Proton-Antiproton interactions

(Experimental Status of Baryonium States)

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I. Introduction

After the discovery of the narrow J/ψ resonances and its explanation as $\bar{c}c$ (charmonium) system, attention has been drawn recently that $\bar{p}p$ may also be a rich source of narrow resonant structures. These narrow resonances are being commonly called baryonium (or quarkonium). If one considers the picture in terms of nuclear Physics, baryonium are baryon-antibaryon ($B\bar{B}$) structures which are bound by strong attractive nuclear potential. According to quark model and duality, these structures represent exotic diquark (q^2)-diantiquark ($\bar{q}^2$) system which have strong coupling to ($B\bar{B}$) rather than to mesons. Experimentally, these states are expected to exist close (or above) to the nucleon-antinucleon threshold and will have narrow widths. Many experiments have been performed in the last few years to search for these states. In this paper the present experimental situation of the baryonium states is reviewed.

II. Theoretical relevence

The existence of narrow baryonium states has been predicted in different theoretical approaches. A brief discussion is given below(++).

1. Potential model

The $\bar{N}N$ system differs from its equivalent NN system in two ways; firstly, that $\bar{N}N$ system can -

(++) Large number of theoretical papers on these topics have appeared in the recent years. Only some prominent ones are given in the article.

annihilate and secondly that $N\bar{N}$ force may be different. It is commonly beleived that the force between two nucleons is mediated by the exchange of some light boson (one boson exchange potential). The $N\bar{N}$ and NN interactions are related to each other through G-conjugation(+). The resulting $N\bar{N}$ force is expected to be very strong (its depth may be $\sim$1 GeV at a distance of $\sim$0.5fm) and thus the hard core of NN force is changed to strong intraction. This results in the formation of $N\bar{N}$ (or $\bar{B}B$) quasi-nuclear resonant states. These states are much more strongly bound as compared to the loesely bound deuteron. It is expected that large annihilation cross-section of $\bar{N}N$ system ($\sim$120 mb for about 200 MeV/c particles in the c.m.) would not destroy or severely disort the $\bar{B}B$ quasi-nuclear resonant structure because the annihilation takes place at much shorter distance than the radius of the $B\bar{B}$ state. The annihilation is expected to take place through baryon exchange and its range should be $\sim$0.2 fm. The theoretical estimation of annihilation widths of these states is 0.1-100 MeV depending on the angular momentum of relative motion of particles (widths are inversely proportional to angular momenta).

This concept is discussed in many papers [1-2] which predict a rich spectrum of quasi-nuclear bound states or resonant states. The posibility of existence of bound states like $Y\bar{Y}$ or $\bar{Y}N$ is also predicted. The

(+) This is in analogy to the way that C-Parity connects e^-e^- and e^-e^+ systems.

spectrum of these quasi-nuclear states can range from $\sim$1.7 GeV (below $N\bar{N}$ threhold) to $\sim$7 GeV depending on the number of baryons included in the system. The widths of these resonant states depend on the $\bar{p}p$ annihilation potential. Some of these states can be very narrow ($\Gamma \sim$ few MeV). They are expected to be populated by radiative or pionic transistions from atomic $\bar{p}p$ states [3].

Thus the study of these states would provide better understanding of nuclear force, nuclear potential and the exchange process.

2. Quark Model

i) Bag version of QCD

The quark model has successfully explained many features of particle interactions in the recent years. It is now well accepted that quark dynamics (or quark-chromo-dynamics-QCD) is described by a non-Abelian guage theory where interactions are mediated by an octet of coloured vector gluons. Although this theory has not been tested directly but it is now well known that many of its predictions with regard to the ordinary mesons and baryons have come out to be true. The colour guage theory predicts simultaneously the existence of certain extra-ordinary states: like, 'glue-balls' (states without quarks); 'exotic states' (states with peculiar quantum numbers) and 'multi-quark states' (states with more than 3 quarks).

The existence of multiquark states has been discussed recently by Jaffe [4] and others [5-7].

The calculations are based on the description of classical 'bag-model' considering that quarks are light and confined. The free hadrons are colour singlets. The interactions between confined quarks is weak and hadron spectrum is calculated using perturbation theory in colour coupling constant $\alpha_c = g^2/4\pi$. This explains satisfactorily the properties of $(q\bar{q})$ mesons and (qqq) baryons.

The absence of exotic hadronic states had always been mysterious to the followers of quark model. Nambu [8] in 1966 indicated the saturation properties of SU(3)-colour forces, that two colour singlets do not exert strong force on each other. Later Lipkin [9] showed that this may be the cause of the absence of strong attractive force in exotic channels. These discussions considered only colour-electrostatic interactions and ignored colour-magnetic force (i.e. spin-colour dependent interaction arising from one gluon exchange). The justification for treating the problems of gluon-exchange through pertubation theory lies in the Bag-model where long range colour-confining forces are replaced by bag-pressure leaving only short range gluon-exchange. This interaction is attractive in antisymmetric flavour states and repulsive in symmetric flavour states. The result of such calculations [4] is that one can get exotic multiquark states ($q^m \bar{q}^n$ with $m+n > 3$) from colour singlet baryons and mesons. One can also make 'Crypto-exotic' states (i.e. states not in exotic flavour representation). The exotic states are expected to be heavy and broad and crypto-exotic states, lighter and narrow. Similar calculations have also been recently done in quark gluon model with dual unitarization by Chan Hong Mo and Høgassen [7].

If one considers the old quarks (u,d,s), the lightest ($q^2 \bar{q}^2$) multiplet is a $J^{PC}=0^{++}$ nonet. Jaffe [4] has calculated their masses and SU(3) structure. This is shown in Fig.1. The predicted masses of these states lie between 650-1100 MeV/c^2. These are strongly coupled to $\bar{p}\bar{p}$ channel. It is contemplated that the observed [ε(1300); S^*(1976); K(1400)]$^{(+)}$ may be related to these predictions.

The bag model calculations have been extended [4,10] to explain ($q^2 \bar{q}2$) configuration which couple to $B\bar{B}$ (baryonium) by considering the deformed bags for high J-value. Thus one can predict the existence of various baryonium states; e.g. states with mass (J^{PC}, I^G) = 2270(3^{--}, 1^+); 2460 (4^{++},0^+) and 2730 (5^{--},1^+). These calculations have also been extended to study the ($q^4\bar{q}$) systems and q^6-dibaryon system. One of the predictions is that a dibaryon with $J^P=0^+$ and mass $\sim$2150 MeV/c^2 should exist as SU(3) flavour singlet.

ii) <u>Dual-resonance model</u>

Complementary discription of reactions by Regge poles (or resonances) is commonly known as

(+) For masses and other properties, see particle data Book-(1978).

duality. It provides simple and direct relations between low energy and high energy scattering mechanism. For inelastic processes most t-channel trajectories behave as if they are 'built' through direct channel resonances. Detailed discussions of duality have appeared in many papers (e.g. see reference 12).

