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Search for the exotic $\Xi^{--}(1860)$ resonance in 340 GeV/c Σ^--nucleus interactions

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We report on a high statistics search for the $\Xi^{--}(1860)$ resonance in Σ^--nucleus collisions at 340 GeV/c. No evidence for this resonance is found in our data sample which contains 676000 Ξ^- candidates above background. For the decay channel $\Xi^{--}(1860)\to\Xi^-\pi^-$ and the kinematic range $0.15 < x_F < 0.9$ we find a 3σ upper limit for the production cross section of 3.1 and 3.5 μb per nucleon for reactions with carbon and copper, respectively.

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At present eleven experimental groups have reported evidence for a narrow baryonic resonance in the KN channel at a mass of about 1530 MeV/c^2 [1–11] (for an updated list of references, see Ref. [12]). Based on previous predictions [13] (for some earlier references, see Ref. [14]) this resonance was interpreted as a pentaquark state. However, doubts have been raised because of possible experimental artefacts [15,16] and, furthermore, interpretations in terms of more conventional processes are under discussion [17–20] (see however, Ref. [21]). A common drawback of the individual observations is the limited statistics and hence e.g. the need to apply Poisson statistics when evaluating the observability of a phenomenon [22].

The interpretation of the observed peaks in terms of a

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five-quark state was significantly strengthened by the subsequent observation of another member of the anticipated antidecuplet of pentaquarks. Based on 1640 Ξ^- candidates produced in $p+p$ interactions at 160 GeV/c beam momentum, both in the $\Xi^-\pi^+$ and the $\Xi^-\pi^-$ channels narrow peak structures at an invariant mass of 1.860 GeV/c^2 were observed by the NA49 collaboration [23]. Possible signals of a Ξ^* resonance at 1.860 GeV/c^2 decaying into $\Xi^-\pi^+$ and $Y\overline{K}$ were reported already in 1977 for K^-p interactions at 2.87 GeV/c [24]. However, no corresponding signals have been seen in other K^- induced reactions (for a compilation and a discussion of these data see Ref. [25]). Searches for the $\Xi(1860)$ resonances by the HERA-B [26], ZEUS [27], CDF [28], ALEPH [28], BABAR [29], and E690 [30] collaborations are presently ongoing, but no final results are available so far.

It is indisputable that further high-statistics experiment are needed to establish the observed resonances beyond any doubt and to determine the quantum numbers of these states if they exist. Moreover, the observation (or nonobservation) of these resonances in different reactions may help to shed some light on the production mechanism and possibly also on the internal structure of these exotic states.

The hyperon beam experiment WA89 had the primary goal to study charmed particles and their decays. At the same time it collected a high statistics data sample of hyperons and hyperon resonances [31–37]. Here we present a search for the $S=-2$ resonance in Σ^- induced reactions on C and Cu at 340 GeV/c. We also include interactions in the tracking detectors (silicon detectors and plastic scintillator) located close to these targets.

The hyperon beamline [38] selected Σ^- hyperons with a mean momentum of 340 GeV/c and a momentum spread of $\sigma(p)/p=9\%$. Although the actual π^- to Σ^- ratio of the beam was about 2.3, high-momentum pions were strongly suppressed at the trigger level by a set of transition radiation detectors [39] resulting in a remaining pion contamination of about 12%. In addition the beam contained small admixtures of K^- (2.1%) and Ξ^- (1.3%) [31]. The trajectories of incoming and outgoing particles were measured in silicon microstrip detectors upstream and downstream of the target. The experimental target itself consisted of one copper slab with a thickness of 0.025 λ_I in beam direction, followed by three carbon (diamond powder) slabs of 0.008 λ_I each, where λ_I is the interaction length.

The momenta of the decay particles were measured in a magnetic spectrometer equipped with MWPCs and drift chambers. In order to allow hyperons and K_S^0 emerging from the target to decay in front of the magnet the target was placed 13.6 m upstream of the center of the spectrometer magnet. The apparatus also comprised a ring-imaging Cherenkov detector, a lead glass electromagnetic calorimeter and an lead/scintillator hadron calorimeter, which were not used in this analysis.

