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July 14, 1977

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EVIDENCE FOR BARYONIUM EXCHANGE
IN
MEDIUM AND HIGH ENERGY SCATTERING*

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July 14, 1977

ABSTRACT

We review the prominent effects supposed to be associated with the exchange of baryonium Regge trajectories. The experimental presence of all expected effects leads us to suggest that the baryonium exchange mechanism is a correct phenomenological picture and that mesons with isospin 2 or $3/2$ or with strangeness -2, strongly coupled to the baryon-antibaryon channels, must be observed. An unexpected enhancement of the pure baryonium channel cross sections in the case of baryon decuplet production is pointed out. We also show that the old ρ' puzzle in $\pi^- p \rightarrow \pi^0 n$ seems to be solved by considering a recent generalization of the baryonium concept.

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I. INTRODUCTION

A new family of narrow width mesons, that couple predominantly to baryon-antibaryon channels, was predicted in 1968 from duality [1, 2]. Some years later, a rather similar prediction was made in the framework of the potential model [3, 4].

The several very narrow states in the 2-3 GeV region of mass [5-16] recently discovered in nucleon-antinucleon and $e^+e^- \rightarrow$ hadrons experiments (see Table I) can possibly be identified as members of the new class of mesons, which we shall call, following the definition introduced in refs. 17 and 18, baryonium [19].

Subsequent to a stimulating discussion by Chew and Rosenzweig [17, 18, 20] on the baryonium states and on the relevance of a new kind of Okubo-Zweig-Iizuka (OZI) - type selection rule [21] for these states, a number of interesting theoretical developments were made recently in the framework of the Topological Expansion, Dual Unitarization scheme, and Quantum Chromodynamics [22-30]. Interesting studies of the baryonium states were also made in the framework of the potential model [31-35]. However, the descriptions of baryonium differ from one another because different models for baryons (or, alternatively, different models for the $N\bar{N}$ potential) are used by different authors. On the other hand, extensive phenomenological studies of the baryonium exchange reactions, which could possibly put stringent restrictions on the theory of baryonium, are still missing.

In the present article we will review the phenomenological Regge picture emerging from the theoretical concept of "baryonium".

We will show that the baryonium exchange picture is an alternative or even favored dynamical mechanism when compared with other

existing models. Indirect but strong arguments in favor of the existence of isospin 2 and $3/2$ or strangeness -2 mesons will be presented. By comparing the baryonium Regge couplings to the meson-meson and baryon-antibaryon channels, the validity of the new OZI selection rule will be tested in the small negative t region. Finally we will show that the old ρ' puzzle in the pion-nucleon charge-exchange reaction seems to be solved by considering a recent generalization [24, 29] of the baryonium concept.

II. THE PHENOMENOLOGICAL PICTURE OF THE BARYONIUM EXCHANGE

Let us begin by making a few historical remarks concerning the concept of baryonium.

After the formulation of duality it was very soon recognized by Rosner [1] that it is impossible to draw a duality diagram for $B\bar{B}$ scattering with only $q\bar{q}$ intermediate states in each channel; namely, new $qq\bar{q}\bar{q}$ states (baryonium states) are needed. The need for these new states can easily be seen directly from the s - t crossing relation in the illustrative example of the forward $\Delta\bar{\Delta}$ scattering: no nontrivial solution of the crossing relation can be obtained with only $I=0$ and 1 contributions in both channels [36]. In a general way, it was shown by Mandula, Weiers and Zweig, that the duality equations in $B\bar{B}$ scattering have no solution if the baryonium states are not introduced [36].

The communication between baryonium states and the usual $q\bar{q}$ mesons was thought to be forbidden by the Freund-Rosner-Waltz rules for the duality diagrams [37]. It was therefore expected that the baryonium would manifest itself as narrow-width mesons. Concerning the

masses of the baryonium states, it was shown that they can be neither too low nor too high (compared with the respective spins). Were they too low the conclusion drawn from the dual approximations of Regge poles and nonexotic resonance dominance in MM and MB scattering would be invalidated [36, 38]; were they too high the dual description of $B\bar{B}$ scattering would be contradicted [36]. Assuming that the baryonium states lie on linear Regge trajectories with the universal slope, one obtains from the above considerations an estimate of the intercept of the leading baryonium trajectory $\alpha_B(0) \lesssim -0.5$. As we shall see in the following, this very rough estimate in fact agrees both with more elaborate, recent theoretical schemes of the baryonium and with the experimental data.

The intercept of the baryonium trajectory is sufficiently high to produce observable effects in the medium energy region ($p_L \simeq 2$ -10 GeV/c) via the interference with the contributions of the usual Regge trajectories, for example in polarization experiments [39]. However, it is obvious that, in general, the separation of the baryonium contribution will be delicate and ambiguous. Therefore, in order to make crucial tests of the existence of the baryonium, one must look at the special class of reactions involving pure baryonium t -channels.

By definition, a "pure baryonium channel" is a channel whose quantum numbers cannot be obtained as the quantum numbers of a $q\bar{q}$ system, but only, as those of a $qq\bar{q}\bar{q}$ system.

Correspondingly we distinguish the following triad of leading baryonium trajectories in the pure baryonium channels:

1) the non-strange $S=0$ baryonium.

This corresponds to an isospin $I=2$ exchange. The quantum numbers are associated with a combination of quark boundaries of the

type $u\bar{u}\bar{d}\bar{d}$. It will occur in the forward scattering in reactions like $pn \rightarrow \Delta^+ \Delta^{++}$ or $\pi^- p \rightarrow \pi^+ \Delta^-$;

ii) the strangeness $S=-1$ baryonium.

This trajectory, corresponds to an isospin $I=3/2$ exchange. The quantum numbers are those of $s\bar{d}u\bar{u}$ or $s\bar{u}\bar{d}\bar{d}$. It will occur in reactions like $\bar{p}p \rightarrow \bar{Y}^{*+} Y^{*-}$ or $K^- p \rightarrow \pi^+ Y^{*-} (Y^{*-} Y^* (1385))$;

iii) the strangeness $S=-2$ baryonium.

