An Analysis of Early Data on Heavy Exotic Mesons Based on the Diquark Cluster Model

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Abstract: Early data with respect to heavy exotic mesons with narrow width ($\leq$ 80 MeV) found in $\pi^- p$ reactions by Anderson et al. and Baud et al. in 1969-1970 are analyzed using the diquark cluster model. It is shown that the simple mass formula of the diquark cluster model, which involves no free parameters, can clearly reproduce the mass spectrum for the heavy exotic mesons (11 candidates) indicated by the empirical data.

Recently, the ASTERIX collaboration[1] and Crystal Barrel Collaboration [2] confirmed the existence of an exotic meson with a mass of nearly 1.5 GeV, I = 0 and $J^{PC} = 2^{++}$ through analysis of the $\bar{p}p$ annihilation reaction at rest into three pion states. This exotic meson is undoubtedly the most favorable candidate for the four quark state $q^2\bar{q}^2$. This discovery of a promising candidate for the four quark state indicates strongly the existence of higher multiquark states $q^k\bar{q}^k (k \geq 3)$ with baryon number 0 which should be observable as exotic mesons with mass above 2 GeV. The search for heavy exotic mesons could well be one of the most interesting subjects for future particle physics. For this reason, we present an analysis of early data on heavy exotic mesons using the diquark cluster model.[3-7]

The diquark cluster model is a semi-phenomenological model for the multiquark system which was originally introduced to explain the mass spectrum and the widths of dibaryon resonances [3-5] and later applied to more general multiquark systems.[6-7] In the present analysis, we focus our attention on the mass spectrum of the narrow exotic mesons with widths less than 80 MeV. Before going into the analysis, we touch breifly on the history of the heavy exotic meson.

In 1966, the investigation of heavy exotic mesons with narrow widths began with the finding of three sharp peaks above 2 GeV in the missing mass spectrum of the forward recoil protons by Focacci et al.(CERN Missing Mass Spectrometer Group).[8] This was done using the $\pi^- p \to pX^-$ reactions at incident laboratory pion momentum of 12 GeV/c. The results were interpreted as three bosons S(1930), T(2190) and U(2380). Subsequently, during 1969-1970, the same experiments were carried out by Baud et al.[9-10] at the incident pion momenta 8.9, 9.1, 9.5, 10.2, 10.5, 12, 13, 14, 15 and 15.5 GeV/c. A group of narrow resonances with resonating energy above 2.6 GeV were found in these experiments. The missing mass spectrum for the backward recoil protons in the same reactions were measured by Anderson et al. in 1969 at incident beam momentum 16 GeV/c and three narrow resonances were found at 2260, 2370 and 2500 MeV.[11] Among them, the one at 2370 MeV was identified with U(2380). It seemed that many exotic mesons existed in the mass region above 2 GeV.

The situations changed in 1972. The same experiments as in ref.[8-10] were carried out by Antipov et al. [12] at incident pion momenta 25 and 40 GeV/c and they found no clear structure above 2 GeV in the missing mass spectra. In 1973, Bowen et al. also measured the missing mass spectra at incident momenta 11, 13.4 and 16 GeV/c with comparable mass resolution and improved statistics compared to ref.[8] and they again found no evidence for the existence of the S, T and U mesons.[13] In 1981, Evangelista et al. reported the results for the same experiment with higher statistics at incident pion momenta 12 GeV/c.[14] Again, their data did not support the existence of S, T and U mesons. As a result of these experiments it was thought that no heavy exotics with narrow widths existed in the high mass region above 2 GeV and the data of Baud et al. and Anderson et al. were gererally ignored. It should be emphasized, however, that the negative results by Antipov et al. can not be used to deny the results of Baud et al. because the incident pion momenta used were very different from each other.The narrow resonances reported by Baud et al. may simply need a more approproately disigned experiment to replicate the results. We illustrate the mass spectrum of these heavy exotic mesons in Fig.1.

We summarize here the basic assumptions of the diquark cluster model.

(I) Most of the quarks (antiquarks) in the multiquark system $q^k\bar{q}^h$ are in the diquark state with the 3*-color state (antidiquark state with the 3-color state).

