OBSERVATION OF THE ORBITALLY EXCITED Λ(1520) BARYON IN e^+e^- ANNIHILATION

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We report the first observation of an orbitally excited baryon, the $\Lambda(1520)$, in quark and gluon fragmentation. The production rate is found to be $(1.15\pm0.21\pm0.16)\times10^{-2}$ and $(0.80\pm0.17^{+0.10}_{-0.13})\times10^{-2}\Lambda(1520)$ hyperons per event in direct Υ decays and in the continuum, respectively. In contrast to the observed situation for ground state baryons, the production rate of the $\Lambda(1520)$ in direct Υ decays shows little or no enhancement with respect to continuum production.

The study of baryon production in e^+e^- interactions provides important information about the underlying fragmentation of partons [1]. Performing separate measurements for direct Υ decays and the nearby continuum offers a unique opportunity to compare quark and gluon fragmentation. Studies of baryon production in this context are of special interest, since the known ground state baryons are more abundantly produced in direct Υ decays than in the continuum [2–6]. This observation is in contrast to fragmentation studies of heavy mesons, where only an enhancement compatible with the expected increase of the overall multiplicity has been measured [3,7]. These differences between meson and baryon production are not adequately described by present fragmentation models.

Up to now only baryons of the lowest octet and decuplet have been observed in e^+e^- annihilation. The production of spin $\frac{3}{2}$ hyperons is found to be suppressed with respect to those of spin $\frac{1}{2}$ [6]. Here we address the question of whether a similar suppression exists as well for baryons where the quarks are in a p-wave state.

The most successful fragmentation models, the LUND string model [8] and the parton shower model [9], have so far not considered the production of p-wave baryons. In ref. [8] the abundance of p-wave states compared with ground states is estimated to be of the order 10%. Experimental information on the relative production of p-wave baryons and tensor mesons would be valuable in this context.

In this paper we report the first observation of $\Lambda(1520)$ production in e^+e^- annihilation. This baryon belongs to the first radially and orbitally excited multiplet and is assigned to a $J^P=\frac{3}{2}^-$ state with a totally antisymmetric quark wave function [10]. For this study the decay channel $\Lambda(1520)\to pK^-$ has been used, which has a branching ratio of 22.5% [11].

The data were collected with the ARGUS detector at the DORIS II storage ring at DESY. The center-of-mass energies ranged from 9.4 to 10.6 GeV. The detector, the trigger and particle identification capabilities are described in ref. [12]. The event sample used in this analysis corresponds to an integrated luminosity of 39.4 pb^{-1} on the $\Upsilon(1S)$, 29.3 pb^{-1} on the $\Upsilon(2S)$, 95.4 pb^{-1} on the $\Upsilon(4S)$ and 42.3 pb^{-1} in the continuum. In order to study quark and gluon fragmentation separately, $\Upsilon(1S)$ and $\Upsilon(2S)$ data were combined while the $\Upsilon(4S)$ was treated as continuum. In the further analysis we ignore B meson decays as possible source of $\Lambda(1520)$ production but assume as one standard deviation limit $\Lambda(1520)$ production from direct $\Upsilon(4S)$ decays to be half of the continuum rate. From this we derive a +13% contribution to the systematic error for the $\Upsilon(4S)$ data.

Multihadron events were selected by requiring $\geqslant 3$ reconstructed tracks from the main vertex of $\geqslant 3$ reconstructed tracks plus 1.7 GeV energy deposited in the shower counters. A cut on a linear combination of the scalar momentum sum of all detected charged and neutral particles and the sum of their momentum components along the beam axis

$$\sum_i p_i - 1.5\left|\sum_i p_{z,i}\right| > 0.25\sqrt{s}$$

reduces the background from beam-gas and beam-wall events. The acceptance for charged particles was defined by a cut on the transverse momentum

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$p_t > 0.06$ GeV/c and the polar angle $|\cos\theta| < 0.92$. For a given charged track all mass hypotheses were accepted for which the likelihood ratio [13] constructed from the combined time-of-flight and dE/dx measurements exceeded 30%. The latter cut represents a compromise between a good signal to background ratio and a reliable acceptance determination. The efficiencies of this cut were determined for protons and kaons from the data itself by measuring the effect of the same cuts on the appropriate daughter particles of the high statistic Λ and ϕ signals. In order to reduce the contributions of reflections in the pK^- mass spectrum, the ranges of the proton and kaon momenta were restricted to 0.3 GeV/$c \leqslant p_p \leqslant 1.6$ GeV/c and 0.2 GeV/$c \leqslant p_K \leqslant 0.9$ GeV/c, where a good particle separation can be expected. In addition the total momentum of the pK^- combinations was restricted to the interval $0.1 < x_p = p/p_{max} < 0.4$.