The quantum numbers are those of $ss\bar{u}\bar{u}$, $ss\bar{d}\bar{d}$ or $ss\bar{u}\bar{d}$. It will contribute to reactions like $\bar{p}p \rightarrow \Xi^{*+} \Xi^{*-}$ or $K^- p \rightarrow K^+ \Xi^{*-} (\Xi^{*-} \Xi^* (1530))$.

(Let us note that what we call "pure baryonium channels" are sometimes named "exotic" channels and the corresponding Regge trajectories are called "exotic" trajectories. However, because the effects we will consider are explained in a natural manner by the baryonium concept and the usual Regge pole theory, no degree of "exoticity" being involved, we will not use, for the sake of clarity, the older terminology. In any case, the general definition for exotic particles [40] involves a class of particles much richer than the group of "exotic" mesons belonging to the baryonium family.)

Now, one can ask what will be the major effects of the existence of the baryonium states and of their associated Regge trajectories in the pure baryonium channels at medium energy? In other words, what are the prominent experimental manifestations of the baryonium states, independent of the details of their dynamics?

We distinguish the following four major effects, described in the hierarchy of their generality:

1) The existence of clean forward peaks in the pure baryonium channels.

These peaks are usually considered to be "forbidden" because of the supposed nonexistence of "exotic" particles. However, if the baryonium states exist, they must produce marked forward peaks in the pure baryonium channels at medium energy. These forward peaks must decrease in magnitude when the energy increases in agreement with the Regge pole behaviour of the baryonium contribution.

2) The change of the energy variation regime from the low energy to the medium energy region.

The baryonium Regge trajectories must produce an energy dependence $\sim s^{-3} s^{-4}$ of the forward differential cross-sections, much slower than the energy variation in the low energy region ($\sim s^{-9} s^{-10}$). This expected break in the energy dependence is a similar phenomenon to that already observed in the non-baryonium channels.

3) The approximate validity of the new OZI rule in the small negative t region.

The new selection rule, forbidding the decay of baryonium into mesons is supposed to be valid in the positive t region. Using a smoothness assumption, one can expect a rather large ratio of the coupling of the baryonium to the $B\bar{B}$ channel when compared to that to the $M\bar{M}$ channel. Therefore, the forward cross section of, say, $pn \rightarrow \Delta^+ \Delta^{++}$ must be considerably larger than the forward cross section of $\pi^- p \rightarrow \pi^+ \Delta^-$ (or $\pi^+ n \rightarrow \pi^- \Delta^{++}$).

4) The absence of strong dynamical suppressions in the pure baryonium channels.

There is no theoretical argument indicating the suppression of baryonium states. We therefore expect the pure baryonium channel cross sections to be comparable to those in the reactions involving the exchange of the usual meson trajectories.

For example, the forward cross section in $pn \rightarrow \Delta^- \Delta^{++}$ must be of the same order of magnitude as the forward cross section in $pn \rightarrow \Delta^{++} \Delta^-$ at sufficiently low energies (namely, just above the break in the energy dependence of the cross sections).

The above major qualitative features of the baryonium exchange reactions will be confronted with the data in the next section.

III. ANALYSIS OF THE MAJOR EXPERIMENTAL EFFECTS IN THE PURE BARYONIUM CHANNELS

The reactions involving pure baryonium t-channels studied in this section can be classified into two groups:

a) reactions involving the coupling of the baryonium only to baryon-antibaryon channels; they are of the form

$$B_1 B_2 \rightarrow D_1 D_2 \quad (1)$$

$$\bar{B} B \rightarrow \bar{D} D \quad (2)$$

or

$$\bar{B}_1 B_1 \rightarrow \bar{B}_2 B_2, \quad (3)$$

where B denotes baryons belonging to the $1/2^+$ octet and D- baryons belonging to the $3/2^+$ decuplet;

b) reactions involving the coupling of the baryonium to both meson-meson and baryon-antibaryon channels; they are of the form

$$M_1 B_1 \rightarrow M_2 D_2 \quad (4)$$

or

$$M_1 B_1 \rightarrow M_2 \bar{B}_2, \quad (5)$$

where M denotes mesons belonging to the 0^- octet.

In fact, we will focus our discussion on the reactions of the type (1), (2) and (4) involving production of $3/2^+$ decuplet baryons. The reasons for this restriction are both theoretical and practical.

It is well known that empirically there is an important suppression of the reactions (3) and (5) involving production of $1/2^+$ octet baryons when compared with the reactions of the type (1), (2) or (4). For example, at $p_L = 4.2$ GeV/c the forward differential cross section for $K^- p \rightarrow \pi^+ Y^{*-}$ is ten times larger than the one for $K^- p \rightarrow \pi^+ \Sigma^-$ [43k, 46].

Theoretically, as was shown by Hoyer and Quigg [41], one can understand this suppression using the triple-Regge expansion at fixed s and different (mass)² of the produced baryon. The explicit (mass)² dependence of cross sections implies that the larger the mass of the produced resonance - the larger the "forbidden" cross section. For some particular cases the suppression of octet final states is reinforced by SU(6) Clebsch-Gordan coefficients. For example, the coupling of $\bar{p} Y^{*-}$ to baryonium is $4\sqrt{2}$ that of $\bar{p} \Sigma^-$ [40].

This suppression phenomenon of low-mass produced baryons is a phenomenon occurring within the class of reactions involving pure baryonium channels, and must not therefore be invoked as an argument for the general suppression of "exotic" reactions.

On a practical level, the above discussed suppression implies that the detection of the experimental effects in the pure baryonium channels for the reactions (3) and (5) is possible only in high precision experiments, which unfortunately are rare at the present time.

One must note that the quality of the existing data for the reactions (1), (2) and (4) do not allow a very detailed quantitative Regge analysis; however, there is a relatively large number of data points in the medium energy region ($p_L \approx 2-10$ GeV/c) and their precision is sufficient to test the major qualitative effects expected from the exchange of baryonium trajectories.

One must also remark that much of the existing data in the medium energy region is concentrated at the lower end of this energy range ($p_L \approx 2-4$ GeV/c) where a Regge expansion is not accurately valid. However, this fact is not essential for the present purpose which is to look for generic and not for detailed quantitative features associated with the exchange of baryonium. Therefore we expect that our basic conclusions will not be altered by a more accurate treatment.

