Coalescence estimate of H dibaryon production in high-energy $p+A$ collisions

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A model of H dibaryon production is developed for high-energy $p+A$ collisions. The model is based on the coalescence of a neutron onto a Ξ^0 baryon, and rates for the processes involved are estimated from data collected at Fermilab. A form for the H's differential cross section is developed, and its total cross section is estimated to be approximately 1 μb.

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I. INTRODUCTION

The hadronic state with $B=2$ and $S=-2$ has been studied for more than a decade. Jaffe, using the MIT bag model, first proposed the existence of the dibaryon, which he coined the H. He predicted the state would have a mass of 2150 MeV/c^2 and a metastable lifetime typical of $\Delta S=1$ weak decays [1]. Since this initial work, the H has been studied in the framework of different theoretical models, with some yielding negative binding energies and others indicating positive binding. For example, a bag estimate corrected for center-of-mass effects resulted in the H being unbound by about 10 MeV [2]. A lattice gauge estimate predicted that the H has negative binding [3], while a more recent study using a smaller lattice size found the H to be stable relative to strong decay [4]. Some Skyrme models seem to predict positive binding for the H and thus metastable lifetimes [5–7]. Rosner, accounting for SU(3) breaking in quark masses when computing the hyperfine energy of the H, also finds positive binding [8]. Weak decays of the H have also been studied in detail [9].

Experimental searches for the H have been made, but no conclusive results have yet been reached [10,11]. The existence of the H remains an open question which must eventually be settled by experiment.

This paper outlines a model for the production of the H dibaryon in $p+A$ collisions at 400 GeV. The H is a six-quark composite containing $2u$, $2d$, and $2s$ quarks. Since the quark content is identical to the sum of the n and Ξ^0 baryons, the H production model developed below is based on the production of a $\Xi^0 n$ nucleus.

The cross sections for the H and the $\Xi^0 n$ nucleus can be related by $\sigma_H = F_1 F_2 \sigma_{\Xi^0 n}$, where the factors F_1 and F_2 are discussed below. The first factor arises because the $\Xi^0 n$ baryon pair represents only $\frac{1}{4}$ of the H's baryon-baryon wave function [12], since the quark content of other baryon pairs ($\Lambda\Lambda$, $\Sigma^+\Sigma^-$, $\Sigma^0\Sigma^0$, and $\Xi^- p$) also match that of the H. If each piece of the baryon-baryon basis contributes equally in the coalescence of an H, then $\Xi^0 n$ nucleus production should be enhanced by about a factor of $F_1 \sim 4$ when applied to H production. The second factor is needed because the coalescence probability for $\Xi^0 n$ nucleus formation will be different from the H since the binding and hence the physical size of the two composites are different: a $\Xi^0 n$ nucleus is likely to have a radius similar to a deuteron ($R_{\Xi^0 n} \sim 2$ fm), while an H is expected to have a radius more like that of a single hadron ($R_H \sim 1$ fm). The following argument will help to set the scale of this effect. As discussed in Ref. [13], if parent baryons are restricted to an interaction region with radius R, and R is large compared to the composite particle of radius R_c, then the coalescence probability for the parent baryons should go as $(R_c/R)^3$. Under these conditions [14], the coalescence probability ratio of the H to the $\Xi^0 n$ nucleus would be about 2^{-3}, so $\Xi^0 n$ nucleus production should be diminished by about a factor of $F_2 \sim \frac{1}{8}$ when applied to H production.

The factors F_1 and F_2 cannot be calculated with great precision, but the above estimates show that their product, $F_1 F_2$, is of order 1. The H production model discussed herein is thus taken to be equivalent to the coalescence production of a $\Xi^0 n$ nucleus.

Section II of this paper contains background information to the model and is comprised of two parts: the first supplies a simple parametrization of Ξ^0 production based on Fermilab data, and the second computes the penalty factor for the coalescence of a neutron, also based on Fermilab data. Section III combines results from the above section into the H production model.

II. BACKGROUND INFORMATION

A. A simple parametrization of Ξ^0 production

The aim of this parametrization of Ξ^0 production is to find an accurate yet simple form of production that can be easily modified to represent the H. To this end, I assume that the form of the Ξ^0's differential cross section is separable in rapidity and transverse momentum:

$$\frac{1}{\pi}\frac{d^2\sigma}{dy\,dp_t^2} = f(y)g(p_t^2) , \qquad (1)$$

where y is the rapidity in the center-of-mass frame and p_t is the transverse momentum. I assign the units of the differential cross section to the function $f(y)$, and keep $g(p_t^2)$ unitless.

