

Tel Aviv University Preprint TAUP 2255-95, 21 June 1995
Submitted to Zeitschrift fur Physik A, Hadrons and Nuclei
Archive hep-ph@xxx.lanl.gov - 9506405, (HEPPH-9506405)

How to Search for Doubly Charmed Baryons and Tetraquarks

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Abstract

Possible experimental searches of doubly charmed baryons and tetraquarks at fixed target experiments with high energy hadron beams and a high intensity spectrometer are considered here. The baryons considered are: Ξ_{cc}^+ (ccd), Ξ_{cc}^{++} (ccu), and Ω_{cc}^+ (ccs); and the tetraquark is T ($cc\bar{u}\bar{d}$). Estimates are given of masses, lifetimes, internal structure, production cross sections, decay modes, branching ratios, and yields. Experimental requirements are given for optimizing the signal and minimizing the backgrounds. This paper is designed as an experimental and theoretical review. It may therefore be of assistance in the planning for a future state-of-the-art very charming experiment, in the spirit of the aims of the recent CHARM2000 workshop.

Introduction

The Quantum Chromodynamics hadron spectrum includes doubly charmed baryons: Ξ_{cc}^+ (ccd), Ξ_{cc}^{++} (ecu), and Ω_{cc}^+ (ccs), as well as ccc and ccb . Properties of ccq baryons were discussed by Bjorken [1], Richard [2], Fleck and Richard and Martin [3], Savage and Wise and Springer [4, 5], Kiselev et al. [6, 7], Falk et al. [8], Bander and Subbaraman [9], and Stong [10]. Singly charmed baryons are an active area of current research [11, 12, 13, 14, 15, 16], but there are no experimental data on the doubly charmed variety. A dedicated double charm state of the art experiment is feasible and required to observe and to investigate such baryons. The required detectors and data acquisition system would need very high rate capabilities, and therefore would also serve as a testing ground for LHC detectors. Double charm physics is in the mainstream and part of the natural development of QCD research. This paper is an experimental and theoretical review, as part of the planning for a state-of-the-art very charming experiment, in the spirit of the aims of the recent CHARM2000 workshop [17]. The present work is an expanded version of a workshop contribution [18] dealing with a CHarm Experiment with Omni-Purpose Setup (CHEOPS) at CERN [19].

The ccq baryons should be described in terms of a combination of perturbative and non-perturbative QCD. For these baryons, the light q orbits a tightly bound cc pair. The study of such configurations and their weak decays can help to set constraints on phenomenological models of quark-quark forces [3, 20]. Hadron structures with size scales much less than $1/\Lambda_{qcd}$ should be well described by perturbative QCD. This is so, since the small size assures that α_s is small, and therefore the leading term in the perturbative expansion is adequate. The tightly bound $(cc)_3$ diquark in ccq may satisfy this condition. For ccq , on the other hand, the radius is dominated by the low mass q , and is therefore large. The relative (cc) - (q) structure may be described similar to mesons $\bar{Q}q$, where the (cc) pair plays the role of the heavy antiquark. Savage and Wise [4] discussed the ccq excitation spectrum for the q degree of freedom (with the cc in its ground state) via the analogy to the spectrum of $\bar{Q}q$ mesons. Fleck and Richard [3] calculated excitation spectra and other properties of ccq baryons for a variety of potential and bag models, which describe successfully known hadrons. Stong [10] emphasized how the QQq excitation spectra can be used to phenomenologically determine the QQ potential, to complement the approach taken for $Q\bar{Q}$ quarkonium interactions.

The ccq calculations contrast with ccc or ccb or b-quark physics, which are closer to the perturbative regime. As pointed out by Bjorken [1], one should strive to study the ccc baryon. Its excitation spectrum, including several narrow levels above the ground state, should be closer to the perturbative regime. The ccq studies are a valuable prelude to such ccc efforts.