The resulting pK^- invariant mass distribution is shown in figs. 1a and 1b for the combined ϒ(1S) and ϒ(2S) data and the combined ϒ(4S) and continuum data, respectively. A clear peak at the position of the Λ(1520) is observed. We have studied the possibility that the observed signal is due to a reflection of an abundantly produced meson resonance. Contributions from ρ^0, K^{*0}, ϕ and K_s^0 have been considered (fig. 2), but none of these channels was found to be responsible for the observed peak.

To verify that the signal results from real pK^- combinations, the cut on the normalized likelihood of protons and kaons was varied. No signal was detected for a cut of 5%, due to a large combinatorial background, while the significance of the signal increased strongly as the likelihood cut was raised.

A relativistic d-wave Breit–Wigner function [14] with a fixed mass value of $m = 1519.5$ MeV/c^2 and a fixed width of $\Lambda = 15.6$ MeV/c^2 [11] was used to describe the resonance signal, while the background was parametrized by a third-order polynomial with a square-root threshold behaviour. The mass region between 1.56 and 1.62 GeV/c^2, where indications of the K^{*0} reflection can be seen, has been excluded from the fit. The fit shows that the shape of the observed signal is in good agreement with the predicted mass and width of the Λ(1520) hyperon.

The signal was integrated in the mass region between 1.5 and 1.56 GeV/c^2. In total 687 ± 60

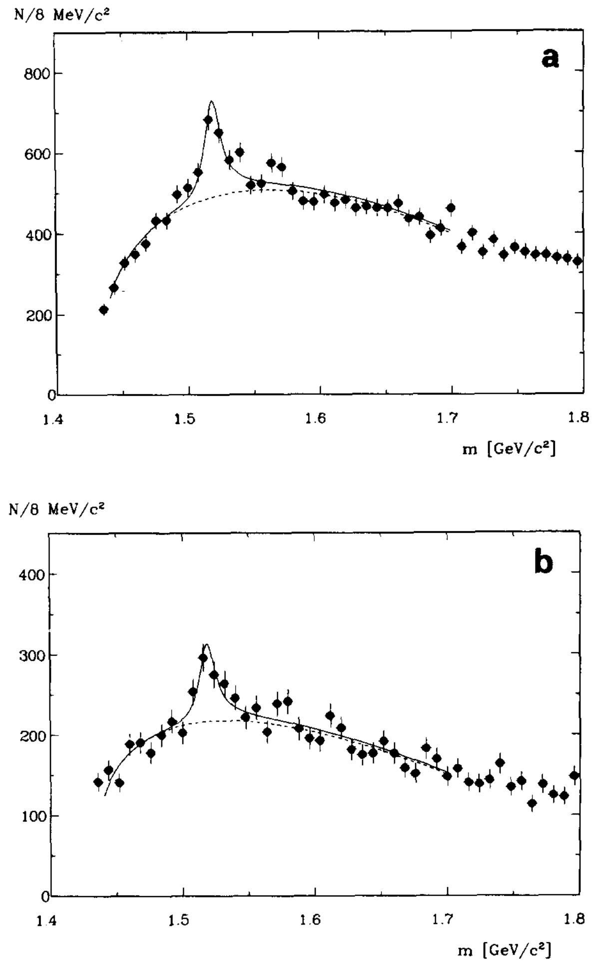

Fig. 1. Observed invariant mass spectrum of all pK^- combinations with 0.3 GeV/$c \leqslant p_p \leqslant 1.6$ GeV/c and 0.2 GeV/$c \leqslant p_K \leqslant 0.9$ GeV/c. The momentum range of the pK^- system was restricted to $0.1 < x < 0.4$. Data were included (a) from the ϒ(1S) and ϒ(2S) resonances, (b) from the ϒ(4S) resonance and the continuum.