The existence of meson resonances with strong coupling to $\bar{B}B$ system was originally suggested by Rosener [11]. This is represented by simple planar diagrams in Fig.2 where for $\bar{N}N$ elastic scattering the meson exchange in t-channel is equivallent to $\bar{q}q$ exchange in quark model and is sum of the $q^2\bar{q}^2$ resonances in the S-channel. Thus baryonium is diquark-diantiquark system and is an exotic meson. This has been further discussed by Chew [13] and by Phillips and Roy [12]. It is also shown that such exotic baryonium states will have I=0,1,2. It is also shown that OZI-rule will suppress the decay of a baryonium to $(q\bar{q})(q\bar{q})$ channels and decay to $\bar{B}B$ will be allowed. This is also shown in Fig.2 (+). Chew [13] also predicts Regge trajectories for baryonium.

Thus the experimental verification of baryonium states will be a good check on the predictions of duality and of QCD.

III. EXPERIMENTAL STATUS

The present review will cover first the prominent resonances reported earlier (like S,T,U enhancements) and then some further structures observed recently. Three

(+) This is similar to the decay of ϕ-meson (which is $s\bar{s}$ system, some time termed as strangonium) where the OZI rule suppresses the decay $\phi \rightarrow \rho\pi$ and allows $\phi \rightarrow K\bar{K}$. Also for the decay of the charmonium ($c\bar{c}$ system) similar explanation of the decay channels is put forward by the OZI-rule.

recent reviews on the subject, by Montanet [14], Miller [15] and Kilian and Pietrzyk [15], have also given useful summary of the experimental data.

The experiments conducted so far can be classified into the following three categories.

a) $\bar{p}N$ formation experiments: These include measurements of total and elastic scattering cross-sections in the $\bar{p}p$ system. In these experiments one has to differentiate between true resonances and threshold effects; hence, some times the interpretation of the data is not unique. We also include here experiments where $\bar{B}B$ (or $\bar{p}p$) atomic structures are formed and their radiative transitions are measured.

b) Experiments in which $\bar{B}B$ states are produced in u-channel via N or Δ exchange.

c) Experiments in which $\bar{B}B$ states are produced in t-channel which decay in states including $(B\bar{B})$.

1. <u>S-Meson resonance:</u>

Focacci [16] about 10 years back observed the presence of S-enhancement in a missing mass spectrometer experiment studying the production of charged bosons (X^-) in the reactions $\pi^- p \rightarrow p + X^-$. The mass of the S-resonance was inferred to be 1929$\pm$14 MeV and width $\Gamma \leq 35$ MeV with prominent decay into 3 charged pions (and possible neutrals). The first positive evidence of S-enhancement being a $B\bar{B}$ system came from the experiment of Carroll et al [17], Kelogeropoulos et al [18] and Chaloupka et al [19]. The experiment of Carroll et al on $\bar{p}p$ and $\bar{p}d$ total cross-sections indicated the presence of a structure at $\bar{p}$ momentum of 475 MeV/c corresponding to a mass of 1932±2 MeV with Breit-Wigner width, $\Gamma=9^{+4}_{-3}$ MeV. Chaloupka et al in an experiment with CERN 2-meter bubble Chamber exposed to a separated $\bar{p}$ beam of 571±5.5 MeV/c observed a similar structure between 1930-1940 MeV in the elastic channel. Their results are reproduced in Fig.3. The observed enhancement corresponds to a resonance with mass 1935.9±1.0 MeV and $\Gamma=8.8^{+4.3}_{-3.2}$ MeV. The S-enhancement has also been confirmed by Brückner et al [20] where $\bar{p}p$ elastic scattering and annihilation cross-sections have been measured between 400-850 MeV/c using magnetic spectrometer. The mass of the resonance has been observed as 1939±3 MeV with $\Gamma \lesssim 4$ MeV.

The prominent decay of S-resonance is through $\bar{p}p$ channel, with a branching ratio $\geqslant$20 percent. As phase space for the decay to $\bar{p}p$ is much smaller as compared to that available for the decay to pions, the decay transistion prefers the elastic channel. There is no indication of this resonance in the charge exchange ($\bar{p}p \rightarrow \bar{n}n$) channel [19,21]. This may indicate strong interference effect (i.e. interference of resonance with background or that of two resonances within the structure).

The iso-spin (I) of the S-resonance is preferably =1 but I=0 can not be excluded. Spin (J)=0 and inelasticity (x)=1 are consistent with the data. The observed total and charge exchange cross-sections have been discussed by Montanet [14] in the light of the theoretical arguments of Dover and Kahana [21] and Kelly and Phillips [22]. Final interpretation is that S is a narrow resonance of spin 1 or 2 and with large elasticity. There are indications that $J^{PC}=2^{++}$ may be preferred for this resonance.

Table I gives the summary of the present status.

2. Broad resonances

(i) Two further enhancements (called T,U-resonances) were also reported by Focacci et al [16] in the mass region ~2195 MeV and ~2382 MeV. Abrams et al [24] in a counter experiment measured the total cross-section for $\bar{p}p$ interactions. The T-enhancement at mass ~2190 (I=1) and U-enhancement at mass ~2350 (I=0 and 1) were observed. The earlier speculations that these enhancements may be threshold effects ($\bar{p}p \to \bar{p}p\pi$ or $\rho\rho$ etc) were found to be incorrect. Further experiments of Eisenhandler et al [25] and Coupland [26] confirmed the presence of T and U resonances as Baryonium states with mass in the same region as reported by Abrams et al. The results of Eisenhandler et al are shown in Fig.4 and those of coupland et al in Fig.5. In both the figures, the T and U structures are clearly observed. The summary of various experiments is given in Fig.6 which has been taken primarily from reference [26].

The spin values of T and U resonances are estimated [14] to be $J \leq 1$, $(x > 0.74)$ and $J \leq 2$, $(x > 0.85)$ respectively; x being inelasticity. These predictions are again based on the theoretical arguments of references [22,23].

(ii) Further resonant structures representing baryonium states have been observed by Carter et al [27] in the differential cross-sections for $\bar{p}p \to \pi^+ \pi^-$ reactions in the C.M. energy range of 2020-2580 MeV/c². The $\bar{p}p$ annihilations into $\pi^+\pi^-$ represent about 10 percent of the total cross-section and hence are not representative of the annihilation channels. However, their amplitude structure is rather simple and can be analysed in detail for the observed resonant structures. The results are summarized in Table II.

These results are also shown in Fig.6. One wonders if the resonances at 2310 and 2480 are infact part of U-resonance. The coupling of all these states to $B\bar{B}$ is much stronger than for pion decays. The low cross-section of the decay to $\bar{n}n$ (from $\bar{p}p \to \bar{n}n$) to $\bar{p}p$ can be explained by involving strong interference with other resonant states or with the background as explained in the case of S-meson.

Montanet [14] indicated that the preliminary data of Bari-Brown-MIT collaboration indicates strong evidence of a resonance at 2350±60 MeV/c² with Γ=190±60 MeV (J^P=4^+). The results of Peaslee et al [28] published recently exclude this mass region.