A tetraquark ($cc\bar{u}\bar{d}$) structure (designated here by T) was described by Richard, Bander and Subbaraman, Lipkin, Tornqvist, Ericson and Karl, Nussinov, Chow, Maonohar and Wise, Weinstein and Isgur, Carlson and Heller and Tjon, and Jaffe, [2, 9, 21, 22, 23, 24, 25, 26, 27, 28, 29]. Tetraquarks with only u,d,s quarks have also been extensively studied [2, 30, 31]. The doubly charmed tetraquark is of particular interest, as the calculations of these authors indicate that it may be bound. Some authors [2, 9, 24, 25] compare the tetraquark structure to that of the antibaryon $\bar{Q}\bar{u}\bar{d}$, which has the coupling $\bar{Q}_3(\bar{u}\bar{d})_3$. In the T, the tightly bound $(cc)_3$ then plays the role of the antiquark \bar{Q} . The tetraquark may also have a deuteron-like meson-meson weakly bound $D^{*+}D^0$ component, coupled to 1^+ , and bound by a long range one-pion exchange potential [22, 24], which corresponds to light quark exchanges in the quark picture. Such a structure has been referred to as a deuson by Tornqvist [22]. The deuson is analogous with the H_2 molecule; where the heavy and light quarks play the roles of protons and electrons, respectively. The discovery of such an exotic hadron would have far reaching consequences for QCD, for the concept of confinement, and for specific models of hadron structure (lattice, string, and bag models). Detailed discussions of exotic hadron physics can be found in recent reviews [36]. Some other exotics that can be investigated in CHEOPS are: Pentaquarks $uud\bar{c}s, udd\bar{c}s, uds\bar{c}s, uud\bar{c}c, udd\bar{c}c, uds\bar{c}c$ [32], Hybrid $q\bar{q}g$ [33], $us\bar{d}\bar{d}$ $U^+(3100)$ [34], $uuddss$ H hexaquark [35], $uuddcc$ H_{cc} hexaquark [25], $q\bar{q}s\bar{s}$ or $q\bar{q}g$ $C(1480)$ [36], and $\bar{c}\bar{c}qqqqq$ heptaquark [9]. But we do not discuss these various exotic hadrons in detail in this report.

Should only the $cc\bar{u}\bar{d}$ ($D^{*+}D^0$) be bound; or should the $c\bar{c}d\bar{u}$ ($D^{*-}D^0$) also be bound? The $D^{*+}D^0$ state, if above the $DD\pi$ threshold, can only decay strongly to doubly charmed systems. But it is easier to produce only one $c\bar{c}$ pair, as in $D^{*-}D^0$. However, this state has numerous open strong decay channels. These include charmonium plus one or two pions and all the multipion states and resonances below 3.6 GeV, and it is therefore not strong interaction stable. One may argue that a $D^{*-}D^0$ state is unlikely to be bound. In a deuson, bound by pion-exchange, the sign of the potential

which binds the two D mesons depends on the product of the sign of the two vertices associated with the pion exchange. The sign of the D^* vertex depends on T_z , the z-component of isospin, which changes from +1 to -1 in changing from positive to negative D^* . Therefore, if the potential is attractive in the case of $D^{*+}D^0$, it will be repulsive in the case of $D^{*-}D^0$. Consequently, the calculations [22, 24] for a bound $D^{*+}D^0$ suggest that the $D^{*-}D^0$ may be unbound. Shmatikov [37] explicitly studied the widths and decay mechanisms of $D^{*-}D^0$, including some bound possibilities. Therefore, in the $D^{*+}D^0$ search, it would be of value to also look at $D^{*-}D^0$ data. Even if no peak is observed, the combinatoric backgrounds may help understand those for $D^{*+}D^0$.

Mass of ccq Baryons and T

Bjorken [1] suggests mass ratios $M(\Omega_{ccc}^{++}/\Psi) = 1.60$ and $M(\Omega_{bbb}^-/\Upsilon)=1.57$, which follows from the extrapolation of $M(\Delta^{++}/\rho, \omega)$ and $M(\Omega^-/\phi)$. He assumes the validity of the "equal-spacing" rule for the masses of all the $J=3/2$ baryons, which gives the possibility to interpolate between ccc, bbb, and ordinary baryons. The masses of ccq baryons with $J=1/2$ were estimated relative to the central $J=3/2$ value. The cc diquark is a color antitriplet with spin $S=1$. The spin of the third quark is either parallel ($J=3/2$) or anti-parallel ($J=1/2$) to the diquark. The magnitude of the splitting is in inverse proportion to the product of the masses of the light and heavy quarks. These are taken as 0.30 GeV for u and d, 0.45 GeV for s, 1.55 GeV for c, and 4.85 GeV for b. The equal spacing rule for $J=3/2$, with n_i the number of quarks of a given flavor, is then [1]:

$$M = 1/3[1.23(n_u + n_d) + 1.67n_s + 4.96n_c + 14.85n_b]. \quad (1)$$

For ccq, the $J=1/2$ states are lower than the $J=3/2$ states by about 0.1 GeV [2]. This approach for ccq gives results close to those of Richard et al. [2, 3]. Fleck and Richard [3] also estimate the tetraquark mass. Fleck and Richard, and Nussinov [24] have shown that ccq and $cc\bar{u}\bar{d}$ masses near 3.7 GeV are consistent with expectations from QCD mass inequalities.