(II) The system can be described without serious problems by adopting the jj-coupling scheme.

(III) The residual short range interaction can exist only between two quarks in a diquark (two antiquarks in an antidiquark).

(IV) Two quarks (antiquarks) in a diquark (antidiquark) are tightly bound to make a cluster called a diquark cluster (antidiquark cluster) if both of them are in the $1s\frac{1}{2}$-shell.

Hereafter, the notation ϕ and ϕ_1 ($\bar{\phi}$ and $\bar{\phi}_1$) are used for the diquark cluster (antidiquark cluster) with spin 0 and 1, respectively. Adopting the approach given in ref.[3-4], the mass formula for the $q^k\bar{q}^h$ system which consists only of the u and d quarks is given by

$$M = mn + M(1p_{\frac{1}{2}})n(1p_{\frac{1}{2}}) + M(1p_{\frac{3}{2}})n(1p_{\frac{3}{2}})$$

$$+M(1d_{\frac{3}{2}})n(1d_{\frac{3}{2}}) + \Delta_0(n_\phi + n_{\bar{\phi}}) + \Delta_1(n_{\phi_1} + n_{\bar{\phi}_1}) + \sum \Delta_{TS}. \tag{1}$$

Here

$$\Delta_0 = a - \frac{3}{4}b, \qquad \Delta_1 = a + \frac{1}{4}b, \tag{2}$$

and m is the effective quark mass, $n(= k + h)$ is the total quark number, and $M(\xi)$ is the single-particle excitation energy from a $1s\frac{1}{2}$-shell to the shell for the state ξ with orbital and total angular momenta l and j. The term $n(\xi)$ is the total numbers of the excited quarks and antiquarks in the shell, n_ϕ and $n_{\bar{\phi}}$ (n_{ϕ_1} and $n_{\bar{\phi}_1}$) are the number of the ϕ and $\bar{\phi}$ (ϕ_1 and $\bar{\phi}_1$) involved in the system, a and b represent the spin-independent and spin-dependent two-particle correlation energies for the two quarks in a diquark cluster, respectively, and Δ_{TS} is the correlation energy for the quarks in the excited diquark with a configuration $[(1p\frac{1}{2})(1s\frac{1}{2})]$ and with isospin T and spin S. The summation in (1) runs over all of the excited diquarks. No attempt will be made to disuss the methodology in detail, the reader is referd to [4]. Some points should be made here, in particular, the correlation energy is taken to be zero for the excited diquarks in which a constituent quark is in the shell with $j \geq \frac{3}{2}$. The radial excitation and the excitation for the shell characterized by $j \geq \frac{5}{2}$ are neglected. In terms of the anguler frequency ω in the harmonic-oscillator model[3], the single-particle excitation energies are given by

$$M(1p_{\frac{1}{2}}) = \omega - \frac{\omega^2}{2m}, \quad M(1p_{\frac{3}{2}}) = \omega + \frac{1}{2}\frac{\omega^2}{2m}$$

$$M(1d_{\frac{3}{2}}) = 2\omega - \frac{3}{2}\frac{\omega^2}{2m} \tag{3}$$

The mass formula (1) then involves eight parameters $m, \omega, a, b, \Delta_{00}, \Delta_{10}, \Delta_{01}$, and Δ_{10}. All of these were determined in ref.[4] using the baryon masses and the πd phase-shift reported by the ETH group [16]. The parameters (in MeV) in formula (1) are given by:

$$m = 300 \quad M(1p_{\frac{1}{2}}) = \; 150, \quad M(1p_{\frac{3}{2}}) = \; M(1d_{\frac{3}{2}}) = \; 375,$$

$$\Delta_0 = \; 40, \quad \Delta_1 = \; 235, \quad \Delta_{01} = \; 10,$$

$$\Delta_{10} = \; -60, \quad \Delta_{00} = \quad \Delta_{11} = \; 0. \tag{4}$$

It should be emphasized that no free parameter remains in the mass formula (1).