The particular reactions used in our analysis are the following:

i) pure $I=2$ baryonium channel [42 a)-h)]

$$pn \rightarrow \Delta^- \Delta^{++} \quad (6)$$

and

$$\pi^- p \rightarrow \pi^+ \Delta^-$$

or

$$\pi^+ n \rightarrow \pi^- \Delta^{++} ;$$

ii) pure $I=3/2$ baryonium channel [42 c)-d), 43 a)-k)]

$$\bar{p}p \rightarrow \bar{Y}^{*+} Y^{*-} \quad (8)$$

$$\pi^- p \rightarrow K^+ Y^{*-} \quad (9)$$

and

$$K^- p \rightarrow \pi^+ Y^{*-} \quad (10)$$

iii) pure $S=-2$ baryonium channel [42 c)-d), 43h), 44 a)-b)]

$$K^- p \rightarrow K^+ \Xi^{*-} \quad (11)$$

(There is no data for the interesting reaction $\bar{p}p \rightarrow \bar{\Xi}^{*+} \Xi^{*-}$).

Let us notice that the $I=3/2$ and the $S=-2$ baryonium channels can also be reached from the corresponding reactions involving the production of $1/2^+$ octet baryons. There is some significant data [45, 46] for reactions like

$$\bar{p}p \rightarrow \bar{\Sigma}^+ \Sigma^- \quad (12)$$

and

$$K^- p \rightarrow \pi^+ \Sigma^- \quad (13)$$

which will also be used in our analysis.

1) The existence of forward peaks in the pure baryonium channels.

This subject received some attention in the early 1970's, after the discovery of "forbidden" peaks in the reactions (6)-(11) [47], where the differential cross section shows a typical decrease of one order of magnitude in the forward hemisphere (see figs. 1 a) - f) for some examples). A comprehensive review of the experimental situation at that time was given by Rosner [40]. The excitement provoked by this discovery was soon dulled by skepticism, due to the following three fundamental objections:

a) the lack of evidence for forward peaks in octet-production reactions;

b) the possibility of simulating forward peaks in decuplet-production reactions by "kinematical" reflections, as first suggested by Berger [48, 49] or of producing them by double-reggeon exchange [50];

c) the spectroscopic absence of baryonium states.

This skeptical attitude persisted until last year. However, now the experimental situation is completely changed.

First, forward peaks in octet-production reactions are observed. For example, high statistics experimental data showing the definite confirmation of a forward peak in $K^- p \rightarrow \pi^+ \Sigma^-$ at $p_L = 4.2$ GeV/c were published this year [46]. Also, there is evidence of a forward peak in $\bar{p}p \rightarrow \bar{\Sigma}^+ \Sigma^-$ at $p_L = 3.6$ GeV/c [45]. As we explained above, the fact that it is so difficult to observe the expected effects in the octet-production reactions must not be considered surprising, due to the natural suppression of lower-mass produced baryons in the class of reactions involving pure baryonium

channels.

Secondly, the "kinematical" reflections (see fig. 2 for an example) which are surely a possible process, can not account quantitatively for the forward peaks in the reactions (6)-(11), as was discussed extensively in the literature [e.g. 42b), 42d), 43f), 43k)]. Moreover, the "kinematical" reflections obviously can not occur in the reactions involving stable particle final states, like $K^- p \rightarrow \pi^+ \Sigma^-$, where the forward peaks are nevertheless observed. Therefore the "kinematical" reflections cannot be the general mechanism giving forward peaks in the pure baryonium channels.

The alternative mechanism of double-Regge exchange can, of course, account qualitatively for all the observed "forbidden" forward peaks. However, at the quantitative level, the existing models [50-53] show a tendency of giving too low values for the forward cross sections. For example, they predict for $K^- p \rightarrow \pi^+ \Sigma^-$, at $p_L \simeq 4$ GeV/c a value of $\sim 0.1 \mu\text{b}/\text{GeV}^2$, while the experimental value is 10 times larger.

Finally, narrow-width mesons which are good candidates for being baryonium states were recently discovered [5-11, 13-16]. It is true that these mesons have the usual quantum members (i. e. they can be considered only as "cryptoexotics") but in the baryonium scheme they appear on the same footing as the $I=2$ or $3/2$ or $S=-2$ mesons. It is interesting to note that recently some experimental indications of the existence of an $I=2$ narrow-width meson ($M=2660$ MeV, $\Gamma < 20$ MeV) were reported [12]. The confirmation of such a meson will be crucial for the assesement of the baryonium scheme.

In conclusion, the main objections against the description of the "forbidden" forward peaks resulting from baryonium exchange

seem now to vanish. The present situation is summarized in Table II and also in fig. 3, where we present a compilation of world-data for the reactions (6)-(11).

2) The change of the energy variation regime from the low energy to the medium energy region.

The fast decrease of the cross sections with the energy ($\sim s^{-9}$ - s^{-10}) below 2 GeV/c is common to many inelastic reactions, involving or not pure baryonium channels. After 2 GeV/c there is known to be a break in the energy dependence, showing the transition to a Regge regime, not only in the reactions involving the usual meson exchanges but also in the octet-production reactions (3) and (5) [50]. Here we will show that the same break, in agreement with the Regge-pole behavior, occurs in the decuplet-production reactions (1), (2) and (4). In order to extract the Regge intercepts corresponding to the baryonium trajectories, we will use the data on the integrated cross section in the forward direction, σ_f , which, in the Regge pole model, has the approximate form:

$$\sigma_f \approx K \cdot \left(\frac{s}{s_0} \right)^{2\alpha(0)-2} / \ln \left(\frac{s}{s_0} \right) \quad (14)$$

(here K is a constant and s_0 is fixed at the standard value $s_0 = 1 \text{ GeV}^2$). By plotting the quantity $\ln s \cdot \sigma_f$ as a function of s one can directly extract from the data the baryonium intercepts.

1) $I = 2$ ($S=0$) baryonium.