The estimates lead to masses [1, 2, 3]:

- (ccs), 1/2+, 3.8 GeV;
- (ccu), 1/2+, 3.7 GeV;

(ccd) , $1/2^+$, 3.7 GeV;
 $(cc\bar{u}\bar{d})$, $1/2^+$, 3.6 GeV;

Lifetime of ccq Baryons and T.

The Ξ_{cc}^{++} and Ω_{cc}^+ decays should probably be dominated by spectator diagrams [1, 3, 11, 38, 39, 40] with lifetimes about $200fs$, roughly half of the D^0 or Ξ_c^+ . Fleck and Richard [3] suggest that positive interference will occur between the s-quark resulting from c-decay, and the pre-existing s-quark in Ω_{cc}^+ . Its lifetime would then be less than that of Ξ_c^{++} . Bjorken [1] and also Fleck and Richard [3] suggest that internal W exchange diagrams in the Ξ_{cc}^+ decay could reduce its lifetime to around $100fs$, roughly half the lifetime of the Λ_c^+ . The lifetime of the T should be much shorter, according to the pattern set by the D^{*+} lifetime. These estimates are consistent with the present understanding of charmed hadron lifetimes [11, 38, 39, 40]. One expects that predominantly doubly charmed hadrons are produced with small momentum in the center of mass of the colliding hadrons. They are therefore sufficiently fast in the laboratory frame. The lifetime boost in the laboratory frame for a ccq baryon is roughly [41] $\gamma \approx \sqrt{p_{in}/2M_N}$, if it is produced at the center of rapidity with a high energy hadron beam of momentum p_{in} . For a CERN experiment with $p_{in} \approx 400$ GeV/c, this corresponds to $\gamma \approx 15$, with ccq energies near 55 GeV.

Production Cross Section of ccq Baryons

One can consider production of doubly charmed hadrons by proton and Sigma and pion beams. Pion beams are more effective in producing high- X_F D^- mesons, as compared to Σ^- beams. Here, X_F designates the Feynman X_F -value, $X_F = p_D/P_{beam}$, evaluated with laboratory momenta. And baryon beams are likely more effective than pion beams in producing ccq and cq q baryons at high X_F .

Consider a hadronic interaction in which two $c\bar{c}$ pairs are produced. The two c's combine and then form a ccq baryon. Calculations for ccq production via such interactions have not yet been published. Even if they are done, they

will have large uncertainties. Some ingredients to the needed calculations can be stated. For ccq production, one must produce two c quarks (and associated antiquarks), and they must join to a tightly bound, small size anti-triplet pair. The pair then joins a light quark to produce the final ccq . The two c -quarks may arise from two parton showers in the same hadron-hadron collision, or even from a single parton shower, or they may be present as an intrinsic charm component of the incident hadron, or otherwise. The two c -quarks may be produced (initial state) with a range of separations and relative momenta (up to say tens of GeV/c). In the final state, if they are tightly bound in a small size cc pair, they should have relative momentum lower than roughly $1. \text{ GeV}/c$. The overlap integral between initial and final states determines the probability for the cc - q fusion process. For cqq production, a produced c quark may more easily combine with a (projectile) di-quark to produce a charmed baryon. A ccq production calculation in this framework, based on two parton showers in the same hadron-hadron collision, is in progress by Levin [42].

As an aid in comparing different possible calculations, one may parameterize the yield as:

$$\sigma(ccq)/\sigma(cqq) \approx \sigma(ccq)/\sigma(cq) \approx k[\sigma(c\bar{c})/\sigma(in.)] \approx kR. \quad (2)$$

Here, $\sigma(c\bar{c})$ is the charm production cross section, roughly $25 \mu\text{b}$; $\sigma(in.)$ is the inelastic scattering cross section, roughly 25mb ; and R is their ratio, roughly 10^{-3} [43]. Here, k is the assumed "suppression" factor for joining two c 's together with a third light quark to produce ccq ; compared to cqq or cq production, where the c quark combines with a light diquark to give cqq or a light quark to give cq . Eq. 2 does not represent a calculation, and has no compelling theoretical basis. It implicitly factorizes ccq production into a factor (R) that accounts for the production of a second c -quark, and a factor (k) describing a subsequent ccq baryon formation probability. Considering the overlap integral described in the preceding paragraph, one may expect k values less than unity for simple mechanisms of ccq formation. It is possible to have a factor $k > 1$, if there is some enhancement correlation in the production mechanism. Reliable theoretical cross section calculations are needed, including the X_F -dependence of ccq production. In the absence of such a calculation, we will explore the experimental consequences of a ccq search for the range $k=0.1$ - 1.0 , corresponding to

$\sigma(ccq)/\sigma(cqq) \approx \sigma(ecq)/\sigma(cq) \approx 10^{-4} - 10^{-3}$. Assuming $\sigma(c\bar{c})$ charm production cross sections of 25 microbarns, this range corresponds to ccq cross sections of 2.5-25. nb/N.