We assume that the simplest multiquark states, which consist of many ϕ and $\bar{\phi}$ with chain color-structure and the quarks and/or antiquarks in the end of the chain as illustrated in Fig.2, should be assigned to the candidates for the narrow exotic mesons observed by Anderson et al. and Baud et al. Since the quarks in the diquark cluster (antiquarks in the antidiquark cluster) stay always in the $1s\frac{1}{2}$-shell in the diquark cluster model, the excitation of these systems occurs via the excitation of the quarks and/or antiquarks in the end of the chain. For this reason, the structure of the mass spectrum does not depend on the number of ϕ and $\bar{\phi}$ or on the parameters Δ_{TS}.

We show in the right-hand side of Fig.1 the mass spactra for systems ($k = 3, 4, 5$) with this specific structure as predicted by the mass formula (1). One can see in this figure the repetition of the same pattern, of which the spacing equals the mass of a ϕ (= 640 MeV). Strikingly enough, the predictions of the diquark cluster model agree dramatically with the data of Anderson et al. and Baud et al. Further, the interesting fact that all of the first excited states in the k = *3*, *4* and *5* systems are missing suggests the existence of a periodic law for the production rate of the excited states as well as for the mass spectrum. We remark that the existence of the states near the $p\bar{p}$-threshold (1880 MeV) is not excluded by the present $p\bar{p}$ phase-shift analysis.[17] The missing level at 2180 MeV will be discussed shortly. Of course, it is possible to interpret this agreement as purely an accidental fit. To settle whether this fit is an accident or not, it would be desirable to examine the validity of the data of Anderson et al. and Baud et al. under the same conditions as their original experiments with improved statistics.

Finally, we would like to comment on the experimental data with respect to the production of exotics by hadronic reactions. As seen in Fig.1, a missing level at 2180 is very close to the mass of a T-meson which had been found once by the CERN Missing Mass Spctrometer Group in a $\pi^- p$ missing mass experiment using an incident pion momentum of 12 GeV/c. However, since that experiment no one else has succeeded in duplicating that observation. A similar situations may exist for two narrow baryonia with masses 2020 and 2200 MeV which were found by Benkheiri et al.[18] in the reactions $\pi^- p \rightarrow p_f p\bar{p}\pi^-$ at incident pion momenta 9 and 12 GeV/c. One possible interpretation for these records is that the experiments were properly done but reproduction was very difficult because these exotics are produced mainly through narrow excited states of a baryon as in a nuclear reaction via a compound nucleus. Note that, in this resonant production picture, an appreciable production of exotics occurs only at some specific c.m. energies (resonating energies) but the yield would cease with a slight change in the incident pion momentum; making difficult the reproduction of the experiment.

We try to examine this possibility using the mass formula (1) of the diquark cluster model. Let us consider the $q^{h+3}\bar{q}^h$ states with a chain structure which consists of three quarks (two quarks and an antiquark) and many ϕ and $\bar{\phi}$, as illustrated in Fig.3. To examine the validity of the mass formula (1) for these baryonic multiquark systems, we study the smallest system with $h = 1$ where the energy levels lie at 1500 - 2300 MeV. Recently, Capstick and Roberts calculated the $N\pi$ decay amplitudes for all N^* and Δ resonances and suggested that the well-established resonance N(1720) with $J^P = \frac{3}{2}^+$ is possibly a low-lying exotic state.[19] Considering that the spin-parity of this state is $\frac{3}{2}^+$ and that there is no similar state in the Δ-resonance at around 1700 MeV, it may be reasonable to interpret this exotic baryon as a member of the states shown in Fig.3(a) in which two quarks in one end form a diquark with configuration $[(1p\frac{1}{2})(1s\frac{1}{2})]$, isospin 0 and spin 1, and the single antiquark in the other end stays in the $1s\frac{1}{2}$-shell. In this case, the mass estimated by formula (1) is 1700 MeV which is quite consistent with the experimental value $\approx 1720MeV$.[20] The partner with $J = \frac{1}{2}$ can be assigned to the resonance $N(1720)$ with $J^p = \frac{1}{2}^+$.[20] These good agreements seem to indicate that the mass formula (1) can be applicable to the baryonic multiquark systems. We remark that the finding of the baryonic multiquark states by an analysis of the elastic πN scattering is generally not easy because these states can be expected to decay emitting more pions than the simple three quark states. This is by virtue of the real $q\bar{q}$-pairs involved in the system and indicates a smaller elasticity in the πN scattering.