From the data on $\pi^- p \rightarrow \pi^+ \Delta^-$ and $\pi^+ n \rightarrow \pi^- \Delta^{++}$, one obtains (see fig. 4 a))

$$\alpha_B(I=2)(0) = -0.75 \pm 0.2 \quad (15)$$

The data on $pn \rightarrow \Delta^- \Delta^{++}$ are in agreement with the corresponding energy variation $\sim s^{-3.5}$ (fig. 4a)).

This value (15) of the isospin 2 baryonium intercept is in agreement with the theoretical estimates based upon the diquark model [17], dual unitarization scheme and QCD or string models [24-29, 54-55], which predict $\alpha_{\frac{3}{2}(I=2)}(0) \lesssim -0.5$. It is also in agreement with a previous phenomenological estimate, $\alpha(0) \simeq -0.5 \pm 0.3$, by Hoyer, Roberts, and Roy from the analysis of the reaction $\pi^- p \rightarrow pX$ [56].

We will assume that the slope of the $I=2$ baryonium is the universal one ($\alpha' \simeq 1 \text{ GeV}^{-2}$). We will also assume the approximate but systematic isospin 0, 1, and 2 degeneracy, as suggested by Chew [17]. One can so predict a rich spectrum of baryonium states associated with the baryonium trajectory

$$\alpha(t) \simeq -0.75 + t \quad (16)$$

For example, one expects a spin-2 particle at a mass $\simeq 1660$ MeV and a spin-3 particle at a mass $\simeq 1940$ MeV (see fig.5). This last baryonium state is compatible with the narrow states observed in the 1930-1940 MeV region of mass [5-8] (the so-called S meson region) or at $m=2020 \pm 3$ MeV [10]. The spins of these experimental states are not yet firmly established. For example, Kelly and Phillips [57], who analyzed some of the experiments showing the structure at the 1930-1940 MeV region of mass, found a range of possible J values which includes $J=3$. However, Carter [58], using the method of differential cross section zeros for $\bar{p}p \rightarrow \bar{p}p$ scattering, concluded that only the assignment $J^{PC} = 2^{++}$ is possible (in which case the S meson will not lie on our trajectory).

At the mass $\simeq 2180$ MeV one expects from (16) a spin 4 particle. A narrow resonance with $m = 2204 \pm 5$ MeV but with unknown spin was recently observed [10].

The spin 5 particle on the trajectory (16) has a mass $\simeq 2400$ MeV, compatible with the experimental spin 5 meson of mass $\simeq 2480$ MeV discovered by Carter et al. [59]. One must note that this meson has a large width, $\Gamma \sim 280$ MeV, and therefore is not included in Table I. In ref. 59 two other broad resonances of spin 3 and 4 were established, but they correspond to a lower lying trajectory, $\alpha(t) \simeq -1.5 + t$.

The spin 6 recurrence has a mass $\simeq 2600$ MeV, not far from the region of mass ($m \simeq 2660$ MeV) in which a narrow $I = 2$ meson seems to be observed [12]. Finally, the spin 7 recurrence has a mass $\simeq 2780$ MeV, compatible with the narrow state of mass $\simeq 2850$ MeV discovered by Braun et al. [13].

We also predict the existence of resonances at $m \simeq 2960$ MeV, $m \simeq 3120$ MeV etc.

Obviously, we by no means claim that all the quoted experimental states lie on our baryonium trajectory, due to the arbitrary assignment of the different quantum numbers and in particular of the spin. However, the agreement between the predicted and the experimental mass spectrum of baryonium states is rather impressive, especially taking into account that we have discussed only the spectrum associated with the parent baryonium trajectory (16). The daughters of this trajectory have the same spectrum of mass, but smaller spin values for the corresponding particles.

Finally, let us note that recently Dash and Navelet [60] have advocated the existence of a low lying vacuum trajectory σ from a study of the anomalous energy dependence of the pp and pn elastic polarizations at medium energy. This trajectory has an intercept $\alpha_\sigma(0) \simeq -0.4$ and couples more strongly to baryons than to mesons. It can therefore be identified as the $I = 0$ companion of the $I = 2$

baryonium trajectory discussed in this section.

ii) $I = 3/2$ ($S = -1$) baryonium.

From the data on $\pi^- p \rightarrow K^+ Y^{*-}$ or $K^- p \rightarrow \pi^+ Y^{*-}$, one obtains (see fig. 4b))

$$\alpha_B(I = 3/2)(0) \approx -1.2 \pm 0.2 \quad (17)$$

The data on $\bar{p} p \rightarrow \bar{Y}^{*+} Y^{*-}$ are in agreement with the corresponding energy variation $\sim s^{-4.4}$.

One notes the relative suppression of the $S = -1$ pure baryonium channels compared with the $S = 0$ ones. For example, $\sigma_f(\pi^- p \rightarrow K^+ Y^{*-}) = 4.74 \pm 1.66 \mu\text{b}$ at $p_L = 3 \text{ GeV/c}$ [42 d)], while $\sigma_f(\pi^- p \rightarrow \pi^+ \Delta^-) = 50.1 \pm 12.2 \mu\text{b}$ at a similar value of p_L ($p_L = 3.2 \text{ GeV/c}$) [42 d)]; at $p_L \approx 3.7 \text{ GeV/c}$, $\sigma_f(\bar{p} p \rightarrow \bar{Y}^{*+} Y^{*-}) = 8 \pm 3 \mu\text{b}$ [43 a)], while $\sigma_f(p n \rightarrow \Delta^- \Delta^{++}) = 550 \pm 200 \mu\text{b}$ [42 a)].

One can also note the difference in magnitude between $K^- p \rightarrow \pi^+ Y^{*-}$ and $\pi^- p \rightarrow K^+ Y^{*-}$: $\sigma_f(K^- p \rightarrow \pi^+ Y^{*-})$ is systematically higher than $\sigma_f(\pi^- p \rightarrow K^+ Y^{*-})$. For example, at $p_L \approx 4 \text{ GeV/c}$, $\sigma_f(K^- p \rightarrow \pi^+ Y^{*-}) = 2.8 \pm 0.5 \mu\text{b}$ [43 k)], while $\sigma_f(\pi^- p \rightarrow K^+ Y^{*-}) \approx 1 \mu\text{b}$ [43 g)]. This difference in magnitude, which results from the line-reversal symmetry breaking, is a similar phenomenon to that observed in the analogous reactions involving usual meson exchanges, for example $K^- p \rightarrow \pi^- \Sigma^+$ and $\pi^+ p \rightarrow K^+ \Sigma^+$ [61], and which was explained in the framework of the dual unitarization scheme [62] or the quark-rearrangement model [63-64].