The Ξ^- were reconstructed in the decay chain $\Xi^- \to \Lambda\pi^- \to p\pi^-\pi^-$. The invariant mass distributions of the Ξ^- candidates are shown Fig. 1 for two regions of the total momentum of the $\Lambda\pi$ pair. The cut at 80 GeV/c corresponds to an x_F value of about 0.25 (see below). In our data sample the

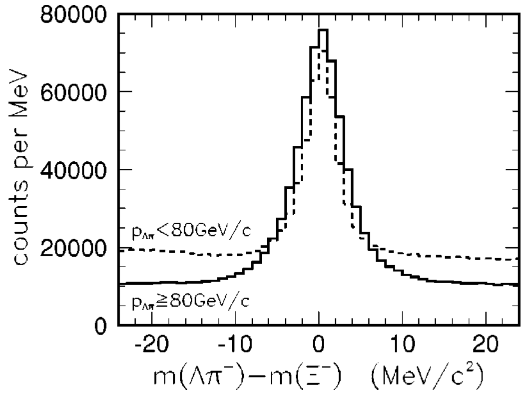

FIG. 1. Invariant mass distributions of $\Lambda\pi^-$ pairs with $p_{\Lambda\pi}<80$ GeV/c (solid histogram) and <80 GeV/c (dashed histogram) in 340 GeV/c Σ^- induced interactions.

central peak-to-background ratio varies between about 4 at small momenta and 8 at larger momenta. The rms-width of the Ξ^- peak can be approximated by the relation $\sigma = \sqrt{3.5\ \mathrm{MeV}^2/c^4 + 2.2\cdot 10^{-10} p_\Xi^2/c^2}$, where p_Ξ denotes the total momentum of the $\Lambda\pi$ pair. Ξ^- candidates within a $\pm 2\sigma$ window around the nominal Ξ^- mass were used in the further analysis. The present analysis is based on a total of 676k Ξ^- candidates observed over a background of 170k $p\pi^-\pi^-$ combinations [40]. Out of these candidates 240k, 281k and 155k can be attributed to the C, Cu, and "Si+C+H" target, respectively.

Because of the strangeness content of the Σ^- beam the cross sections for Ξ resonances are shifted towards large x_F with respect to the Σ^--nucleon cm-system [33]. Since in the WA89 setup the efficiency drops significantly at $x_F<0.1$ the yield of Ξ^- peaks at $x_F\approx 0.2$ (upper histogram in Fig. 2). $\Xi^-\pi^-$ pairs within the mass range of 1.82–1.90 GeV/c^2 are shifted to even larger x_F (lower histogram in Fig. 2). In both cases background was subtracted by means of two 2σ wide sidebands located at $[-24\ \mathrm{MeV}/c^2, 24\ \mathrm{MeV}/c^2+2\sigma]$ and $[24\ \mathrm{MeV}/c^2-2\sigma, 24\ \mathrm{MeV}/c^2]$ (cf. Fig. 1). For comparison, the Ξ^- events observed by NA49 are distributed over an x_F range between -0.25 and $+0.25$ [41].

Figure 3 shows the invariant mass spectrum of all ob-

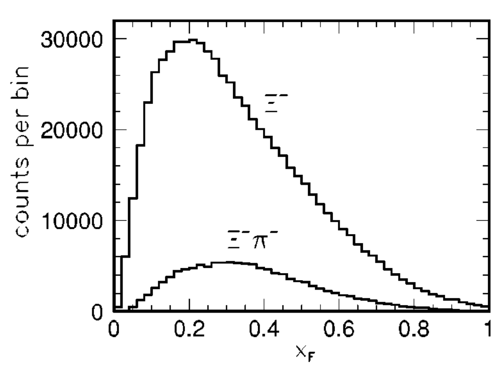

FIG. 2. Upper histogram: x_F distribution of the observed Ξ^- events within a $\pm 2\sigma$ mass window. Lower histogram: x_F distribution of the observed $\Xi^-\pi^-$ pairs within the mass range between 1.82 and 1.90 GeV/c^2. In both cases the background has been subtracted by means of sideband events.