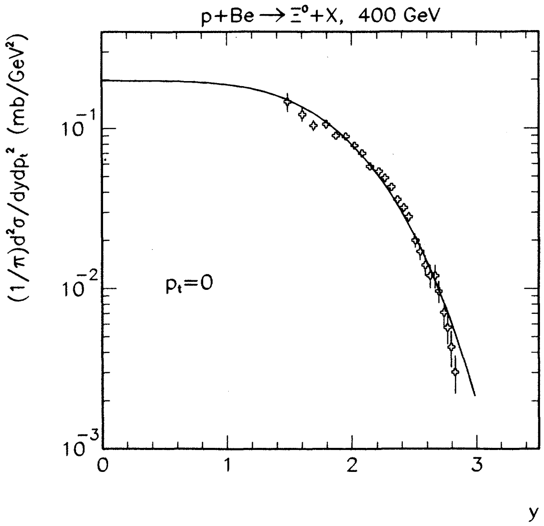

FIG. 1. Inclusive Ξ^0 production vs y at $p_t=0$ in 400-GeV $p+\mathrm{Be}$ collsions. Data points are from Ref. [15]; the line is the result of a fit to ae^{-by^4}.

Inclusive Ξ^0 differential cross-section data at $p_t=0$, collected in 400-GeV $p+\mathrm{Be}$ collisions [15], are shown in Fig. 1 as a function of y. A Gaussian fit in y does not conform to the rapid dropoff of the data, so a fit to the form

$$f(y)=ae^{-by^4} \tag{2}$$

is used. The result of the fit is $a=0.198\pm0.006$ mb/GeV^2, $b=0.057\pm0.001$, with $\chi^2/N_{\mathrm{DF}}=1.8$. This fit is shown as a line in Fig. 1. The initial and final reaction particles and the nature of the variable y suggest that the production is symmetric about $y=0$. The above fit for $f(y)$ is therefore used in the $y<0$ hemisphere as well.

There are limits on the rapidity available to the Ξ^0. These limits are well approximated by assuming that the maximum energy a Ξ^0 can receive is the energy of the incident proton beam. The rapidity limit in the center-of-mass frame is then given by

$$y_{\mathrm{lim}}\approx\pm[\operatorname{arccosh}(E_{\mathrm{beam}}/m_{\Xi^0})-y'_{\mathrm{cms}}] , \tag{3}$$

where y_{lim} is the rapidity limit, E_{beam} is the energy of the incident proton beam, m_{Ξ^0} is the mass of the Ξ^0, and y'_{cms} is the center-of-mass rapidity value in the laboratory frame. This gives $y_{\mathrm{lim}}=\pm3.0$ [16].

Figure 2(a) shows the inclusive differential cross section of the Ξ^0 vs p_t^2 at $y=1.5$ as reported in Ref. [15]. The cross section decreases roughly exponentially in p_t^2 over the range of p_t^2 available in this figure. The functional form of the transverse momentum spectrum is therefore taken as

$$g(p_t^2)=\exp(-p_t^2/\langle p_t^2\rangle) , \tag{4}$$

where $\langle p_t^2\rangle$ is the mean value of p_t^2. Fitting the data in Fig. 2(a) to the form $kg(p_t^2)$ yields the value $\langle p_t^2\rangle=0.5$ $(\mathrm{GeV}/c)^2$ over the range $0<p_t^2\lesssim1$ $(\mathrm{GeV}/c)^2$. The constant k is just the overall constant used to make the fit.

Figure 2(b) shows the same plot for $y=2.5$, where data at larger p_t^2 are available. The data in the region $p_t^2\gtrsim1$ $(\mathrm{GeV}/c)^2$ again go exponentially in p_t^2, but are characterized by a larger $\langle p_t^2\rangle$. Define a new function which is a sum of two exponentials:

$$g'(p_t^2)=c_1g(p_t^2)+c_2\exp(-p_t^2/\langle q_t^2\rangle) . \tag{5}$$

The variable $\langle q_t^2\rangle$ is the mean p_t^2 in the $p_t^2\gtrsim1$ $(\mathrm{GeV}/c)^2$ region of the spectrum, $g(p_t^2)$ represents $p_t^2\lesssim1$ $(\mathrm{GeV}/c)^2$ [its definition is unchanged from Eq. (4)], and the constants c_1 and c_2 are the relative weights of the shorter and longer transverse momentum components. The result of a fit to the data in Fig. 2(b) is $\langle q_t^2\rangle=1.3$ $(\mathrm{GeV}/c)^2$,