Let us finally remark that, assuming the universal slope and the approximate isospin 1/2 and 3/2 degeneracy, one obtains also a rich spectrum of the strange baryonium states. For example, one expects

a narrow-width spin 2 particle with $m \approx 1800 \text{ MeV}$, a narrow-width spin 3 particle near the $N\bar{\Sigma}$ threshold, and a narrow-width spin 4 particle near the $N\bar{Y}^*$ threshold. It is interesting to note that arguments which favor the existence of strange $I = 3/2$ mesonic resonances with masses near 2 GeV were recently proposed by Bogdanova, Dalkarov, and Shapiro in a different context - that of the potential model [35]. It is also interesting that an object of high mass ($2600 \pm 100 \text{ MeV}$) and narrow width ($\Gamma \leq 18 \text{ MeV}$) having the "crypto-exotic" quantum numbers of nucleon-antihyperon system (namely, those of $p\bar{\Lambda}$) was already observed [11].

iii) $S = -2$ baryonium.

There is not a sufficient number of data on $K^- p \rightarrow K^+ \Xi^{*-}$ in order to make a precise evaluation of the corresponding baryonium intercept. However, from fig. 4b) one can deduce that

$$\alpha_B(S = -2)(0) \approx \alpha_B(I = 3/2)(0) \approx -1.2 \pm 0.2 \quad (18)$$

One may also observe the relative suppression of the $S = -2$ pure baryonium channels compared with the $S = -1$ ones. For example, at $p_L = 3 \text{ GeV/c}$, $\sigma_f(K^- p \rightarrow K^+ \Xi^{*-}) = 2 \pm 2 \mu\text{b}$, while $\sigma_f(K^- p \rightarrow \pi^+ Y^{*-}) = 12 \pm 2 \mu\text{b}$ [43 h)]. Concerning the mass spectrum of the $S = -2$ baryonium states, one expects from (18) and the assumed universal slope, that it will be rather similar to that of $S = -1$ baryonium states.

3) The approximate validity of the new OZI rule in the small negative t region.

A new kind of OZI rule is generally supposed to be valid in the positive t region, in order to insure the stability of the baryonium states (see fig. 10 for an illustration of the new selection rule in the framework of different existing schemes).

The dynamical content of such a rule is not yet completely clarified. In some of the existing models the baryonium is coupled to the mesonic channel even at the "planar" level (e.g. [27]).

Presently, one can understand the dynamical content of the new OZI rule by recognizing the need for an artificial Hilbert space (larger than the physical Hilbert space) in which the particle order is important; one then contracts the Hilbert space of ordered states via the "topological expansion", connecting in such a way the "ordered" S matrix to experiment [65].

It is interesting to test the experimental validity of the new selection rule also in the negative t region; one must then compare reactions of the type (1)-(3) with those of the type (4)-(5).

For example, assuming that

$$\sigma_f(pn \rightarrow \Delta^- \Delta^{++}) = K_1 \cdot s^{-3.5/\ln s} \quad (19)$$

and

$$\sigma_f(\pi^- p \rightarrow \pi^+ \Delta^- \text{ or } \pi^+ n \rightarrow \pi^- \Delta^{++}) = K_2 \cdot s^{-3.5/\ln s}$$

one obtains from the existing data on these reactions

$$K_1/K_2 \simeq 25-50 \quad (20)$$

(see fig. 5, which corresponds to $K_1/K_2 \simeq 38$).

The obvious meaning of the large value (20) of the ratio K_1/K_2 is that the $I = 2$ baryonium is much more strongly coupled to the $N\Delta$ channel than to the MM channel. Therefore it seems that the new OZI rule, responsible for the small widths of the baryonium states, is not too badly violated in going from the positive t to the small negative t region.

A similar conclusion is obtained by looking at $I = 3/2$ baryonium exchange reactions. By comparing

$$\sigma_f(\bar{p}p \rightarrow \bar{Y}^{*+} Y^{*-}) = K_3 \cdot s^{-4.4/\ln s} \quad (21)$$

and

$$\sigma_f(\pi^- p \rightarrow K^+ Y^{*-}) = K_4 \cdot s^{-4.4/\ln s} \quad (22)$$

with the data one obtains a relatively large ratio

$$K_3/K_4 \simeq 5 - 10 \quad (23)$$

(see fig. 6, which corresponds to $K_3/K_4 \simeq 7.5$).

It is interesting to note that a large value of the ratio of the couplings can also be obtained by comparing the octet-production reactions (3) and (5). For example, $\sigma_f(\bar{p}p \rightarrow \bar{\Sigma}^+ \Sigma^-) = 5.9 \pm 1.1 \mu b$ at $s = 8.76 \text{ GeV}^2$ [45], while $\sigma_f(K^- p \rightarrow \pi^+ \Sigma^-) = 0.6 \pm 0.1 \mu b$ at $s = 9.06 \text{ GeV}^2$ [46], and these values correspond to a ratio of the couplings of the order $\simeq 10$.

The fact that the new selection rule seems to be rather weakly violated in the small negative t region is an interesting feature which must be incorporated in the theory of baryonium.

4) The absence of strong dynamical suppressions in the pure baryonium channels.

A striking feature of the experimental data is the fact that the pure baryonium channel cross sections (σ_B) for the decuplet-production is quite comparable with those corresponding to the usual mesonic Regge exchanges (σ_R). From the assumed Regge behavior of the cross sections one has

$$\frac{\sigma_B}{\sigma_R} = \frac{\beta_B^2}{\beta_R^2} s^{2[\alpha_B(0) - \alpha_R(0)]} \quad (24)$$

where β denotes the respective Regge residue.