3. Narrow resonances

(i) Benkheiri et al [29] studied the reactions $\pi^- p \to p_f p \bar{p} \pi^-$ (p_f is fast proton with $P > P_{beam}/2$ and emitted in the forward direction within ± 150 mrad) with a π^- beam at 9 and 12 GeV/c using CERN Ω spectrometer. It is a high statistics experiment using 1.65×10^6 events at 12 GeV/c (4-C fit). The contamination of channels (like $\pi^- p \rightarrow p K^+ K^- \pi^-$) is <10 percent. No enhancement is observed in ($p_f \bar{p}$) or ($p\bar{p}\pi$) invariant mass distribution. The data indicate the presence of $\Delta(1232)$ and $N^*(1520)$ in ($P_f \pi^-$) and $\bar{\Delta}$ (1232) in $\bar{p}\pi$ channels. There is strong evidence for 2 peaks in the data (mass $\sim$2020 and 2200 MeV/c^2) in association with Δ and one peak (mass $\sim$2020 MeV/c^2) in association with N^*. The data also indicate that these resonant states are produced in the forward direction. The results are given in Table-III.

The decay angular distribution in the Jackson frame of the resonances in the $\bar{p}p$ system shows strong forward backward asymmetry which is suggestive of meson or pomeron-exchange in the production mechanism of $p_f \bar{p} \pi^-$ or $p_f \bar{p}$ states. The angular distribution is quite different in $\bar{1}_2$ resonance region.

The results are shown in Fig.7. The two peaks are clearly observed. The peak at 1930 MeV can perhaps be interpretted with that of S-meson. The production mechanism of these resonances can be best explained by the diagram in Fig. 8-a.

(ii) In another experiment Evangelista et al [30] again using CERN Ω spectrometer studied the following $\pi^- p$ interactions at 16 GeV/c:

$$\pi^- p \rightarrow \bar{p} p_f p_s \pi^-$$
$$\bar{p} p_f p_s \pi^- \pi^0$$
$$\bar{p} p_f n_s \pi^- \pi^+$$
$$\bar{p}\, p_f\, p_s\, \pi^- \pi^- \pi^+$$

where subscripts f and s represent faster and slower nucleons in the Lab. system. A narrow peak in the ($\bar{p}p_f \; \pi^-$) invariant mass was observed with mass, M=2950±10 MeV/c^2 and $\Gamma \lesssim 32$ MeV (I=1 or 2) with production cross-section of ~1 μb. Fig. 9(a) shows the results of the experiment. The decay spectrum of the resonance is shown in Fig. 9(b). It is indicated that the decay may go through other $\bar{p}p$ states with masses at 2200 or 2020 MeV/c^2.

If this resonance is confirmed(+), its production will be represented by diffractive dissociation of π as shown in Fig. 8(b).

(iii) Preliminary data of Toronto-York-Purdue collaboration [33] of 1672 events of $\pi^+p \to p\bar{p}p\pi^+$ interactions at 11.5 GeV/c indicates a narrow resonance in the $\bar{p}p$ system. The experiment has been performed using the SLAC 40'' hybird bubble chamber facility. The contribution of $\pi^+p \to K^+K^-p\pi^+$ has been excluded from the data using appropriate trigger. The results of $\bar{p}p$ invariant mass are reproduced in Fig. 10. A narrow bump (~4.4 s.d. above the background) is clearly observed at mass=1954±5 MeV, $\Gamma \lesssim 10$ MeV. The production cross-section is σ=300±60 nb. This enhancement is not strongly associated with recoiling Δ^{++} (1236) production at the other vertex. The decay angular distribution is consistent with $J^{PC}=1^{--}$. The 1954 MeV/c^2 enhancement is not observed in the backward produced $\bar{p}p$ pairs. No signal for a narrow resonace at 2950 MeV/c^2 as reported by Evangelista et al [30] is observed in the data. The diagram explaining the production of the 1954 MeV/c^2 resonance is shown in Fig. 8(c) and it is expected to proceed by either baryon or baryonium exchange.

(+) The preliminary report of the results presented at the H.E. Physics conference, Tokyo indicates that the 2950 MeV/c^2 resonance has been submerged by the new data [31,32].

4. Strange Baryonium States

(i) First example of a strangeness = $\pm$ 1 baryonium state comes from the experiment of Apostolakis et al[34]. The experiment was performed using Big European Bubble Chamber (BEBC) exposed to 12 GeV/c $\bar{p}$ beam. All events of 6-prongs and associated V topology were studied. The effective mass distribution of $(K_s^0 \pi^\pm \pi^+ \pi^-)$ is shown in Fig.11. The peak represents a 5.5 s.d. effect and contains 587 events including 32 events which are ambiguous between K^0 and Λ or $\bar{\Lambda}$. No evidence of the neutral state of this resonance $(K^0 \pi^+ \pi^\mp \pi^0)$ or $(K^\pm \pi^\mp \pi^+ \pi^-)$ has been observed but the result is inconclusive because the mass resolution for π^0 events is small and the statistics for $K^\pm$ events is too low. Similarly it could also not be established whether the enhancement is exotic (charge opposite to strangeness) or non-exotic. For this, events from the reaction, $\bar{p}p \rightarrow (K_s^0 K^\mp \pi^\pm \pi^+ \pi^+ \pi^- \pi^- +$ neutrals) were studied where by strangeness conservation the identified $K^+(K^-)$ corresponds to $\bar{K}^0(K^0)$.

The mass of the enhancement with $S=\pm 1$ is 2600 ± 100 MeV/c^2; $\Gamma \leq 18$ MeV, σ. BR=20μb where BR is the branching ratio for the decay of the resonance into $(K_s^0 \pi^\pm \pi^+ \pi^-)$.

(ii) Recently whitmore et al [40] have reported their results of a similar experiment in $\bar{p}p$ experiment at 14.75 GeV/c using 80" BNL hydrogen chamber. The data are based on 80,000 interactions in which they find 367 events of 6 prongs topology corresponding to $\bar{p}p \rightarrow K_s^0 \pi^\pm \pi^+ \pi^-$ as compared to 587 events of reference[34]. No resonant structure at $\sim$2600 MeV/c^2 is observed. With confidence level of about 95 percent, they quote σ.BR<21μb. It is also indicated that the CERN experiment of the Apeldoorn et al [40] fails to confirm the 2600 MeV resonance.

(iii) Montanet [14] has indicated that the preliminary results from CERN-Ω-spectrometer (T.Armstrong et al) indicate a broad resonance (mass $\sim$2200 MeV/c^2) in the $\bar{\Lambda}$ N mass spectrum in an experiment studying $K^+p\to(p_f +$ anything$)$ at 12 GeV/c. There are also indications of other enhancements at $\sim$2800 MeV and $\sim$3050 MeV. Definite results are still not available [32].

5. <u>Exotic states</u>

Efforts have been made for the past several years to search for doubly charged meson resonances without any success. Two recent experiments in this regard are of Boucrot et al [35] and Alam et al [36].

(i) Boucrot et al using Ω spectrometer studied the following reactions at 12 GeV/c.

$\pi^- p \to p_f + M^-$ (M^- being an I=1 meson, $M^- \to \bar{p}p\ \pi^-$)
$\pi^- p \to p_f + M^{--}$ (M^{--} being I=2 exotic meson, $M^{--}\to p\bar{p}\pi^-\pi^-$).

In view of the fact that mesonic decay modes may become dominant if a central barrier suppresses the $\bar{N}N\ \pi(\pi)$ mode, 4π decay modes were studied for the search of M^- and M^{--}. The mass resolution for M in this experiment was 12-18 MeV.