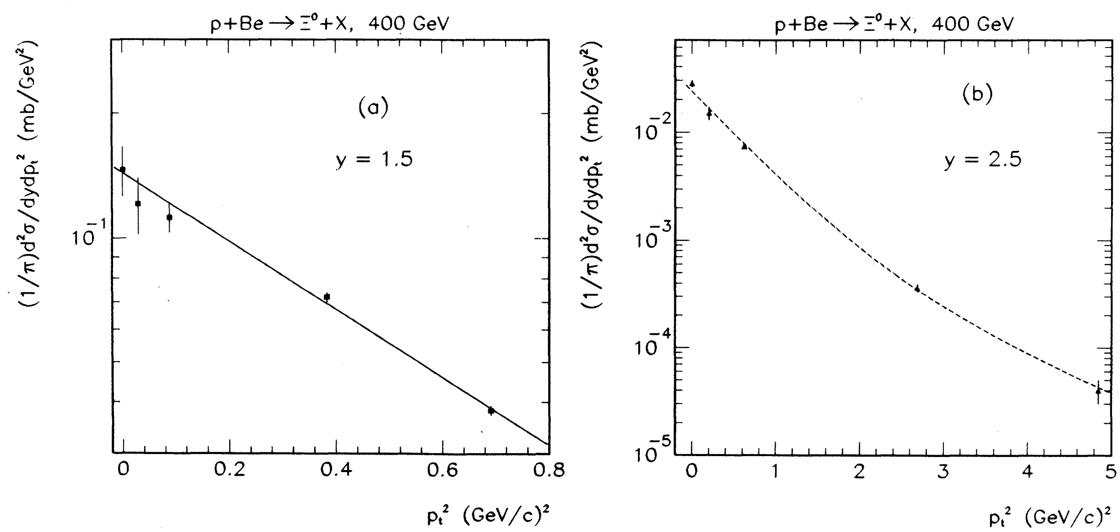

FIG. 2. (a) Ξ^0 production at $y=1.5$ vs p_t^2. The points are from Fermilab data, while the line is the result of a fit. (b) The same plot for $y=2.5$. The data are taken from Ref. [15]. See text for details.

$c_1=0.022$, $c_2=0.0017$. This fit is shown as a line in Fig. 2(b). Integrating Eq. (5) over all p_t^2 shows that the large transverse component of the spectrum [the second term in Eq. (5)] comprises only about 16% of the cross section. For simplicity, I will keep only the function $g(p_t^2)$ to represent the transverse momentum spectrum of the Ξ^0.

In summary, a simple parametrization of Ξ^0 production in $p+A$ collisions at 400 GeV is

$$\frac{1}{\pi}\frac{d^2\sigma}{dy\,dp_t^2}=(ae^{-by^4})[\exp(-p_t^2/\langle p_t^2\rangle)]\ , \qquad (6)$$

where $a=0.198$ mb/GeV^2, $b=0.057$, and $\langle p_t^2\rangle=0.5$ (GeV/c)^2. The rapidity is restricted to the range $-3.0<y<3.0$.

B. Penalty factor for the coalescence of a neutron

The coalescence process occurs when two or more particles are near enough to each other in $(\mathbf{x},\mathbf{p})$ space so that the particles bind and form a composite structure. For example, a proton and a neutron can coalesce to form a deuteron. The ratio of the deuteron production to the proton's production is a measure of the "penalty factor" for the coalescence of a neutron onto another baryon. The production ratios of deuterons to pions and protons to pions were measured at 0° in 300- GeV $p+$W collisions [17]:

$$\mathcal{R}\left[\frac{d_{y=0.7}}{\pi^+_{y=3.4}}\right]=1\times10^{-4}\ , \qquad (7)$$

$$\mathcal{R}\left[\frac{p_{y=0.7}}{\pi^+_{y=2.7}}\right]=9\times10^{-2}\ . \qquad (8)$$

Each production ratio was measured at a single momentum, which corresponds to a measurement at different rapidity values as indicated in Eqs. (7) and (8). Pion production data at 300 GeV and 0° is needed to obtain the ratio of deuterons to protons at $y=0.7$. Figure 3 shows low-p_t^2 π^+ production at 303 GeV/c measured as a function of x at Fermilab [18]. The line in the figure is a result of an exponential fit in x. A π^+ with rapidities of 3.4 and 2.7 has an x of 0.17 and 0.08, respectively. Using the exponential fit in Fig. 3, the data indicate that the ratio of pion production at these rapidities is $\mathcal{R}(\pi^+_{y=2.7}/\pi^+_{y=3.4})\simeq1.5$, which, when combined with Eqs. (7) and Eq. (8), yields the deuteron to proton production ratio at $y=0.7$:

$$\mathcal{R}\left[\frac{d}{p}\right]_{y=0.7}=\frac{1}{1350}\ . \qquad (9)$$

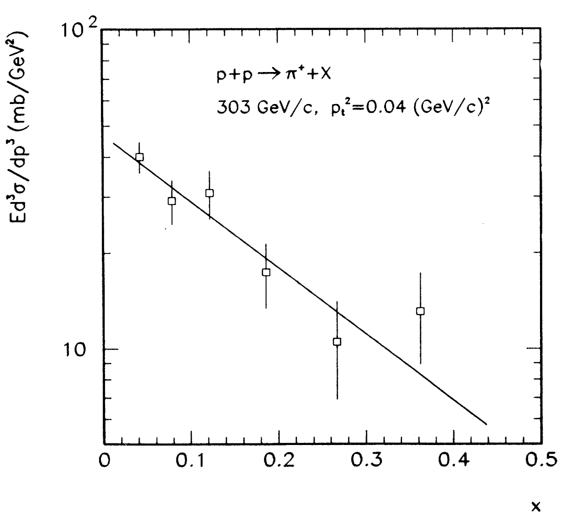

FIG. 3. Inclusive π^+ production at $p_t^2=0.04$ (GeV/c)^2 in 303-GeV/c $p+p$ collisions. Data are from Ref. [18].

III. A MODEL OF *H* PRODUCTION

The development of the H production model begins with Eq. (6). The first term in the equation contains the information on the shape of the rapidity spectrum and also the size of the cross section for the Ξ^0, while the second term represents the transverse momentum. Analogous terms can be written for the H: $(Ae^{-By^4})[e(-p_t^2/\langle P_t^2\rangle)]$, where A, B, and $\langle P_t^2\rangle$ are to the H what a, b, and $\langle p_t^2\rangle$ are to the Ξ^0.

The rapidity term in Eq. (6) is adapted to the H in two steps. The first step changes the limit of the y distribution for the H because it is more massive than the Ξ^0. The H's limit in y, found by replacing m_{Ξ^0} with Jaffe's estimate of $m_H=2150$ MeV/c^2 in Eq. (3), is $y_{\text{lim}}=\pm2.5$. This is incorporated into the term e^{-by^4} of Eq. (6) by setting $y\to(3.0/2.5)y$, where the fraction 3.0/2.5 is the ratio of rapidity limits for the Ξ^0 and the H. This gives a new form for the H: $e^{-2.1by^4}$, or e^{-By^4}, where $B=0.120$, with the newly imposed cutoff at $y=\pm2.5$. This effectively narrows the rapidity distribution (otherwise an H produced at the tail of the distribution would violate energy conservation) while retaining the distribution's shape. The second step reduces the H's cross section compared to the Ξ^0 to account for the coalescence of a neutron. Equation (9) suggests that $\mathcal{R}(\Xi^0 n/\Xi^0)=1/1350$ at $y=0.7$. Following the discussion in the Introduction, I apply this same penalty factor to the case of the H:

$$A=\frac{a}{1350}\left[\frac{e^{-by^4}}{e^{-By^4}}\right]_{y=0.7}\ , \qquad (10)$$

or $A=1.5\times10^{-4}$ mb/(GeV/c)^2.

The transverse momentum term in Eq. (6) is altered to accommodate the H by scaling the Ξ^0's $\langle p_t^2\rangle$ by mass:

$$\langle P_t^2\rangle=\frac{m_H}{m_{\Xi^0}}\langle p_t^2\rangle\ , \qquad (11)$$

or $\langle P_t^2\rangle=0.8$ (GeV/c)^2. This scaling makes sense if one views the coalescence process as a random walk in momentum space [19], so that the mean "displacement" in momentum goes as $\langle p_t\rangle\propto\sqrt{A}$. In this picture, the value of $\langle p_t^2\rangle$ would reasonably scale with mass.

H dibaryon production in 400-GeV $p+$Be collisions may therefore be written in the same general form as Eq. (6). It is convenient, however, to normalize the rapidity and transverse momentum spectra:

$$\frac{1}{\pi}\frac{d^2\sigma}{dy\,dp_t^2}=\frac{1}{\pi}\sigma_H\left[Ne^{-By^4}\right]\left[\frac{1}{\langle P_t^2\rangle}\exp(-p_t^2/\langle P_t^2\rangle)\right]. \quad (12)$$

The rapidity distribution's normalization was determined numerically to be $N=0.325$, and the spectrum is limited to the extremes $y=\pm 2.5$. The constants $B=0.120$ and $\langle P_t^2\rangle=0.8$ $(\mathrm{GeV}/c)^2$ were determined above. The H dibaryon's total cross section is thus $\sigma_H=1.2\times 10^{-3}$ mb.

The total absorption cross section for high-energy $p+\mathrm{Be}$ collisions was measured to be $\sigma_{\mathrm{tot}}=216$ mb [20], so this model suggests that the H should be produced an average of once in every 180 000 high-energy $p+A$ collisions. This number should not change much as a function of the type of nuclear target used, although there would likely be a modest change in the shapes of the spectra in Eq. (12) if the above analysis were repeated using other targets.

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