Aoki et al. [44] reported a low statistics measurement at $\sqrt{s}=26$ GeV for double to single open charm pair production, of 10^{-2} . This $D\bar{D}D\bar{D}$ to $D\bar{D}$ ratio was for all central and diffractive events. This high ratio is encouraging for ccq searches, compared to the value from NA3 [45] of $\sigma(\Psi\Psi)/\sigma(\Psi) \approx 3 \times 10^{-4}$. We assume that the $\Psi\Psi$ result is relevant, even though Ψ production is only a small part ($\approx 0.4\%$) of the charm production cross section, with most of the cross section leading to open charm. For double Ψ or double charm pair hadroproduction, the suppression factor k for two c-quarks to join into the same ccq is missing. These two results for double charm production therefore establish a range of values for R in Eq. 2, consistent with the value 10^{-3} estimated above in the discussion of Eq. 2. Robinett [46] discussed $\Psi\Psi$ production and Levin [42] discussed ccq production in terms of multiple parton interactions. Halzen et al. [47] discussed evidence for multiple parton interactions in a single hadron collision, from data on the production of two lepton pairs in Drell-Yan experiments.

It will be of interest to compare ccq production in hadron versus electron-positron collisions, even if CHEOPS deals with hadron interactions. Following production of a single heavy quark from the decay of a Z or W boson produced in an electron-positron collision, Savage and Wise [4] discussed the expected suppression for the the production of a second heavy quark by string breaking effects or via a hard gluon. Kiselev et al. [6] calculated low cross sections for double charm production at an electron-positron collider B factory, for $\sqrt{s}= 10.6$ GeV. They find $\sigma(ccq)/\sigma(c\bar{c}) = 7. \times 10^{-5}$. Although this result is inapplicable to hadronic interactions as in CHEOPS; the work describes some important calculational steps, and also demonstrates the continued wide interest in this subject.

A number of works [7, 48, 49, 50, 51, 52, 53, 54, 55] consider the production and decay of doubly heavy hadrons (bcq, $\bar{b}c$, etc.) at future hadron collider experiments at the FNAL Tevatron or CERN LHC. Kiselev et al. [7] give a preliminary estimate of $\sigma(ccq) \approx 10$. nb/N in hadronic production at $\sqrt{s}= 100$. GeV. This corresponds to k=0.4 in the parameterization of Eq. 2. In hadronic production, the process $gg \rightarrow b\bar{b}$ or $q\bar{q} \rightarrow b\bar{b}$ may be followed by gluon bremsstrahlung and splitting $\bar{b} \rightarrow \bar{b}g \rightarrow \bar{b}c\bar{c}$ to yield B_c ($\bar{b}c$) mesons [8, 5, 56, 57, 58, 59, 60, 61, 62, 63]. Doubly charmed baryon production may

then possibly proceed via the weak decay $\bar{b} \rightarrow c\bar{c}\bar{s}$. This quark process has recently been claimed [64] to dominate charm baryon production in B decay. A CHEOPS fixed target study for ccq (possibly including some B_c mesons) can be a valuable prelude to collider studies of doubly heavy hadrons.

Brodsky and Vogt [65] suggested that there may be significant intrinsic charm (IC) $c\bar{c}$ components in hadron wave functions, and therefore also $cc\bar{c}$ components. The IC probability was obtained from the measurements of charm production in deep inelastic scattering. The Hoffmann and Moore analysis [66] of EMC data yields 0.3% IC probability in the proton. Theoretical calculations of the IC component have also been reported [67]. The double intrinsic charm component can lead to ccq production, as the cc pairs pre-exist in the incident hadron.