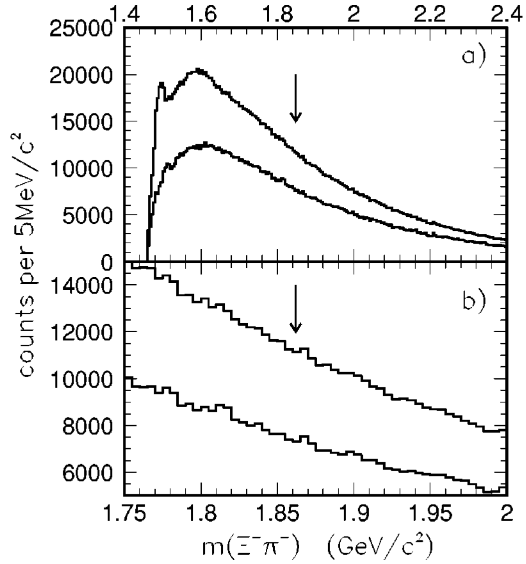

FIG. 3. Effective mass distribution of $\Xi^-\pi^-$ combinations of all reactions, including also reactions in the tracking detectors (Si+C+H) close to the C and Cu targets. Part (b) shows an extended view of the region around 1.862 GeV/c^2 marked by the arrows. Note the offset of the y-axis in this panel. In each panel the lower histogram shows the distribution after background subtraction via sidebands.

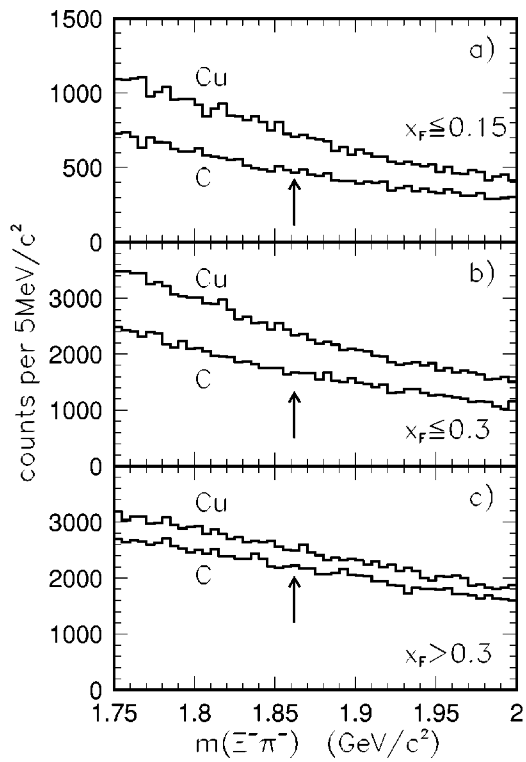

FIG. 4. Effective mass distribution of $\Xi^-\pi^-$ combinations with $x_F(\Xi^-\pi^-)\leqslant 0.15$ (a), $x_F(\Xi^-\pi^-)\leqslant 0.3$ (b), and $x_F(\Xi^-\pi^-)>0.3$ (c). In each plot the lower and upper histogram correspond to the carbon and copper target, respectively.

served $\Xi^-\pi^-$ pairs. Figure 3(b) shows an extended view of the region around a mass of 1.862 GeV/c^2 marked by the arrows. All reactions, including also interactions in the tracking detectors close to the C and Cu targets, contribute to this figure. The structure observed at around 1.5 GeV/c^2 in the upper histogram of Fig. 3(a) is caused by events where the negative pion from the decay of the Ξ^- was wrongly reconstructed as a double track. As can be seen from the lower histogram in Fig. 3(a), these fake pairs are reduced substantially by subtracting background from Ξ^- sideband events.

The NA49 collaboration has observed a ratio of Ξ^{--} to Ξ^- candidates of about 1/140. If we assume the same *relative* production cross sections over the full kinematic range for the reaction in question and similar *relative* detection efficiencies $[\varepsilon(\Xi^{--})/\varepsilon(\Xi^-)]_{WA89} \approx [\varepsilon(\Xi^{--})/\varepsilon(\Xi^-)]_{NA49}$ we would expect of the order of 17000 $\Xi^{--}\to\Xi^-+\pi^-$ events in our full data sample. The FWHM of the peaks observed by NA49 is 17 MeV/c^2 and is limited by the experimental resolution. Since in our experiment the resolution is expected to be slightly smaller $\approx$10 MeV/c^2 (FWHM), this excess should be concentrated in less than 6 channels in Fig. 3(b). Obviously, no such enhancement can be seen in the spectra. Fitting for example a second order polynomial to the lower distribution in Fig. 3(b) gave a chi-square per degree of freedom of $\chi^2/n = 56/47$.

