

After a preliminary analysis, using all the data collected in our 2002 run, we find about 9 thousands Ξ^0 beta decays. The background is estimated to be around 3%. The statistics is more than a factor 10 larger with respect to the other existing samples for the same decay. The invariant mass distribution is shown in Fig. 2.

The statistics power of the 2002 run is emphasized in Fig. 3 which shows the data collected for the Ξ^0 semileptonic decay with an outgoing muon. After the background subtraction about 100 events are extracted. This sample shows a remarkably clear evidence for the decay $\Xi^0 \to \Sigma^+ \mu^- \bar{\nu}_\mu$.

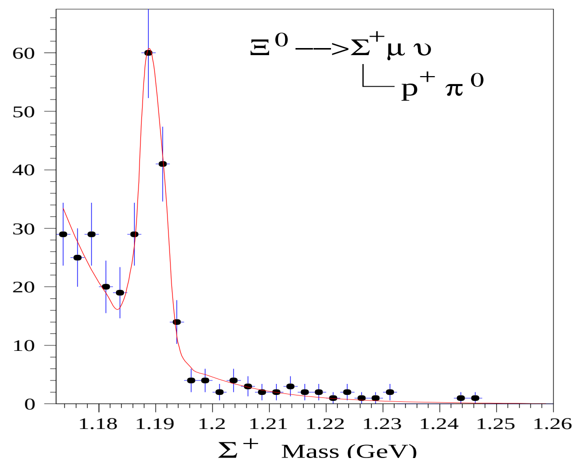

Figure 3. invariant p-π^0 mass for the decay $\Xi^0 \to \Sigma^+ \mu^- \bar{\nu}_\mu$

6. Ξ^0 radiative decays

The $\Xi^0 \to \Lambda\gamma$ decay asymmetry plays an important role in solving a long standing discrepancy between the Hara theorem[14] and the observed decay asymmetries of weak radiative hyperon decays (see [15,16] on this argument). The Hara theorem states that the parity violating amplitude of weak radiative hyperon decays vanishes in the SU(3) limit. Accordingly, the decay asymmetries will vanish in this case. Introducing weak breaking of SU(3) symmetry one expects to observe small decay asymmetries. In contrast to this, a large negative decay asymmetry in the weak radiative decay $\Sigma^+ \to p\gamma$ was measured[17]. To address this observation, models were developed which tried to obtain large decay asymmetries in spite of weak SU(3) breaking. One category consists of pole models, which satisfy the Hara theorem by construction, and approaches based on chiral perturbation theory [18–20]. They predict negative decay asymmetries for all weak radiative hyperon decays. Vector meson dominance models and calculations based on the quark model on the other hand violate the Hara theorem[21,22]. This second group of models favors a positive decay asymmetry for the channel $\Xi^0 \to \Lambda\gamma$. Therefore, this decay plays a crucial role in differentiating between the groups of models. The only previous measurement[23] of the $\Xi^0 \to \Lambda\gamma$ decay asymmetry was not able to make the distinction.

In 2004 the NA48 collaboration has published[24] a new measurement based on data from a special two-day run period in 1999

This 1999 test run was different from the 2002 run for the energy of proton beam, which was 450 GeV/c, for a beam intensity of 5×10^9 proton per spill and for the absence of the absorber. The trigger was also different: in the 1999 special run only one hyperon trigger was used and it was downscaled by a factor 5. This trigger included only the $K^0 \to \pi^+\pi^-$ condition in veto and no restriction for the Λ reconstruction.

After the selection of the Ξ^0 mass 730 $\Xi^0 \to \Lambda\gamma$ candidates were reconstructed within ± 7.8 MeV/c^2 (3 standard deviations). The $\Lambda\gamma$ invariant mass distribution is shown in Fig.4.

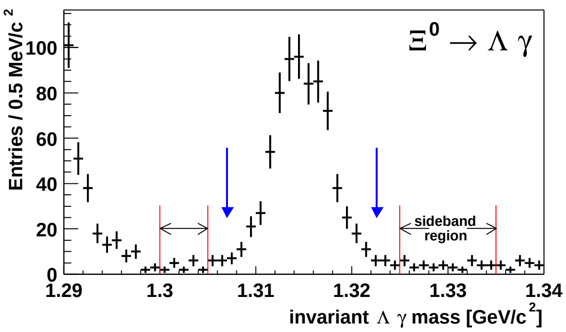

Figure 4. Distribution of the Λ-γ invariant mass for $\Xi^0 \to \Lambda\gamma$ decays. The signal region is indicated by the vertical arrows. Also shown are the side-band regions used for the background subtraction. The sharp increase of events below 1.3 GeV/c^2 is due to $\Xi^0 \to \Lambda\pi^0$ events with a lost photon.