Because of the relatively large gap between the Regge intercepts one expects large suppression factors to occur. For example, if $0 \lesssim \alpha_R(0) \lesssim 1/2$ and if $\beta_R^2/\beta_B^2 \simeq 1$, one expects at $s \simeq 10 \text{ GeV}^2$ a suppression factor $\simeq 1/30 - 1/300$ for the $I = 2$ baryonium cross

sections, and a suppression factor $\simeq 1/250 - 1/2500$ for the $I = 3/2$ baryonium cross sections.

The experimental ratios σ_B/σ_R are in fact much larger than these values expected from the naive Regge arguments. For example $\sigma_f(pn \rightarrow \Delta^- \Delta^{++}) / \sigma_f(pn \rightarrow \Delta^{++} \Delta^-) \simeq 1/2$ at $s = 8.94 \text{ GeV}^2$ [42a)] and $(d\sigma/dt)_{t=0}(K^- p \rightarrow \pi^+ Y^{*-}) / (d\sigma/dt)_{t=0}(K^- p \rightarrow \pi^- Y^{*+}) \simeq 1/6$ at $s = 9.06 \text{ GeV}^2$ [43 k)]. One is therefore forced to draw the rather surprising conclusion that, for decuplet-production reactions,

$$\beta_B^2 \gg \beta_R^2. \quad (25)$$

In particular, the baryonium coupling to the baryon-antibaryon channel is much stronger than the usual meson coupling. (Obviously this conclusion depends critically on the assumption, which we regard as reasonable, that the scale factor $s_0 \simeq 1 \text{ GeV}^2$). Therefore one has a much weaker suppression of the pure baryonium channels than that expected on the basis of the rather large gap between the reggeon intercepts.

One must note that, at comparable energies, there is a much stronger suppression of the pure baryonium channels for the baryon octet production. For example, $(d\sigma/dt)_{t=0}(K^- p \rightarrow \pi^+ \Sigma^-) / (d\sigma/dt)_{t=0}(K^- p \rightarrow \pi^- \Sigma^+) \simeq 1/700$ at $s \simeq 9.06 \text{ GeV}^2$ [46]. This value of the suppression factor is in the range given by the above discussed naive Regge arguments.

The unexpected enhancement of the pure baryonium channel cross sections in the case of baryon decuplet production is an interesting phenomenological fact which surely deserves further theoretical investigation.

IV. THE ρ' PUZZLE IN $\pi^- p \rightarrow \pi^0 n$ AND A GENERALIZATION OF THE BARYONIUM CONCEPT.

The pion-nucleon charge-exchange scattering in one of the sacred

reactions of high-energy phenomenology, being the most nonambiguous example of Regge pole behavior in hadronic scattering amplitudes. One can note, in the context of our discussion, that this reaction involves in the t -channel a reggeon-baryon-antibaryon vertex, which in principle involves not only the usual mesonic Regge trajectories but also the baryonium ($I=1$) trajectories. Because of the pure $I=1$ quantum numbers we expect the baryonium to have observable effects in $\pi^- p \rightarrow \pi^0 n$. Before analyzing the models for baryonium having a possible relevance for the discussion of these effects [24, 29], let us briefly summarize the existing phenomenological situation concerning this reaction.

As is well known, the ρ Regge pole alone cannot describe all the data on $\pi^- p \rightarrow \pi^0 n$. The large positive polarization observed for small t at medium energy ($p_L \simeq 5-11 \text{ GeV}/c$) clearly indicates the existence of a supplementary contribution. The simplest and most successful description of all the existing data can be achieved using the $\rho + \rho'$ Regge pole model [66-69]. The best parameters for the ρ' trajectory (see fig. 7), obtained by analyzing the data in the 5-200 GeV/c energy region are [69]:

$$\alpha_{\rho'}(t) = -0.13 + 0.3t \quad (26)$$

(one observes that a slightly different ρ' trajectory, $\alpha_{\rho'}(t) = 0.29t$, was obtained in ref. 68, due to the different assumptions on the structure of Regge residues. However, this small difference in the ρ' Regge parameters will be irrelevant for the following discussion).

Obviously, the ρ' trajectory (26) should not be confused with the trajectory associated with the so-called ρ' (1600) meson. This last trajectory has the universal slope, a much lower intercept than (26), and a very small coupling to the $\pi\pi$ channel.

Let us note that in the initial version of the $\rho + \rho'$ model [65], the ρ and ρ' trajectories were supposed to be parallel, both

having the universal slope. Based on the experimental indication of a possible zero in the polarization near $t \sim -1$ (GeV/c)², we argued, some years ago [67], that the ρ and ρ' trajectories must intersect the ρ' trajectory having in fact a rather small slope ($\alpha'_{\rho'} \sim 0.3$ GeV⁻²). We therefore predicted that an important curvature of the effective trajectory in $\pi^- p \rightarrow \pi^0 n$ must be observed for large negative t . This curvature was definitely confirmed in recent high energy data on the differential cross section [70].

In spite of its success in describing all the available data on $\pi^- p \rightarrow \pi^0 n$, the $\rho + \rho'$ model was considered to lack a deep significance, the ρ' trajectory being merely a simple parametrization of complicated contributions rather, than a genuine Regge pole. In particular, the existence of Regge recurrences compatible with the ρ' trajectory (26) (which requires, for example, the existence of a spin 1 meson of a mass ~ 1940 MeV, if the slope continues to be $\alpha'_{\rho'} = 0.3$ (GeV)⁻² in the positive t region) was doubtful. Now, however, the rich experimental structure observed in the 2 GeV region of mass (see Table I) can be compatible with the existence of a vector meson having the quantum numbers of the ρ meson. Also, a recent generalization of the baryonium concept [29] leads to an evaluation of the leading $I=1$ baryonium Regge trajectory whose intercept and slope are very close to those in eq. (26).

Let us review this recent generalization of the baryonium concept made by Rossi and Veneziano [24] and Toyoda and Uehara [29], in order to understand the connection between the phenomenological ρ' trajectory and the leading $I=1$ baryonium trajectory.