The $\Xi(1860)$ events observed by NA49 are concentrated at small x_F. For a better comparison with the NA49 experiment we therefore scanned our data for different ranges of x_F. Figure 4 shows the effective mass distributions of $\Xi^-\pi^-$ combinations with $x_F(\Xi^-\pi^-)\leqslant 0.15$, $\leqslant 0.3$ and >0.3 in the region around 1.862 GeV/c^2. In each panel, the upper and lower histograms correspond to reactions with the carbon and copper target, respectively. No background subtraction was applied to these spectra. Assuming again a Ξ^{--} to Ξ^- ratio of 1/40 as observed by NA49 and considering now only the x_F range between 0 and 0.15, we estimate that approximately 700 and 900 $\Xi^{--}\to\Xi^-\pi^-$ events should be seen in Fig. 4(a) for the C and Cu target, respectively. None of these spectra shows evidence for a statistically significant signal around 1.862 GeV/c^2, nor does such a signal appear in any other subsample.

Upper limits on the production cross sections were estimated separately for the copper and carbon targets, in five bins of x_F between $x_F=0.15$ and $x_F=0.9$. For this purpose, we calculated limits, $n_{\max}$, on the number of $\Xi^{--}(1860)\to\Xi^-+\pi^-$ decays as follows: Based on the claimed experimental width of the $\Xi^{--}(1860)$ of <17 MeV/c^2 FWHM [23], we calculated $n_{\max}$ from the observed number of $\Xi^-\pi^-$ combinations, n_i, inside three mass windows of 20 MeV/c^2 width, centered at 1850, 1860, and 1870 MeV/c^2, resp., for $i=1,2,3$. From a fit to the observed $\Xi^-\pi^-$ mass spectrum between 1700 and 2000 MeV/c^2 (excluding the presumed signal region), we calculated the nonresonant backgrounds b_i in each bin. The 3σ limits were then obtained by the formula $n_{\max}=\max_{i=1,2,3}\{\max(0,n_i-b_i)+3\sqrt{b_i}\}$ and are listed in column 3 of Table I. From these numbers we derived the upper limits on the product of BR, the decay branching ratio, and the differential production cross sections $d\sigma/dx_F$ *per nucleus* given in column 4 of Table I. Assuming a dependence of the cross section on the mass number as $\sigma_{\text{nucl}}\propto\sigma_0\cdot A^{2/3}$, where σ_0 is the cross section *per nucleon*, we finally obtained the

TABLE I. 3σ limits n_{max} for the number of events and the corresponding limits on the differential cross section for $\Xi^{--}(1860)$ production in copper and carbon, for different x_F intervals.

			$BR \cdot d\sigma/dx_{F,max}[\mu b]$	
Target	x_F	η_{max}	per nucleus	per nucleon
Cu	0–0.15	170	[a]	[a]
	0.15–0.30	270	170	11
	0.30–0.45	300	190	12
	0.45–0.60	220	160	10
	0.60–0.75	180	150	9
	0.75–0.90	85	150	10
C	0–0.15	140	[a]	[a]
	0.15–0.30	240	62	12
	0.30–0.45	220	50	10
	0.45–0.60	180	52	10
	0.60–0.75	140	46	9
	0.75–0.90	60	28	5

[a]The sharp rise of the efficiency between $x_F=0$ and 0.15 which is reflected in the observed x_F distributions (Fig. 2), prevents a reliable determination of the cross section below $x_F \leqslant 0.15$.

limits on $BR \cdot d\sigma_0/dx_F$ in the last column of the table.

Limits on the integrated production cross sections σ were calculated by summing quadratically the contributions $d\sigma/dx_F \cdot \Delta x_F$ in the five individual x_F bins listed in column 4 of Table I. The results are $BR \cdot \sigma_{max}(0.15 < x_F < 0.9) = 16$ and 55 μb per nucleus in case of the carbon and copper target, respectively. An extrapolation to the cross sections per nucleon yields the two values $BR \cdot \sigma_{0,max} = 3.1$ μb for the carbon and 3.5 μb for the copper target, in excellent agreement with each other. As can be seen from Table II, these limits do not exceed the production cross sections of all other observed Ξ^* resonances.