The results are shown in Fig. 12 where invariant mass of ($p\bar{p}\pi^-\pi^-$) system has been plotted from the reaction $\pi^- d \rightarrow p_{spect} p_f (p\bar{p}\ \pi^-\pi^-)$. One event of the distribution corresponds to a cross-section of 1.7 nb. It is clear from the figure 12 that there is no evidence for a resonance. The upper limit for the production of M^- or M^{--} is 10-50 nb for mass of these resonances between 2-3 GeV with $\Gamma < 20$, or $\Gamma < 100$ MeV respectively.

(ii) Alam et al [36] searched for doubly charged exotic mesons (X^{--}) in baryon exchange reactions.

$$\pi^- d \rightarrow (p_s) + X^{--} + p_f$$

The experiment was performed at 13.2 GeV/c at the SLAC 2-meter streamer chamber with a sensitivity of 240 events per μb per nucleon cross-section. The results for invariant mass of ($\bar{p}p\ \pi^-$) in ($\bar{p}p\ \pi^- p_f$) events and of ($\bar{p}p\ \pi^-\pi^-$) in ($\bar{p}p\ \pi^-\pi^- p_f$) events is shown in Fig. 13 for 4-c fits. Again there is no evidence of any enhancement in the mass range of 1.8-3.2 GeV.

6. Production of $\bar{p}p$ states below threshold

(i) As discussed in section II. 1, antiprotons stopped in hydrogen can form bound states. An earlier evidence of a $\bar{p}n$ bound state was presented by Gray et al [37] in $\bar{p}d$ interactions. The experiment was performed in 30'' deuterium bubble chamber exposed to stopping $\bar{p}$. The resonance was detected in the study of the decay reactions. The mass of the resonance has been estimated as 1794.5 ± 1.4 MeV/c², $\Gamma \leq 8$ MeV and binding energy of 83.3 ± 1.4 MeV at 95 percent confidence level.

(ii) In a recent experiment by Pavlopoulos et al [38] γ-ray spectrum from $\bar{p}p$ annihilations at rest has been measured using a large NaI (TI) spectrometer in the energy range of 30-1100 MeV. A total of $(7\pm0.5)\times10^7 \bar{p}$ were stopped in H_2. The back ground contribution from π^0 decays and from neutrons produced from the interactions of charged pions of annihilation with surrounding has been suitably subtracted. The results are shown in Fig.14 and are also shown in Table IV.

The (132 ± 6) MeV γ-ray is from $(\pi^- p)$ radiative capture. Thus three bound states of $(\bar{p}p)$ are clearly established. It can be noted that 420 MeV line has energy which is the sum (within errors) of the other two lines at 183 and 216 MeV. These γ transitions corresponds to states with masses 1684, 1646 and 1395 MeV respectively. The quantum numbers of these states could not be calculated in this experiment but assuming that initial state is a s-state, the observed γ-transitions most probably corresponds to popular p-states.

7. Six-quark states

As already discussed in section II. 2, the bag model calculations of QCD predict the existence of a q^6 dibaryon. The lightest state is expected [4] to be stable except against weak interactions. It is predicted to have $J^P=0^+$; SU(3) singlet, mass $\sim$2150 MeV (i.e. 80 MeV less than $\Lambda\Lambda$ mass), strangeness = -2. In formation, it couples to $\Lambda\Lambda$, $\Sigma\Sigma$ and $N\Xi$ in the ratio of 1:3:4. The most conven-ient method to produce these states is in pp interactions. The production mechanism in the reaction $pp \rightarrow K^{+}K^{+}$ X (X is dibaryon) is explained in Fig. 8(d). The production cross-section, however, is expected to be small.

A.S. Carroll et al [39] searched for six-quark states in the missing mass spectrum of the reaction $pp \rightarrow K^{+}K^{+}X$ in the mass range of 2.0 -2.5 GeV/c^2 using a double arm spectrometer at BNL. The beam momentum was 5.1, 5.4 and 5.9 GeV/c. Fig. 15 shows the missing mass spectrum. No structure is observed. Upper limit for the production of X is put 30-130 nb depending on the mass.

8. Summary of the experimental data.

The experimental data presented in the preceeding sections have been summarized in Fig. 16. Excluding the resonance at mass=2950 MeV/c^2 which now seems to have submerged in larger data, one can observe the following.

i) Narrow bound $\bar{p}p$ structures below the $\bar{p}p$ threshold are clearly established. However, their quantum numbers are not decided.

ii) The S-resonance can be accepted as a clear evidence of a Baryonium. It should be regarded as well established. It is narrow and its elasticity is large.

iii) There are many narrow and broad ($\bar{p}p$) resonances in the mass region 1950-2600 MeV/c^2. More data are required for their confirmation and for deciding their quantum numbers, though many of these are already on relatively firm footing.

The resonance at mass=2600 MeV/c^2 which was supposed to be a good example of strange (S=1) baryonium, has been placed in the doubtful category.

iv) No state with I=2 has yet been found.

In addition to the states summarized in fig. 16, there are many unconfirmed resonances. For example, there are indications [15] of two resonances, one at (mass $\simeq$ 2850, $\Gamma \lesssim$ 39 MeV) and the other at (mass $\simeq$ 3050, $\Gamma \lesssim$ 15 MeV) observed in $\bar{p}p \rightarrow \pi X$ with cross-sections, $\sigma \sim 83$ μb and and ~ 22 μb respectively. There is also an indication [32] that an exotic state at mass $\sim$ 2500 MeV/ exists. This resoance has been observed in reactions ($K^+p \rightarrow \bar{\Lambda}p\pi^+n$) in the ($\bar{\Lambda}p\pi^+$) system. The observed enhancement is $\sim$3-5 s.d. effect. If it is confirmed, it may be an example of exotic resonance with Q=2, S=1.

The experimental uncertinties do not yet allow to establish whether states separated from others by small mass differences belong to one state or to different states. It is likely that with better experimental precision some states may submerge with others.

The question of the existence of broad and narrow resonances is not yet clear. Jaffe [4], chan-Hong-Mo and Høgassen [7] have discussed the problem theoretically. It is quite possible that some of these broad resonances ultimately may be observed to have substructures.

9. Conclusions

i) The existence of baryonium states is well established. Such states have been reported both below and above the $\bar{p}p$ (or $\bar{B}B$) threshold. Many narrow and broad resonances with strong coupling to $\bar{p}p$ (or $\bar{B}B$) channels have been observed.

ii) There are many resonances reported in references [14,15,32] which need confirmation and have not been included here.

iii) There is no well-established example of strange baryonium and no established evidence of any state with exotic quantum numbers. Similarly there is yet no evidence of q^6 di-baryonium though there are some candidates [32].

iv) Better experimental precision and more experimental data are required to establish these states and to decide if there are any substructures in some of these resonances. For example, if small charge exchange ($p\bar{p}\to n\bar{n}$) cross-sections for S,T,U enhancements is really an interference effect, one would like to know their substructures.

v) More data are required to establish the quantum numbers of the currently observed baryonium states. The picture of Baryonium spectroscopy will be clear only after their quantum numbers are decided.

vi) One would like to know if baryonium with I=2 exists or not?

vii) Qualitatively one can say that the present experimental evidence is sufficient to accept the baryonium states as exotic ($qq\bar{q}\bar{q}$) system. Similarly the observation of bound $\bar{p}p$ system is satisfying to nuclear physicists. It is hoped that a better understanding of the nucleon-antinucleon potential.