In the models of refs. 24 and 29, the baryon or the antibaryon is represented by the topological structure obtained by joining

together three oriented surfaces (each having as a boundary a quark or antiquark line) through a color ("junction" or "antijunction") line (see fig. 8 a)). Therefore, in baryon-antibaryon scattering one obtains three distinct "baryonium" topological configurations ($\mathcal{B}_4$, $\mathcal{B}_2$ and $\mathcal{B}_0$ baryonium) obtained by annihilating 1, 2 or, respectively, 3 pairs of $q\bar{q}$ lines (fig. 8 b)). The $\mathcal{B}_4$ states have the quantum numbers of a $qq\bar{q}\bar{q}$ system and correspond to the baryonium states previously discussed; they must be distinguished from the exotic $(q\bar{q})(q\bar{q})$ states recently discussed by Jaffe in the framework of the quark bag model [71], which are merely "molecular" states of two mesons ("mesonium") very weakly coupled to the baryon-antibaryon channel. The $\mathcal{B}_2$ mesons have the quantum numbers of a $q\bar{q}$ pair, but are distinct from the usual mesons due to their color structure. Finally, the $\mathcal{B}_0$ mesons have the flavor quantum numbers of the vacuum. All three of these baryonium configurations have a pair of "junction" - "antijunction" lines [24, 29].

In the alternative string picture the baryon has the Y shape shown in fig. 9 a); the configurations of the triad of baryonium states are shown in fig. 9 b).

The corresponding triad of baryonium trajectories shows the following exchange degeneracy pattern: $C = \pm 1, I = 0, 1, 2$ for the $\mathcal{B}_4$ states; $C = \pm 1, I = 0, 1$ for the $\mathcal{B}_2$ states and $C = \pm 1, I = 0$ for the $\mathcal{B}_0$ states [24].

We will discuss now only the $\mathcal{B}_4$ and $\mathcal{B}_2$ trajectories, which are the only ones relevant for the present analysis.

Using multiperipheral-model type arguments one can evaluate the intercepts and the slopes of the "bare" baryonium trajectories

(i.e. those obtained before taking into account the coupling of the baryonium to the MM channel). Namely [24, 29]

$$\bar{\alpha}_{B_4}(0) \simeq -0.5, \quad \bar{\alpha}_{B_2}(0) \simeq 0 \quad (27)$$

and

$$\bar{\alpha}'_{B_4} \simeq \alpha', \quad \bar{\alpha}'_{B_2} \simeq 1/2 \alpha' \quad (28)$$

where α' is the universal slope of the ordinary meson trajectories.

One must note that the B_2 states are more strongly coupled to the mesonic channels than the B_4 states [29]. The coupling to the MM channel leaves unchanged the B_4 intercept, but lowers the B_2 intercept [29] to

$$\alpha_{B_2}(0) \simeq -0.13 \quad (29)$$

The leading $I = 1$ baryonium trajectory will obviously be the B_2 one.

The agreement between the value (29) of the B_2 intercept obtained in ref. 29 and the phenomenological ρ' intercept is quite impressive. Also, one expects that the renormalized slope of the B_2 trajectory in the negative t region will be very close to the bare slope $1/2 \alpha'$ [72] i.e. very near the phenomenological ρ' slope.

In conclusion, we are tempted to identify the ρ' trajectory with the baryonium B_2 trajectory. We think that the ρ' is not just a parametrization of our ignorance of the $I = 1$ exchange mechanism in $\pi^- p \rightarrow \pi^0 n$, but is in fact a genuine Regge pole, namely, the baryonium B_2 Regge pole.

V CONCLUSIONS

In the present article we have reviewed the major exper-

imental effects supposed to be associated with the exchange of baryonium trajectories.

We analyzed the reactions involving pure baryonium B_4 channels, corresponding to the quantum numbers of a $qq\bar{q}\bar{q}$ system. The presence of all expected prominent effects (forward peaks, change of the energy variation regime from the low energy to the medium energy region, the approximate validity of the new OZI rule in the small negative t region) strongly suggests that the baryonium exchange mechanism is a correct phenomenological picture and that mesons with isospin 2 or 3/2 or with strangeness -2, coupled essentially to the baryon-antibaryon channel, must be observed.

We also pointed out an unexpected enhancement of the pure baryonium channel cross sections in the case of baryon decuplet production. In this case the baryonium coupling to the baryon-antibaryon channel is much stronger than the usual meson coupling.

Of course, the double-Regge exchange mechanism can explain some of the effects observed in the pure baryonium channels. However, the recent discovery of narrow-width mesons which can be interpreted as baryonium states, the systematic trends in the baryonium Regge couplings, as well as the tendency of all existing double-Regge models to give too low cross-sections for $K^- p \rightarrow \pi^+ \Sigma^-$ neatly favor, in our opinion, the baryonium exchange mechanism.

This conclusion is reinforced by the possible solution of the old ρ' puzzle in $\pi^- p \rightarrow \pi^0 n$ in terms of the exchange of the baryonium B_2 as a genuine Regge trajectory.

An increased amount of high precision experimental data in the pure baryonium channels at medium energy as well as systematic

searches for baryonium states are obviously needed for the definitive assessment of the baryonium exchange mechanism.

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TABLE I. Candidates for the baryonium states [74].

Mass, MeV	Width, MeV	Experiment	Reference	Remarks
1932 ± 2	9^{+4}_{-3}	$\sigma_T(\bar{p}p), \sigma_T(\bar{p}d)$	A. S. Carroll et al. [5]	One or more resonances; $I = 1$ favored.
$1932^{+2.4}_{-0.4}$	4.5 ± 4	$\sigma_{ann}(\bar{p}n)$	T. E. Kalogeropoulos et al. [6]	$I = 1, J \neq 0$
1936 ± 1	9^{+4}_{-3}	$\sigma_T(\bar{p}p), \sigma_{el}(\bar{p}p)$	V. Chaloupka et al. [7]	Probably not a single resonance [75].
1939 ± 3	$\lesssim 4$	$\sigma_{el}(\bar{p}p), \sigma_{ann}(\bar{p}p)$	W. Brückner et al. [8]	
≈ 1968	≈ 35	$pp \rightarrow K_S^0 K_L^0$	A. Benvenuti et al. [9]	$J^{PC} = 1^{--}$
2020 ± 3	24 ± 12	$\pi^- p \rightarrow p_F \pi^-(\bar{p}p)$	P. Benkheiri et al. [10]	Produced in association with $\Delta^0(1232)$ and $N^0(1520)$.
2204 ± 5	16^{+20}_{-16}	$\pi^- p \rightarrow p_F \pi^-(\bar{p}p)$	P. Benkheiri et al. [10]	Produced only in association with $\Delta^0(1232)$.
2600 ± 10	$\lesssim 18$	$\bar{p}p \rightarrow 6\text{-prong-}V^0$	A. Apostolakis et al. [11]	Observed in $(K^0 \pi^+ \pi^+ \pi^-)$ combinations.
≈ 2660	$\lesssim 20$	$\pi^- p \rightarrow p_F(\bar{p}p\pi^-)$	A. Rogers [12]	$I = 1$ or 2 ; not firmly established [76].