Brodsky and Vogt [65] discussed double $\Psi\Psi$ production [45] in the framework of IC. The data occur mainly at large X_F , while processes induced by gluon fusion tend to be more central. They claim that the data (transverse momentum, X_F distribution, etc.) suggest that $\Psi\Psi$ production is highly correlated, as expected in the intrinsic charm picture. A recent experiment of Kodama et al. [68] searched for soft diffractive production of open charm in $D\bar{D}$ pairs with a 800 GeV proton beam and a Silicon target. The experiment set a 90% confidence level upper limit of 26 microbarns per Silicon nucleus for diffractive charm production. Kodama et al. estimated that the total diffractive cross section per Silicon nucleus, above the charm threshold, is 12.2 mb. The ratio of these values gives an upper limit of 0.2% for the probability that above the charm threshold, a diffractive event contains a charm pair. Kodama et al. interpreted this as the upper limit on the IC component of the proton. Brodsky et al [69] discuss the probability for the intrinsic charm in an incident high energy hadron to be freed in a soft diffractive interaction in a high energy hadronic collision. In their formalism, the IC probability is multiplied by a resolution factor μ^2/m_c^2 , where μ^2 is an appropriate soft mass scale [69]. If we take the soft scale to be of order $\Lambda_{qcd}=0.2$ GeV or the ρ mass, one obtains a significant resolution factor suppression for charm production in a soft process. Thus, the charm fraction that should be observed in a soft hadronic or diffractive cross section should be considerably smaller than the intrinsic charm probability. If the suppression factor is for example 10, that would change the upper limit of the Kodama et al. experiment from 0.2% to 2%. The data would not therefore place a useful limit on the IC component. In the case of hard reactions such as the deep inelastic lepton scattering of

the EMC experiment, the suppression factor is not present.

Despite the small IC probability and the suppression factor, Brodsky and Vogt [65] found that the large X_F charmed hadroproduction data is consistent with the IC picture. This includes the A dependence and X_F dependence of J/ψ hadroproduction (NA3) and the leading particle effect seen in the observed production asymmetry for D^-/D^+ mesons at large X_F for an incident π^- beam [65]. Explanations of the leading D data requires that the charm quark coalesce with a valence quark. This happens automatically when one frees the IC Fock state, since the charm quark and valence quark are already moving at approximately the same velocity.

When one frees a double charm IC state in a soft collision, both charm quarks will be moving at approximately the same velocity as the valence quark. Thus, coalescence into a ccq state is likely. With gauge interactions, particles may coalesce into bound states primarily when they are at low relative velocity. One may expect that aside from the IC mechanism, ccq production will be predominantly central. Intrinsic charm ccq production, with its expected high X_F distribution, would therefore be especially attractive. An IC ccq production cross section calculation would be of great interest.

We can also refer to an empirical formula which reasonably describes the production cross section of a mass M hadron in central collisions. The transverse momentum distribution at not too large p_t follows a form given as [70]:

$$d\sigma/dp_t^2 \sim \exp(-B\sqrt{M^2 + p_t^2}), \quad (3)$$

where B is roughly a universal constant $\sim 5 - 6$ (GeV) $^{-1}$. The exponential (Boltzmann) dependence on the transverse energy $E_t = \sqrt{M^2 + p_t^2}$ has inspired speculation that particle production is thermal, at a temperature $B^{-1} \sim 160$ MeV [70]. We assume that this equation is applicable to ccq production. To illustrate the universality of B, we evaluate it for a few cases. For Λ_c and Ξ^0 , empirical fits to data give $\exp(-bp_t^2)$, with $b=1.1$ GeV $^{-2}$ and $b=2.0$ GeV $^{-2}$, respectively [71, 72]. With $B \approx 2$ Mb, this corresponds to $B= 5.0$ GeV $^{-1}$ for Λ_c , and $B= 5.3$ GeV $^{-1}$ for Ξ^0 . For inclusive pion production, experiment gives $\exp(-bp_t)$ with $b = 6$ GeV $^{-1}$ [73]; and $B \sim b$, since the pion mass is small. Therefore, $B= 5-6$ GeV $^{-1}$ is valid for Λ_c , Ξ^0 hyperon, and pion production. After integrating over p_t^2 , including a $(2J+1)$ statistical factor to account for the spin of the produced ccq, and taking the mass of ccq and

D to be 3.7 and 2.0 GeV respectively; we estimate the ratio as:

$$\sigma(ccq)/\sigma(D) \sim (2J + 1)exp[-5[M(ccq) - M(D)]] \sim 4 \times 10^{-4}. \quad (4)$$

This result corresponds to $k=0.4$ in the parameterization of Eq. 2. In applying Eq. 4 to ccq production, we assume that the suppression of cross section for the heavy ccq production (for $q = u,d,s$) as compared to the light D ($\bar{c}q$) production is due to the increased mass of ccq . However, this formula ignores important dynamical input, including threshold effects and a possible suppression factor for the extra charm production in ccq , and therefore can be considered an upper limit. One may apply Eq. 4 with appropriate masses to estimate yield ratios of other particles. For the T , we assume the same production cross section as for the ccq , based on the mass dependence of Eq. 4.