At large x_f a significant fraction of the Ξ^- are produced by interactions induced by the Ξ^- beam contamination [31,37]. Even if we were to assume that the $\Xi^{--}(1860)$ production can be attributed exclusively to the 1.3% Ξ^- admixture in the beam, we obtain, e.g., for the carbon target and $x_F \geqslant 0.5$ a limit for the Ξ^{--} production by Ξ^- of 740 μb. For comparison, even this large 3σ limit corresponds to only 4% of the Ξ^- production cross section in $\Xi^- + \mathrm{Be}$ interactions at 116 GeV/c in the same kinematic range [42].

Finally we note that the $\Xi^-\pi^+$ mass distribution observed by WA89 has already been published previously [32] (see also Table II). This combination is dominated by the peak from $\Xi^0(1530)$ decays. The observed central mass was in good agreement with the known value of $M = 1531.8 \pm 0.3$ MeV/c^2 [43]. Unfolding the observed width

TABLE II. Cross section per nucleon σ_0 or $BR \cdot \sigma_0$ for Ξ^* production in Σ^--nucleus interactions at 340 GeV/c. The 3σ upper limit for $\Xi^{--}(1860)$ production was determined in a mass bin of 20 MeV/c^2 width.

Particle, decay channel	$\sigma_0[\mu b]$	$BR \cdot \sigma_0[\mu b]$	Ref.
$\Xi^-(1320)$	1000 ± 40		[31]
$\overline{\Xi}^+(1320)$	23 ± 2		[36]
$\Xi^0(1530)$	218 ± 44		[33]
$\Xi^0(1690) \to \Xi^-\pi^+$		2.5-6.8	[32,33]
$\Xi^0(1820) \to \Xi^0(1530)\pi^-$		21 ± 5	[33]
$\Xi^0(1950) \to \Xi^0(1530)\pi^-$		12 ± 3	[33]
$\Xi^{--}(1860) \to \Xi^-\pi^-$		$\leqslant 3.1$ (C) $\leqslant 3.5$ (Cu)	this work

with the width of the Ξ_{1530} of $\Gamma = 9.1$ MeV/c^2 [43] gave an experimental resolution of $\sigma_{\Xi^0(1530)} = 3.7$ MeV/c^2. Furthermore, a weak resonance signal with a width of $\Gamma = 10 \pm 6$ MeV/c^2 is visible at $M = 1686 \pm 4$ MeV/c^2 above a large background. In the mass region of the $\Xi^0(1860)$ (last three channels in the left part of Fig. 1(a) in Ref. [32]) no enhancement over the uncorrelated background can be seen in the WA89 data.

If the Ξ^{--} signal observed by the NA49 collaboration is real, then the nonobservation in our experiment is not easily understood. Generally particle ratios do not vary significantly for the beam momentum range in question (160 GeV/c vs 340 GeV/c) [44,45]. The fact that the $\Theta^+(1530)$ has been seen in reactions on complex nuclei [6,8] makes also the different targets (hydrogen vs C, Si, Cu) an unlikely cause for the discrepancy. The internal structure of the Σ^- projectile or of the $\Xi^{--}(1860)$ could be a more plausible reason for the rather low limit of the $\Xi^{--}(1860)/\Xi^-$ ratio. It is well known, that a transfer of a strange quark from the beam projectile to the produced hadron enhances the production cross sections in particular at large x_F (see, for instance, Fig. 8 in Ref. [31]). The different leading effects for octet and decuplet Σ states [34] even hint at an [sd] diquark transfer from the Σ^- projectile [46]. The production of a pentaquark containing correlated quark-quark pairs (see e.g., Ref. [47]) would probably benefit from such a diquark transfer. However, for example in case of an extended $\overline{K} - N - \overline{K}$ molecular structure of the $\Xi(1860)$ [48] an [sd] diquark transfer may not necessarily enhance the Ξ^{--} production leading also to a narrower x_F distribution. As a consequence the cross section in Σ^- induced reactions might not exceed the one for production in pp interactions. The latter cross section is predicted to be ~ 4 μb [45] which is then close to our limit.

Thus, if future high statistics experiments will confirm the production of the $\Xi^{--}(1860)$ resonance in proton-proton interaction, the nonobservation with the Σ^- beam may point to a very exceptional production mechanism possibly related to an exotic structure of the $\Xi^{--}(1860)$.

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