However, this theory has still to provide a satisfactory answer as to why the annihilation is inhibited in $\bar{p}p$ system. The quark model also faces similar problem. Thus further improvements in the theory are also aalled for.

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TABLE-I

Summary of the data on S-meson

ref.	(17)	(19)	(20)
Mass (MeV)	1932±2	1936±1	1939±3
Γ (MeV)	9^{+4}_{-3}	$8.8^{+4.3}_{-3.2}$	$\leqslant 4$
σ_{Tot}(mb)	160±75	10.6±2.4	
σ_{el}(mb)	-	7.0±1.4	
σ_{CE}(mb)	-	=1.6±0.7	-

Iso-Spin = 1(0)
J = 0,1 or 2 ($J^{PC} = 2^{++}$?)

TABLE-II

Data from Carter et al [27]

Mass (MeV/c²)	Width Γ (MeV)	J^{PC} I^G
2150±30	200±25	3^{--} 1^+
2310±30	210±25	4^{++} 0^+
2480±30	280±25	5^{--} 1^+

TABLE-III

Result from Benkhieri et al [29]

Mass (MeV/c^2)	Γ (MeV)	Cross-section (nb): $\pi^- p \to \Delta(1232), M$; $\Delta \to p\pi^-$, $M \to p\bar{p}$	Cross-section (nb): $\pi^- p \to N^*(1520), M$; $M \to p\bar{p}$, $N^* \to p\pi^-$
1930	10	9±5	-
2020±3	24±12	18±5 (9 GeV/c) 10±4 (12 GeV/c)	30±12 (9 GeV/c) 26±8 (12 GeV/c)
2204±5	16^{+20}_{-16}	17±5 (9 GeV/c) 21±5 (12 GeV/c)	-

TABLE-IV

Results from reference [38]

Energy of γ-rays (MeV)	Instrumental line width (MeV)	Confidence level	Yield per 10^3 annihilations
132±6	16	99.3	5.1±2.7
183±7	19	99.0	7.2±1.7
216±9	21	97.5	6.0±1.9
420±17	34	98.2	8.5±2.0

Captions to Figures

Fig.1. The lightest 0^+ nonet from reference [4] calculated in bag model.

a) SU(3) weight diagram ; (b) masses of the states.

Fig.2. Duality diagrams for baryonium and diagrams for OZI-allowed and OZI-suppressed decays.

Fig.3. Proton-Antiproton total inelastic (0+2+4+6 prongs), elastic and 0,2,4,6 prong cross-sections (reproduced from reference [19].

Fig.4. a) Behaviour of Total cross-section (from Ref.[24]) (closed circles) and the partial elastic cross-section (open circles).

b) Partial elastic cross-section after substracting the background.
(reproduced from Eisenhandler et al [25]).

Fig.5. a) $\bar{p}p$ total elastic cross-section.
b) cross-section for $\bar{p}p \rightarrow \bar{n}n$ (Data from D.Cutts et al).
The lower lines are the estimated background (reproduced from reference [26]).

Fig.6. T-U resonances parameters from various $\bar{p}p$ experiments. The masses (MeV/c^2) and widths are shown.

Fig.7. The $\bar{p}p$ invariant mass with $\cos\theta < 0$ (θ =Jackson angle) and $1175 < M_{p\bar{p}\pi^-} < 1300$ MeV for $\pi^- p \; p_f \; \bar{p}p \; \pi^-$ interactions at 9 and 12 GeV/c. (reproduced from reference [29]).

Fig.8. Diagrams representing the production mechanism of Baryonium states.

a) Production from $\pi^- p \rightarrow (\Delta \text{ or } N^*, M) \rightarrow p_f \bar{p}p \pi^-$ (ref. [29]);

b) Production of $\bar{p}_f p\pi^-$ (2950) from ref.[30];

c) Production 1950 MeV ($\bar{p}p$) resonance from ref. [33].

d) Production of a dibaryon in pp reaction as predicted by Jaffe [4].

Fig.9. Results of Evangelista et al [30] on (a) the production of narrow resonance in ($\bar{p}p_f\pi^-$) system at 2950±10 MeV and (b) the decay of the resonance.

Fig.10. Results from ref. [33] for $\bar{p}p$ invariant mass in $\pi^+ p \rightarrow \bar{p}pp\pi^+$ in 20 MeV bins.

a) All pairs of $\bar{p}p$; (b) All $\bar{p}p$ pairs with $-t'_{\pi(p\bar{p})} < 1.2$ $(GeV/c)^2$ where $t' = t - t_{min}$ and t is 4-momentum transfer; (c) with condition (b) and p of $p\bar{p}$ pair not participating in Δ^{++} ($M_{p\pi^+} > 1.4$ GeV/c^2).

Fig.11. Effective mass of $(K^0_s \pi\pi\pi)^\pm$ combination from the (6 prongs + v^0) topology events. (reproduced from ref.[34].

Fig.12. Invariant mass for ($p\bar{p}\pi\pi$) in reactions $\pi^- d \rightarrow P_{sp} P_f p\bar{p}\pi^-\pi^-$.

a) 2C fit with p_f between 7-10 GeV/c;
b) events in (a) with P_{slow} forward in ($p\bar{p}\pi^-\pi^-$);
c) events in (b) with both $\Delta^0(p\pi^-)$ and $(\bar{\Delta})^{--}(p\pi^-)$ mass (reproduced from reference [35]).

Fig.13. Invariant mass of (a) ($p\bar{p}\bar{\pi}$) from ($p\bar{p}\bar{\pi}p_f$) events and (b) ($p\bar{p}\bar{\pi}\bar{\pi}$) from $p\bar{p}\bar{\pi}\bar{\pi}p_f$ events from 13.2 GeV/c π^-d interactions. The solid line is transverse momentum damped phase space. All events are of 4-C fit. (reproduced from ref. [36]).

Fig.14. γ-ray spectrum (true signal) from the transitions of $p\bar{p}$ bound system. The solid line is the computer fit to the peaks in the spectrum (reproduced from ref. [38]).

Fig.15. Missing mass spectrum (GeV/c²) in $pp \rightarrow K^+K^+X$ at different beam momentum (reproduced from ref. [29]).

Fig.16. Summary of the present experimental data on baryonium states.

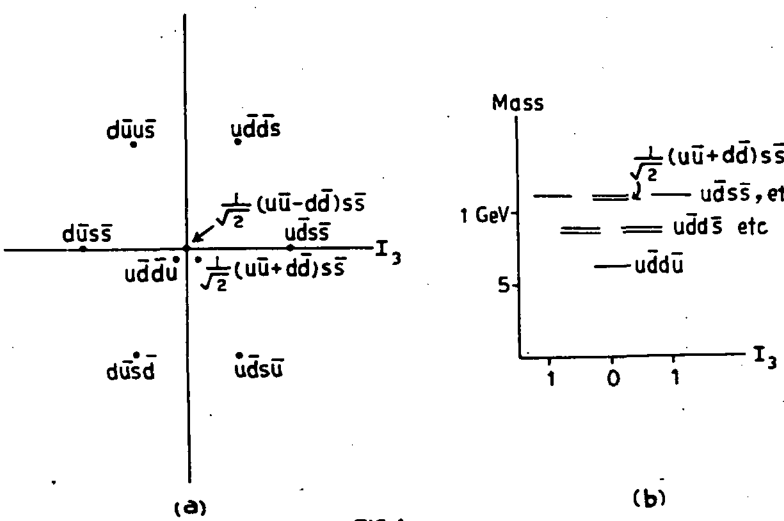
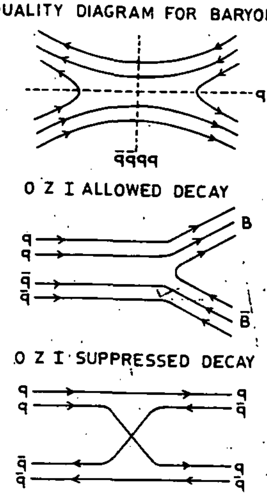


FIG.1.