Λ(1520) baryons were observed at the ϒ energies, while 292 ± 39 Λ(1520) baryons were detected in the combined ϒ(4S) and continuum data. The tails of the Breit–Wigner distribution have been extrapolated outside the integration region up to $\pm 4\Gamma$ and were added to the signal. These rates were corrected for acceptance (on average about 40% for this decay channel) by a method described in detail in ref. [15].

The production rate of Λ(1520) baryons in direct ϒ decays is obtained by subtracting the continuum

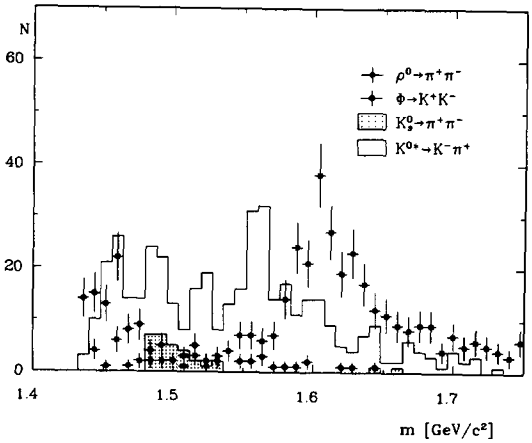

Fig. 2. Expected mass spectrum of reflections of the ρ^0 (open squares), ϕ (filled circles), K^{0*} (full line histogram) and K^0_s meson (hatched histogram), if at least one of their daughter particles has been misidentified.

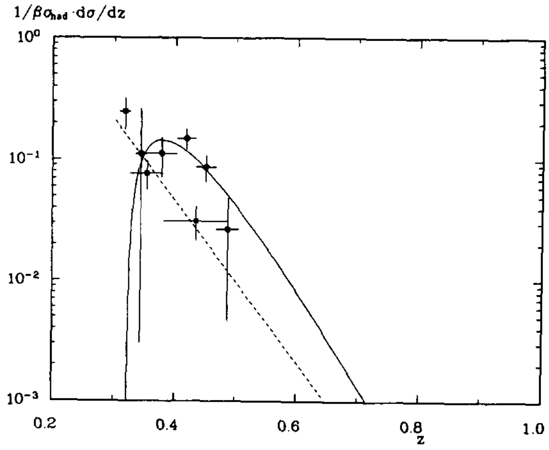

Fig. 3. $\Lambda(1520)$ spectra $(1/\beta\sigma_{had})d\sigma/dz$ in direct Υ decays (filled circles) and continuum (open squares). The full and dashed lines, respectively, show fits described in the text and were used for the momentum extrapolation.

plus the vacuum polarisation contributions from the measured rate on the Υ resonance. Radiative corrections to the continuum data were applied by using the same technique as for the Λ signal [6]. For the integrated rates one obtains in the momentum interval $0.1 < x_p < 0.4$ the values

$$n^{co}_{\Lambda(1520)} = (0.66 \pm 0.14^{+0.05}_{-0.09}) \times 10^{-2}$$

for the continuum data and

$$n^{\Upsilon}_{\Lambda(1520)} = (0.97 \pm 0.18 \pm 0.08) \times 10^{-2}$$

for direct Υ decays. The first error quoted is statistical while the second one reflects the estimated systematic error. Contribution to the systematic error arise from uncertainties in the hadronic cross section ($\approx 5\%$), in the efficiencies for track reconstruction ($\approx 3\%$) and particle identification ($\approx 4\%$) and in the unknown branching ratio for $B \to \Lambda(1520)$. The different contributions to the systematic error were added in quadrature. From the measurements above we obtain the corresponding ratio of production rates, defined as

$$r = \frac{\text{\#hadrons/event in } \Upsilon(1S) \text{ decays}}{\text{\#hadrons/event in the continuum}}\,,$$

with $r = 1.47 \pm 0.44^{+0.28}_{-0.24}$ it turns out to be significantly smaller than the value observed for ground state baryons in the same momentum range [6].

In order to determine the momentum spectra, the mass distributions were divided into 5 (3) momentum bins for the combined Υ (continuum) data and each was then fitted using the function described above. The resulting differential cross sections are shown in fig. 3 as a function of the scaling variable $z = 2E_{\Lambda(1520)}/\sqrt{s}$ for direct Υ decays and continuum data, respectively. This plot yields the surprising result that the $\Lambda(1520)$ rate at medium $z \approx 0.4$ is larger by a factor of about 2 to 3 for direct Υ decays compared with continuum data, in agreement with the observed ratio for ground state baryons. However, at low z the $\Lambda(1520)$ spectrum in the Υ data decreases and even falls below the continuum data. This behaviour at low z accounts for the low r-value of the $\Lambda(1520)$ baryon.