For the asymmetry measurement we exploit the well-known decay asymmetry of the $\Lambda \to p\pi^-$ decay. The hyperons are longitudinally polarized by the parent process $\Xi^0 \to \Lambda\gamma$ with a polarization of $\alpha(\Xi^0 \to \Lambda\gamma)$ in their rest frame. Effectively, one measures the distribution of the angle Θ_Λ between the incoming Ξ^0 (corresponding to the outgoing Λ direction in the Ξ^0 rest frame) and the outgoing proton in the Λ rest frame (see Fig. 5):

$$\frac{dN}{d\ cos\Theta_\Lambda} = N_0[1 - \alpha(\Lambda \to p\pi^-)\alpha(\Xi^0 \to \Lambda\gamma)cos\Theta_\Lambda] \quad (2)$$

In this way the Λ is polarized by the Ξ^0 decay and analyzed by its own decay into $p\pi^-$.

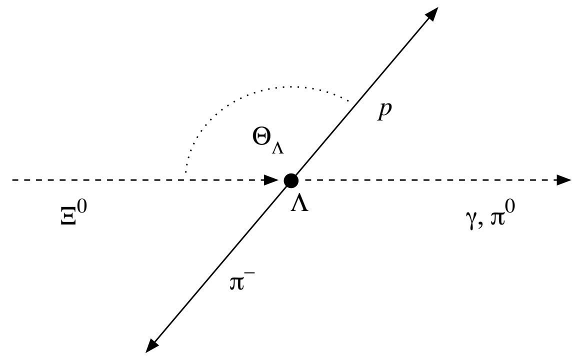

Figure 5. The decay angle Θ_Λ in the Λ rest frame.

Fig. 6a shows the cosΘ_Λ distributions for all $\Xi^0 \to \Lambda\gamma$ candidates and for the properly scaled side-band events compared to the isotropic Monte Carlo simulation.

The ratio of data over Monte Carlo corrects for the detector acceptance. To account for the background contamination, an effective asymmetry α_{bkg} of the background was determined by fitting the side-band events. The ratio of background-corrected signal over Monte Carlo is shown in Fig. 6b. A fit with N_0 and the asymmetry $\alpha(\Lambda \to p\pi^-)\alpha(\Xi^0 \to \Lambda\gamma)$ was performed in the range -0.8< cosΘ_Λ<1, where both data and MC statistics are large.

Using the measured $\alpha(\Lambda \to p\pi^-)$ value from the PDG, the final results for the $\Xi^0 \to \Lambda\gamma$ asymmetry is:

$$\alpha(\Xi^0 \to \Lambda\gamma) = -0.78 \pm 0.18_{stat.} \pm 0.06_{syst.} \quad (3)$$

where the largest systematic uncertainties come from the effective asymmetry of the background and the background normalization.

This is the first clear evidence for a negative decay asymmetry in this channel. The result clearly prefers models consistent with the pole models satisfying Hara theorem, while it cannot be easily explained by the quark or vector meson dominance models.

In addition to the decay asymmetry, the branching fraction of the $\Xi^0 \to \Lambda\gamma$ decay is also

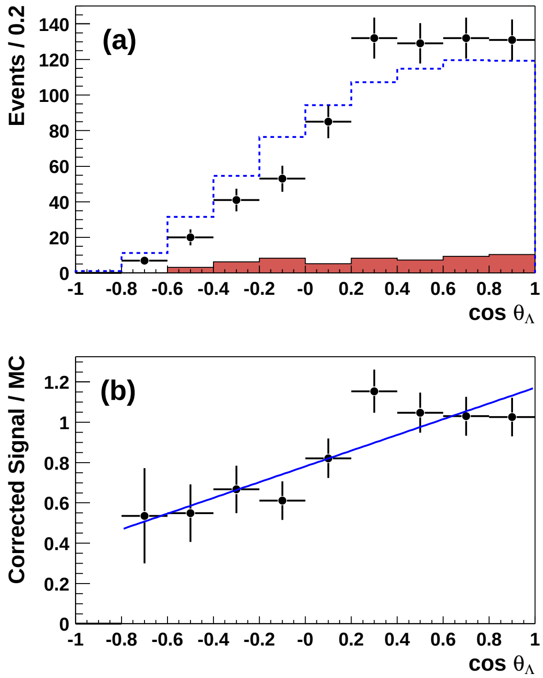

Figure 6. The $\Xi^0 \to \Lambda\gamma$:(a) $\cos\Theta_\Lambda$ distributions of signal candidates (crosses), scaled side-bands event (shaded), and isotropic Monte Carlo events (dashed). (b) Ratio of background-corrected signal candidates over isotropic Monte Carlo simulation. The line shows the result of the fit.

measured:

$$BR(\Xi^0 \to \Lambda\gamma) = (1.16 \pm 0.05_{stat.} \pm 0.06_{syst.}) \times 10^{-3} \quad (4)$$

which is the most precise measurement of this decay rate so far.

For this measurement we use $\Xi^0 \to \Lambda\pi^0$ as normalization channel. The systematic error is dominated by the uncertainty on the decay asymmetry.

The analysis of the 2002 data is ongoing and we expect to significantly increase the event sample size for this decay.

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