(1) DUALITY DIAGRAM FOR BARYONIUM



(2) O Z I ALLOWED DECAY

(3) O Z I SUPPRESSED DECAY

FIG. 2.

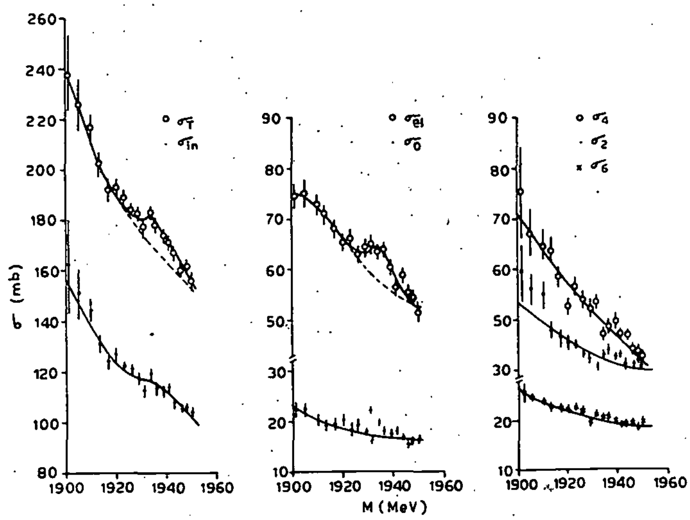
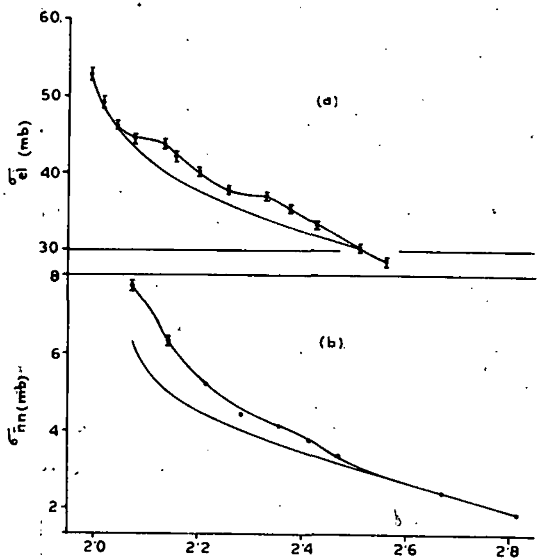
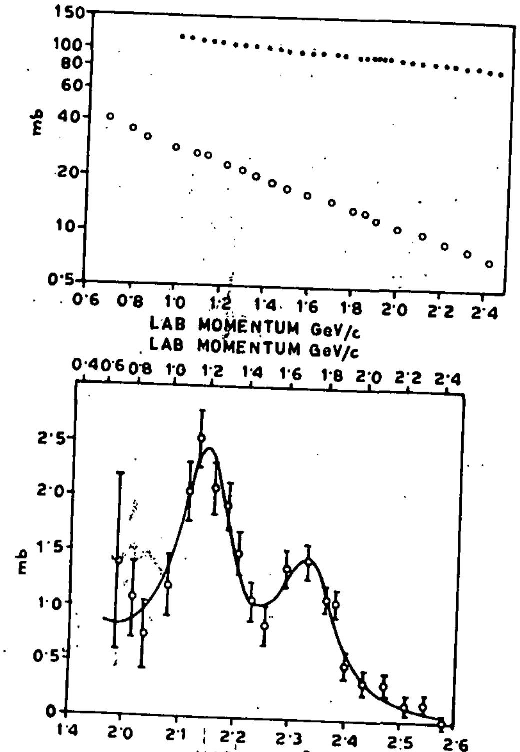


FIG. 3.



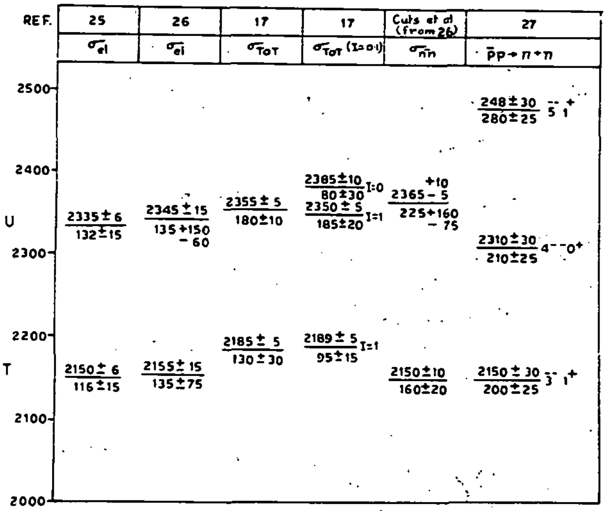
(a)
(b)
σ_{el} (mb)
$\sigma_{\bar{n}n}$(mb)
60
50
40
30
8
6
4
2
2·0
2·2
2·4
2·6
2·8
Ecm (GeV)

FIG. 5.



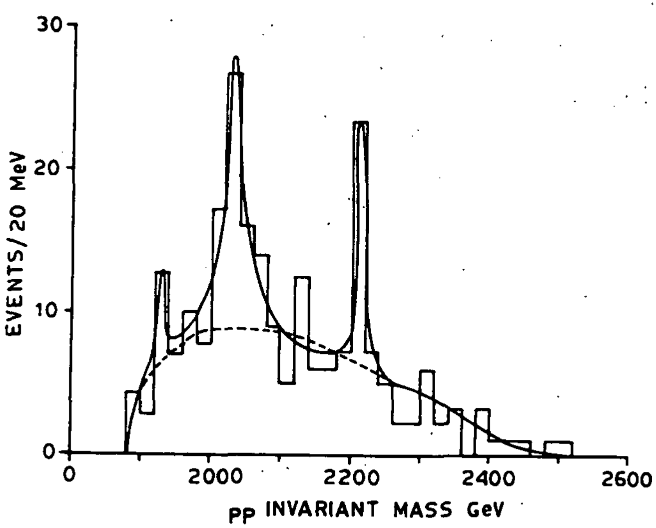
150
100
80
60
40
20
10
0·5
mb
0·6 0·8 1·0 1·2 1·4 1·6 1·8 2·0 2·2 2·4
LAB MOMENTUM GeV/c
LAB MOMENTUM GeV/c
0·4 0·6 0·8 1·0 1·2 1·4 1·6 1·8 2·0 2·2 2·4
2·5
2·0
1·5
1·0
0·5
0
mb
1·4 2·0 2·1 2·2 2·3 2·4 2·5 2·6
MASS GeV/c^2

FIG. 4.