In order to derive the total number of $\Lambda(1520)$ baryons produced per event, one has to extrapolate the data points to the full momentum range. As for ground state baryons, an exponential fit

$$f(z) = A\exp(-bz)$$

gave a satisfactory description of the $\Lambda(1520)$ spectrum in the continuum. Because of its decrease at low z, this parametrization does not well describe the corresponding spectrum in direct Υ decay. Therefore, introducing an additional term with a power behaviour commonly employed for fragmentation functions [8], the form

$$f(z)=A\exp(-bz)\ (z-z_{\min})^{\alpha}$$

with $z_{\min}=2m(\Lambda(1520))/\sqrt{s}$ was used to fit the $\Lambda(1520)$ spectrum of fig. 3 in Υ decay. This function gave a somewhat better description of the data ($\chi^2/N_F=3.2/2$) than a pure exponential ($\chi^2/N_F=6.0/3$). The extrapolation of both spectra to the full momentum range yields a correction of $19\pm10\%$ for Υ decays and $21\pm8\%$ for the continuum data.

With these corrections the measured production rates are

$$n^{\Upsilon}_{\Lambda(1520)}=(1.15\pm0.21\pm0.16)\times10^{-2}$$

in direct Υ decays and

$$n^{\rm co}_{\Lambda(1520)}=(0.80\pm0.17^{+0.10}_{-0.13})\times10^{-2}$$

in the continuum, respectively. The ratio r of $\Lambda(1520)$ production in direct Υ decays compared with continuum data becomes

$$r=1.44\pm0.40^{+0.31}_{-0.27}\,.$$

This value should be compared with the measured values of 2–3 for ground state baryons [6].

As discussed above, the production of excited baryon states has so far not been considered in standard fragmentation models. Nevertheless some comparisons with general model assumptions can be made.

In models which describe hadronization through the decay of massive colour singlet clusters [16], the baryon enhancement in direct Υ decays arises from the larger cluster masses in direct Υ decays as compared with events from continuum production. Hence this model is not able to reproduce the observed low r value of the $\Lambda(1520)$.

This class of models also predicts a production rate proportional to the spin statistics factor $2J+1$, where J is the total angular momentum of the particle, which in case of the $\Lambda(1520)$ is $J=\frac{3}{2}$. Thus $\Lambda(1520)$ production should be comparable with the rate for $\Sigma^{\pm}(1385)$ hyperons, which is experimentally verified within a factor of 2 [6]. This comparison shows that the suppression of spin and orbital angular momentum is of the same order of magnitude. However, since the production ratio of $J=\frac{3}{2}$ to $J=\frac{1}{2}$ states is rather low, i.e. of the order 0.2–0.3 [6], hadron production according to spin statistics does not hold. Hence the approximate equality of production rates from states with equal total angular momentum J, but different spin S and orbital angular momentum L, might be accidental.

The suppression of orbital angular momentum is expressed quantitatively by the ratio of the $\Lambda(1520)$ and Σ^0 production rates [6], provided that both baryons are rarely produced in the decays of heavier hadrons. This ratio, found to be $0.35\pm0.13\pm0.09$ for continuum data, can be compared with the production ratios of tensor mesons and vector mesons with the same flavour content. The production rate of the orbitally excited D(2420) meson amounts to about 20% of that of D^* mesons [17]. In addition the ratio of $f_2(1270)$ to ρ meson production in the continuum has been determined in two experiments to be 0.21 [18] and 0.15 ± 0.04 [19]. These results show that the suppression of states with non-zero orbital angular momentum is similar for baryons and mesons.

In summary we report the first observation of an orbitally excited baryon in quark and gluon fragmentation. A comparison of the $\Lambda(1520)$ and the $\Sigma^{\pm}(1385)$ rates demonstrates that the suppressions due to spin and orbital angular momentum are of comparable strength. In contrast with measurements for ground state baryons, a substantially lower enhancement of $\Lambda(1520)$ production from direct Υ decays is observed. This observation is in contradiction with expectations based on cluster decay models.

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