Decay Modes and Branching Ratios of ccq Baryons

The semileptonic and nonleptonic branching ratios of ccq baryons have been estimated by Bjorken [1] in unpublished notes of 1986. He uses a statistical approach to assign probabilities to different decay modes. He first considers the most significant particles in a decay, those that carry baryon or strangeness number. Pions are then added according to a Poisson distribution. The Bjorken method and other approaches for charm baryon decay modes are described by Klein [13]. Savage and Springer [5] examined the flavor $SU(3)$ predictions for the semileptonic and nonleptonic ccq weak decays. They give tables of expected decay modes, where the rates for different modes are given in terms of a few reduced matrix elements of the effective hamiltonian. In this way, they also find many relationships between decay rates of different modes. Savage and Springer discuss the fact that the $SU(3)$ predictions for the decay of the D -mesons can be understood only by including the effects of final state interactions [74]. They suggest that FSI effects should be much less important for very charming baryons (ccq) compared to charmed mesons.

The c decays weakly, for example by $c \rightarrow s + u\bar{d} + n(\pi^+\pi^-)$, with $n=0,1$, etc. In that case, for example, $ccs \rightarrow css + (\pi^+\pi^+\pi^- \text{ or } \rho^+\pi^+\pi^-)$. The event

topology contains two secondary vertices. In the first, a $c\bar{s}s$ baryon and 3 mesons are produced. This vertex may be distinguished from the primary vertex, if the $c\bar{s}s$ lifetime is sufficiently long. The $c\bar{s}s$ baryon now propagates some distance, and decays at the next vertex, in the standard modes for a $c\bar{s}s$ baryon. The experiment must identify the two secondary vertices.

We describe some decay chains considered by Bjorken [1]. For the Ξ_{cc}^{++} , one may have $\Xi_{cc}^{++} \rightarrow \Sigma_c^{++} K^{*0}$ followed by $\Sigma_c^{++} \rightarrow \Lambda_c^+ \pi^+$ and $K^{*0} \rightarrow K^- \pi^+$. A $\Lambda_c^+ \pi^+ K^- \pi^+$ final state was estimated by Bjorken [1] to have as much as 5% branching ratio. Bjorken also estimated a 1.5% branch for $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$; and 1.5% for $\Omega_c^+ \rightarrow \Xi_c^+ \pi^+ K^-$. Bjorken finds that roughly 60% of the ccq decays are hadronic, with as many as one-third of these leading to final states with all charged hadrons. The decay topologies should satisfy a suitable CHEOPS charm trigger, with reasonable efficiency. There are also predicted 40% semi-leptonic decays. However, with a neutrino in the final state, it is not feasible to obtain the mass resolution required for a double charm search experiment.

Decay Modes and Branching Ratios of the T

One can search for the decay of $T \rightarrow \pi D D$, or $T \rightarrow \gamma D D$, as discussed by Nussinov [24]. The pion or gamma are emitted at the primary interaction point, where the D^* decays immediately. The two D mesons decay downstream. The D^* decay to π - D is useful for a search, since the charged pion momentum can be measured very well. One can get very good resolution for the reconstruction of the T mass. For the gamma decay channel, the experimental resolution is worse. There will therefore be relatively more background in this channel, since the gamma multiplicity from the target is high, and one must reconstruct events having two D mesons, with all gammas.

Signal and Background Considerations

High energies are needed for studies of high mass, and short lifetime baryons. Thereby, one produces high energy doubly charmed baryons. The resulting large lifetime boost improves separation of secondary and primary vertices,

and improves track and event reconstruction. CHEOPS with 450 GeV protons or other 350-450 GeV hadrons [19] has this high energy advantage.