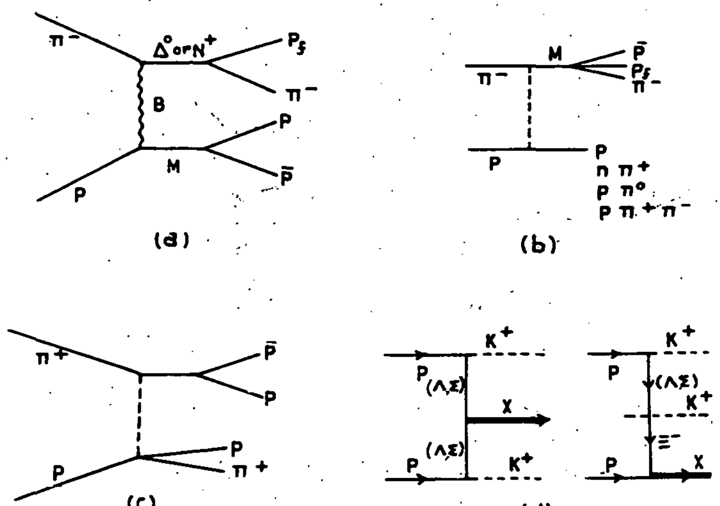
REF.
25
26
17
17
Cuts et al (from 26)
27
σ_{el}
σ_{el}
σ_{TOT}
σ_{TOT} (I=0,1)
$\sigma_{\bar{n}n}$
$\bar{p}p \to n + n$
2500
2400
2300
2200
2100
2000
U
T
248 ± 30 / 280 ± 25
2385 ± 10 / 80 ± 30 I=0
2350 ± 5 / 185 ± 20 I=1
2365 +10 −5 / 225 +160 −75
2335 ± 6 / 132 ± 15
2345 ± 15 / 135 +150 −60
2355 ± 5 / 180 ± 10
2310 ± 30 / 210 ± 25
2185 ± 5 / 130 ± 30
2189 ± 5 / 95 ± 15 I=1
2150 ± 6 / 116 ± 15
2155 ± 15 / 135 ± 75
2150 ± 10 / 160 ± 20
2150 ± 30 / 200 ± 25

FIG. 6



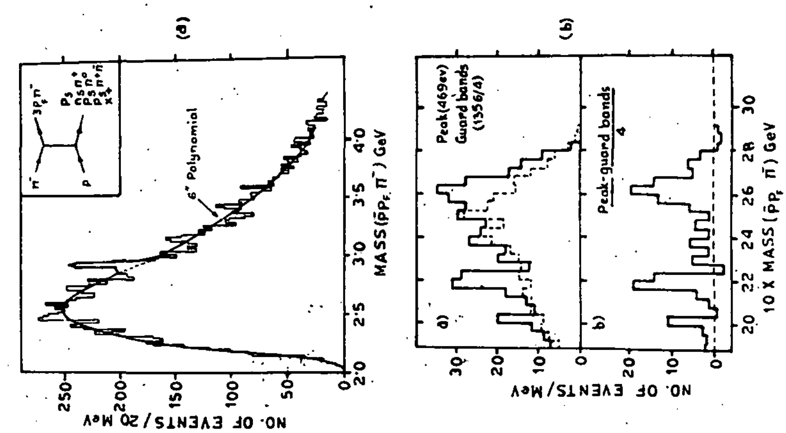
30
20
10
0
EVENTS/20 MeV
0
2000
2200
2400
2600
pp INVARIANT MASS GeV

FIG. 7



(a)
(b)
(c)
(d)

FIG. 8.



NO. OF EVENTS / 20 MeV
MASS ($\bar{p}p_f\pi^-$) GeV
6° Polynomial
(a)
Peak(469ev)
Guard bands (1356/4)
Peak-guard bands / 4
NO. OF EVENTS / MeV
10 X MASS ($\bar{p}p_f\pi^-$) GeV
(b)

FIG. 9

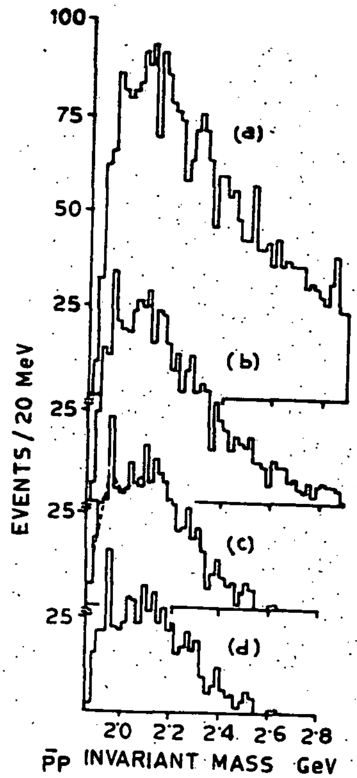

100
75
50
25
25
25
25
(a)
(b)
(c)
(d)
EVENTS / 20 MeV
2·0 2·2 2·4 2·6 2·8
P̄P INVARIANT MASS GeV

FIG. 10.

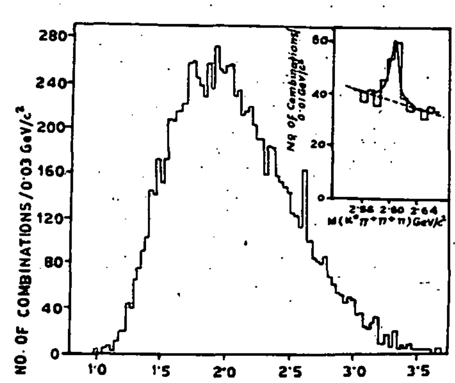

NO. OF COMBINATIONS / 0·03 GeV/c²
0
40
80
120
160
200
240
280
1·0 1·5 2·0 2·5 3·0 3·5
M (K° π⁺ π⁺ π) GeV/c²
NO. OF Combinations / 0·01 GeV/c²
0
20
40
60
2·56 2·60 2·64
M(K° π⁺ π⁺ π) GeV/c²

FIG. 11.

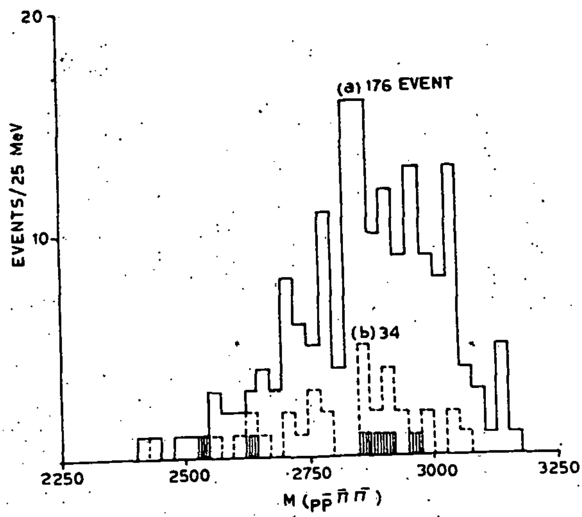

20
10
EVENTS/25 MeV
(a) 176 EVENT
(b) 34
2250
2500
2750
3000
3250
M (pp̄π̄π̄)

FIG.12.