(Table continued)

TABLE I. Candidates for the baryonium states. (Cont.)

Mass, MeV	Width, MeV	Experiment	Reference	Remarks
≈ 2850	$\lesssim 39$	$\bar{p}n \rightarrow X\pi^-$ (X = neutral $\bar{N}N$ or $\bar{N}N\pi$ system)	H. Braun et al. [13]	I = 0 favored.
2950 ± 10	Consistent with the resolution (15 MeV)	$\pi^- p \rightarrow (\bar{p}p_F \pi^-)X$ (X = $p_S, p_S \pi^0,$ $n_S \pi^+, p_S \pi^- \pi^+$ or anything)	C. Evangelista et al. [77]	I = 1 or 2. Decay via intermediate $\bar{p}p$ resonances. Signals seen at 2, 2.2, and 2.62 GeV in the $\bar{p}p_F$ mass spectrum.
≈ 1498	≈ 5	$e^+e^- \rightarrow \text{hadrons}$	Frascati groups [74]	J = 1.
1821 ± 16	31 ± 15	$e^+e^- \rightarrow \text{hadrons}$	R. Bernabei et al. [14]	J = 1.
1819 ± 5	24 ± 5	$e^+e^- \rightarrow \text{hadrons}$	C. Bacci et al. [15]	J = 1.
$1812 \begin{smallmatrix} +7 \\ -13 \end{smallmatrix}$	$34 \begin{smallmatrix} +21 \\ -15 \end{smallmatrix}$	$e^+e^- \rightarrow \text{hadrons}$	M. Ambrosio et al. [16]	J = 1.

TABLE II. Evolution of the Baryonium scheme.

Year		< 1968	1968-1970	1970-1975	1976-1977
Baryonium states	"cryptoexotics"	No	No	Yes?	Yes
	"exotics"	No	No	No	No?
"Forbidden" forward peaks	$\frac{1}{2}^+$ baryon octet production	No	No?	Yes?	Yes
	$\frac{3}{2}^+$ baryon decuplet production	No	Yes	Yes	Yes
Models claiming the existence of baryonium states and/or "forbidden" forward peaks:		No	Yes	Yes	Yes

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75. This conclusion is based upon the absence of a strong resonant signal in the $\bar{p}p \rightarrow \bar{n}n$ cross section. See also M. Alston - Garnjost, R. Kenney, D. Pollard, R. Ross, R. Tripp, and H. Nicholson, Phys. Rev. Lett. 35, 1685 (1975).
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FIGURE CAPTIONS

- Fig. 1. Examples of forward peaks in the pure baryonium channels.
Data from: a) Ref. 42b), b) Ref. 42d), c) Ref. 43a), d) Ref. 42d), e) Ref. 43k), f) Ref. 42d).
- Fig. 2. Possible "kinematical" reflections in $\pi^+ n \rightarrow \pi^- \Delta^{++}$.
- Fig. 3. The integrated cross section in the forward hemisphere σ_f for: $\pi^- p \rightarrow \Delta^- \Delta^{++}$, $\pi^- p \rightarrow \pi^+ \Delta^-$ (or $\pi^+ n \rightarrow \pi^- \Delta^{++}$), $\pi^- p \rightarrow Y^{*-} Y^{*-}$, $\pi^- p \rightarrow \pi^+ Y^{*-}$, $\pi^- p \rightarrow K^+ Y^{*-}$, and $\pi^- p \rightarrow K^+ \Xi^{*-}$ (Refs. 42a)-h), 43a)-k), 44a)-b).
- Fig. 4. The Regge behavior of σ_f . Data as in Fig. 3.
- Fig. 5. The non-strange (S=0) leading baryonium trajectory. The experimental masses of the recently discovered mesons which can possibly be associated with the Regge recurrences of this trajectory are indicated on the horizontal axis.
- Fig. 6. Illustration of the approximate validity of the new OZI rule in the negative t region.
- Fig. 7. The phenomenological ρ and ρ' ($= \mathcal{B}_2$) Regge Trajectories in $\pi^- p \rightarrow \pi^0 n$ (Ref. 69).
- Fig. 8. a) The baryon (B) and the antibaryon ($\bar{B}$) in the model of Refs. 24 and 29. The dashed line is the color ("junction" or "anti-junction") line.
b) The triad of baryonium topological configurations (Refs. 24 and 29).
- Fig. 9. The baryon and baryonium configurations in the string picture.
- Fig. 10. Forbidden decays of baryonium $\mathcal{B}_4$ in:
a) the models of Refs. 24 and 29;
b) the diquark model [17, 18].
Allowed decays of baryonium $\mathcal{B}_4$:
c) Refs. 24 and 29;
d) Refs. 17 and 18.

X BL 776-1350

Fig. 1a)

XBL776-1348

Fig. 1b)

XBL 776-1341

Fig. 1c)

XBL776-1351

Fig. 1d)

XBL776-1347

Fig. 1e)

XBL 776-1346

Fig. 1f)

Fig. 2

XBL776-1352

XBL 776-1349

Fig. 3

Fig. 4a)

Fig. 4b)

XBL776-1344

XBL 776 - 1345

Fig. 5

XBL 776-1343

Fig. 6

XBL 776-1354

Fig. 7

Fig. 8a)

Fig. 8b)

XBL776-1353

Fig. 9a)

XBL 776-1342

Fig. 9b)

Fig. 10a)

Fig. 10b)

Fig. 10c)

Fig. 10d)

XBL776-1340

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