One can identify charm candidates by requiring that one or more decay particles from a short lived parent have a sufficiently large impact parameter or transverse miss distance relative to the primary interaction point. This transverse miss distance (S) is obtained via extrapolation of tracks that are measured with a high resolution detector close to the target. This quantity is a quasi-Lorentz invariant. Consider a relativistic unpolarized parent baryon or a spin zero meson that decays into a daughter that is relativistic in the parent's center of mass frame. Cooper [75] has shown that the average transverse miss distance is $S \approx \pi c\tau/2$. For example, Λ_c with $c\tau \approx 60$ microns should have $S \approx 90$ microns. The E781 on-line filter cut is on the sum of the charged decay products of the doubly charmed baryon and the singly charmed baryon daughter's decay products. Any one of these with $P > 15$ GeV/c and $S > 30$ microns generates a trigger [76]. Events from the primary vertex are typically rejected by the cut on S . With a vertex detector with 20 micron strips, the E781 resolution in S is about 4 microns for very high momenta tracks. For events in E781 with a 15 GeV track, the transverse miss-distance resolution deteriorates to about 9 microns, due to multiple scattering [77]. And the resolution gets even worse for yet lower momenta tracks. As this resolution becomes worse, backgrounds increase, since the S -cut no longer adequately separates charm events from the primary interaction events. The backgrounds are not only events from the primary vertex, but also from the decays of the hadrons associated with the two associated \bar{c} quarks produced together with the two c quarks. One may expect that the requirement to see two related secondary vertices may provide a significant reduction in background levels.

Some bqq production and decay, with two secondary vertices, may be observed in CHEOPS, and must be considered at least as background to ccq production. The bqq and ccq events may be distinguished by the larger bqq lifetime, and the higher transverse energy released in the b decay. It is not the aim of CHEOPS to study bqq baryons. Experiments at CERN gave only a small number of reconstructed bqq baryons, at a center of mass energy around 30 GeV [78].

CHEOPS considers using a multiplicity jump trigger [79], which is intended to be sensitive to an increase in the number of charged tracks following a charm decay. Such a trigger for high rate beams has not yet been

used in a complete experiment, and still requires research and development. Backgrounds are possible with such a trigger, due to secondary interactions in targets and the interaction detector (Cerenkov, possibly [19]) following each target. Also, gamma rays from a primary interaction may convert afterwards to electron-positron pairs, and falsely fire the trigger. If the rejection ratio of such non-charmed events is not sufficiently high, the trigger may not achieve its needed purpose of reducing the accepted event rate to manageable values. This trigger would be sensitive to events with $X_F > -0.1$, and therefore has effectively an "open" trigger X_F -acceptance. Most of the charm events accepted will then be mainly associated with charm mesons near $X_F=0$, since these dominate the cross section in hadronic processes. The decay of ccq to a singly charmed hadron may trigger, or the charmed hadron's decay may fire the trigger. The event also has two anticharmed quarks, associated with charmed hadrons, and they may also fire the trigger. However, low- X_F events may have high backgrounds, since it is more difficult to separate them from non-charmed events, due to the poor miss distance resolution. For higher X_F events, one obtains a sample of doubly charmed baryons with improved reconstruction probability because of kinematic focussing and lessened multiple scattering and improved particle identification. The multiplicity-jump trigger for CHEOPS could be supplemented by a momentum condition trigger $P > 15 \text{ GeV}/c$, similar to this requirement in E781. This could enhance the high- X_F acceptance, and give higher quality events.

For double charm, the target design is important. To achieve a high interaction rate and still have small multiple scattering effects, one may choose five 400 micron Copper targets, separated by 1 mm. The total target thickness is limited to 2% interaction length in order to keep multiple scattering under control. With different target segments, one requires a longitudinal tracking resolution of 200-300 microns, in order to identify the target segment associated with a given interaction. The knowledge of the target segment allows the on-line processor to reconstruct tracks, and identify a charm event. The tracking detectors would then be placed as close as possible to the targets, to achieve the best possible transverse miss-distance resolution. The optimum target design and thickness for double charm requires study via Monte Carlo simulation.

One may require separation distances of secondary from primary vertices of $\approx 1-4 \sigma$, depending on the backgrounds. The requirement for two charm vertices in ccq decays may reduce backgrounds sufficiently, so that this sep-

aration distance cut is less important than in the case of ccq studies. For a lifetime of $100fs$, with a laboratory lifetime boost of 15, the distance from the production point to the decay point is around 450 microns. E781 can attain roughly 300 micron beam-direction resolution for $X_F = 0.2$, with a 650 GeV beam, and 20 micron strip silicon detectors. For lower X_F events, the resolution deteriorates due to multiple scattering, and there is little gain in using narrower strips. CHEOPS aims to achieve 150 micron resolution for the high X_F events. Signal and background and trigger simulations and target design development work are in progress for CHEOPS [19].