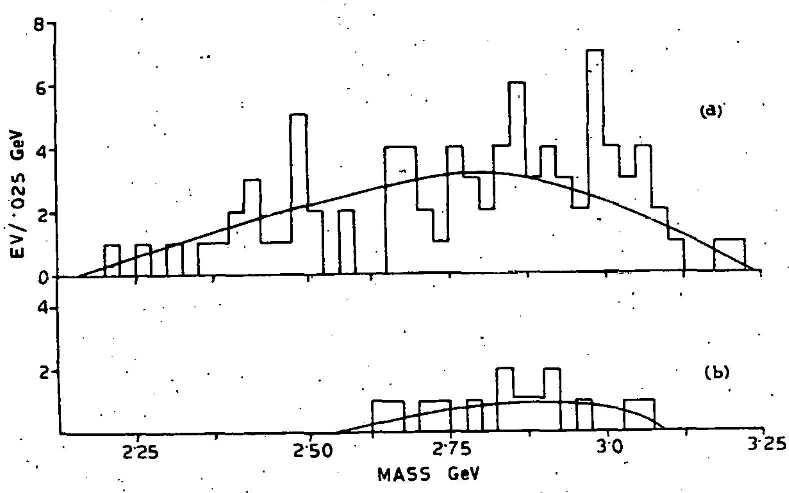

8
6
4
2
0
4
2
EV/·025 GeV
(a)
(b)
2·25
2·50
2·75
3·0
3·25
MASS GeV

FIG.13.

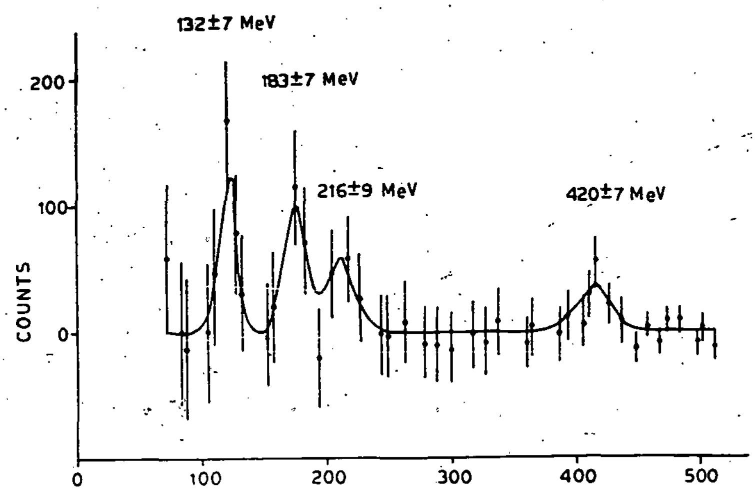

132±7 MeV
183±7 MeV
216±9 MeV
420±7 MeV
COUNTS
0
100
200
0
100
200
300
400
500
ENERGY (MeV)

FIG.14.

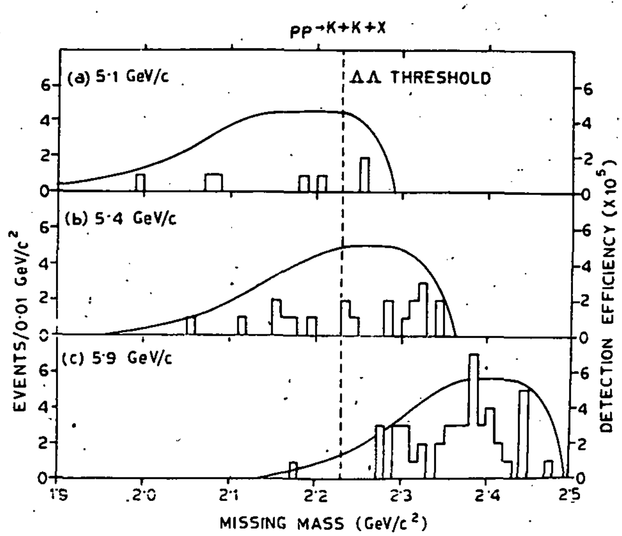

pp→K+K+X
(a) 5·1 GeV/c
ΛΛ THRESHOLD
(b) 5·4 GeV/c
(c) 5·9 GeV/c
EVENTS/0·01 GeV/c²
DETECTION EFFICIENCY (X10⁵)
1·9
2·0
2·1
2·2
2·3
2·4
2·5
MISSING MASS (GeV/c²)

FIG.15

		STATES	Γ (MeV)	J^{PC}	I^G	MODE	COMMENTS
						EXOTIC	NO DEFINITE EVIDENCE
2950		2950±10	⩽32		1,2	$\pi p \rightarrow (\bar{p}p\pi) p_f$	NOT CONFIRMED WITH MORE DATA ?
2750							
		2600±10	⩽18			$(\bar{p}p) \rightarrow K_S^0\ \pi$'S	STRANGENESS = ±1 (ALSO $\bar{\Lambda}$N AT ~ 2200 ?)
2550							
		2480±30	280±25	5^{--}	1^+	$(\bar{p}p) \rightarrow \pi\pi$	PART OF U ?
		2385±10	80±30	4	0		
2350	U	2350±15	160±20	⩽2?	0,1		ANOTHER RESONANCE OF 4^+?
		2310±30	210±25	4^{++}	0^+	$(\bar{p}p) \rightarrow \pi\pi$	
		2204±5	16^{+20}_{-16}			$\pi p \rightarrow \Delta + (p\bar{p})$	U-CHANNEL σ~ 20 nb
2150	T	2190±10	90±20	⩽1?	1		$\bar{n}n$ SMALL
		2150±50	200±25	3^{--}	1^+	$(\bar{p}p) \rightarrow \pi\pi$	
		2020±3	24±12			U-CHANNEL $(\bar{\pi}p) \rightarrow (A\ \text{or}\ N^*) + (\bar{p}p)$ σ~ 15 nb	
1950	S	1954±5	<10	1^{--}		t-CHANNEL, B EXCHANGE σ~ 300	
		1936±1	4–8	0,1,2 (2^{++}?)	1 (0)	$(\bar{p}p),(\bar{p}n)$	$\bar{n}n$ SMALL
							$\bar{p}p$ THRESHOLD
1750		1794±1·4	< 8			$(\bar{p}n)$—HADRONS	B.E.=83·3±1·4 MeV
		1684±7	SMALL			$\bar{p}p$ — γ	B.E=183±7 MeV
		1646±9	SMALL			($\bar{p}p$ FORMS ATOM)	=216±9 MeV
1550							
1350		1395±17	SMALL				=420±17 MeV

FIG. 16.

DISCUSSION

K.V.L. Sarma: It should perhaps be mentioned that there is evidence from polarisation experiments at Argonne for a $^3F_3$ resonance ($M = 2260$ MeV, $\Gamma \sim 200$ MeV, $J^P = 3^-$) in the two-proton system; see H. Hidaka et al., Phys. Letters 70B, 479 (1977). Evidence for resonances in other partial waves such as $^1D_2$, $^1G_4$ also seems to be accumulating.

Yog Prakash: I agree. Similarly information for Dibaryon is also gathering. This should be included to update the available information included in this survey.