Projected Yields for CERN CHEOPS

For CHEOPS with a Baryon beam, one may rely on previous measurements done with similar beams. The open charm production cross section at SPS energies is roughly $25 \mu b$. Taking Eq. 2 with a reduction factor of $kR = 4 \times 10^{-4}$, with $k=0.4$, we have $\sigma(ccq) \approx 10 \text{ nb}/N$. This kR value follows from Kiselev et al. [7] and from Eq. 4. We assume a measured branching ratio $B = 10\%$ for the sum of all ccq decays; this being 50% of all the decays leading to only charged particles. We also assume a measured $B = 20\%$ for the sum of all ccq decays, this being roughly the value achieved in previous experiments. With these branching ratios, we estimate $\sigma \cdot BB = 10 \times 0.2 \times 0.1 = 0.2 \text{ nb}/N$.

For CHEOPS, we now evaluate the rate of reconstructed ccq events. The expectations are based on a beam of 5×10^7 per spill, assuming 240 spills per hour of effective beam, or 1.2×10^{10} /hour. For a 4000 hour run (2 years), and a 2% interaction target, one achieves 9.5×10^{11} interactions per target nucleon. We assume that $\sigma(\text{charm}) = 25 \mu b$ and $\sigma(\text{in}) = 25 \text{ mb}$ for a proton target, and take a charm production enhancement per nucleon of $A^{1/3}$ (with mass $A \approx 64$ for CHEOPS). One then obtains a high sensitivity of 1.5×10^5 charm events for each nb per nucleon of effective cross section (for nucleons in $A \approx 64$ nuclei), where $\sigma_{eff} = \sigma BB \varepsilon$. Here ε is the overall efficiency for the experiment. Fermilab E781 with 650 GeV pion and Σ^- beams is scheduled for 1996-97. This experiment may therefore observe ccq baryons before CHEOPS, as described in recent reports [80, 81]. The CHEOPS Letter of Intent [19] describes plans to achieve roughly ten times more reconstructed charm events than Fermilab E781. However, the CHEOPS experiment is not yet scheduled. The charm sensitivity of E781 is described in detail elsewhere

[32, 76]

We consider also the expected CHEOPS efficiency for the charm events, by comparison to E781 estimated [76] efficiencies. The E781 efficiencies for ccq decays include a tracking efficiency of 96% per track, a trigger efficiency averaged over X_F of roughly 18%, and a signal reconstruction efficiency of roughly 50%. The CHEOPS trigger efficiency for ccq should be higher than E781, if low X_F events are included. However, the signal reconstruction efficiency is low for low X_F events. The reconstruction efficiency should be lower for double charm events, since they are more complex than single charm events. Yet, using the proposed type of vertex detector, multivertex events can be reconstructed with good efficiency [78]. In a spectator decay mode, the final state from ccq decay will likely be a csq charm baryon plus a W decay, either semileptonic (40% total B) or hadronic (25% π^+ , 75% ρ^+ most likely). One may expect the vertex to be tagged more often (roughly a factor of two) for double charm compared to single charm. There should therefore be a higher trigger efficiency and a lower reconstruction efficiency for double compared to single charm. We assume here however that the product of these two efficiencies remains roughly the same. Therefore, the overall average ccq efficiency is taken to be $\varepsilon \simeq 8\%$, comparable to the expected E781 value for ccq detection. The expected yield given above is 1.5×10^5 charm events/(nb/N) of effective cross section. For $\sigma_{BB} = 0.2$ nb/N, one has $\sigma_{eff} = 0.016nb/N$, and therefore $N(ccq) \approx 2400$ events for CHEOPS. This is the total expected yield for ccu,ccd,ccs production for ground and excited states. For $k > 0.4$, the yields are yet higher.

Conclusions

The observation of doubly charmed baryons or T would make possible a determination of their lifetimes and other properties. The expected low yields and short lifetimes make double charm hadron research an experimental challenge. The discovery and subsequent study of the ccq baryons or T should lead to a deeper understanding of the heavy quark sector.

Acknowledgements

Thanks are due to J. Appel, S. Brodsky, P. Cooper, F. Dropmann, L. Frankfurt, S. Gavin, J. Grunhaus, K. Konigsmann, B. Kopeliovich, E. Levin, H. J. Lipkin, B. Muller, S. Nussinov, S. Paul, B. Povh, J. Russ, M. A. Sanchis-Lozano, M. Savage, R. Vogt, R. Werding, and M. Zavertiev for stimulating discussions. This work was supported in part by the U.S.-Israel Binational Science Foundation (B.S.F.), Jerusalem, Israel.

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