When two of the three quarks (two quarks and an antiquark) in a $q^{h+3}\bar{q}^h$ state with a chain structure are excited to the $1d\frac{3}{2}$-shell and the last one stays in the $1s\frac{1}{2}$-shell, the mass of the system is given by a linear function

$$M = 640h + 1650 \quad (MeV), \tag{5}$$

reflecting the periodic law mentioned above. The c.m. energies of $\pi^- p$ reaction at incident pion momenta 9 and 12 GeV/c in which the exotics were found are 4218 and 4840 MeV, respectively. They are very close to the masses 4210 and 4850 MeV for $h = 4$ and 5 in formula (5). This result suggests that, in the experiments by the CERN Missing Mass Spectrometer Group and Benkheiri et al., the production of exotics can be enhanced accidentally by the resonant production mechanism via a specific excited state of a baryon.

We remark that, among the various incident pion momenta at which the experiment of Baud et al. was carried out, the corresponding c.m. energies of the four cases (8.9, 9.1, 12 and 15.5 GeV/c) are very close to the masses given by (5) with $k = 4, 5$ and 6. In the experiment of Bowen et al. none of the incident pion momenta gives a c.m. energy close to the mass given by (5) suggesting the underlying reason why they could not find exotics. As indicated by the above analysis, the experiments with respect to the production of exotic mesons must be carried out carefully taking into account the possibility of resonant production.

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References:

[1] B. May et al., Z. Phys. C46 (1990) 203.
[2] E. Aker et al., Phys. Lett. B260 (1991) 249.
[3] N. Konno and H. Nakamura, Lett. Nuovo Cimento 34 (1982) 313.
[4] N. Konno, H. Nakamura and H. Noya, Phys. Rev. D35 (1987) 239.
[5] N. Konno, H. Nakamura and H. Noya, Phys. Rev. D37 (1988) 154.
[6] H. Nakamura, N. Konno and H. Noya, Nucl. Phys. B (Proc. Suppl. Vol.8, North-Holland, Amsterdam, 1989) p. 57
[7] Y. Uehara, 3rd Workshop on Lightquark Meson Spectroscopy, KEK (1992), Edited by K. Takamatsu and T. Tsuru, p.124
[8] M. N. Focacci et al., Phys. Rev. Lett. 17, 890 (1966)
[9] R. Baud et al., Phys. Lett. 30B (1969) 129.
[10] R. Baud et al., Phys. Lett. 31B 549 (1970) 549.
[11] E. W. Anderson et al., Phys. Rev. Lett. 22 (1969) 1390.
[12] Y. M. Antipov et al., Phys. Lett. 40B (1972) 147
[13] D. Bowen et al., Phys. Rev. Lett. 30 (1973) 332.
[14] C. Evangelista et al., Nucl. Phys. B178 (1981) 197.
[15] Generally, a bracket [ ] represents a diquark.
[16] M. Merdzen et al., J. Phys. Jpn. Suppl. 55 (1986) 842
[17] W. Brückner et al., Z. Phys. A339 (1991) 367.
[18] P. Benkheiri et al., Phys. Lett. 68B (1977) 483.
[19] S. Capstick and W. Roberts, CEBAF-TH-92-05 (1992)
[20] J.J.Hernández et al., Phys. Letts. B239 (1990) 1

Captions

Fig.1: The predictions for the mass spectra of the $q^k\bar{q}^k$ systems (k = 3, 4 and 5). The surviving candidates reported by Baud et al.[9,10] and Anderson et al.[11] are shown in the left-hand side together with the T(2190) and U(2380) suggested by the CERN Missing Mass Spectrometer Group [8] and the baryonia reported by Benkheiri et al.[18]

The boxes represent the widths. Since the excitation energies for the $1p\frac{3}{2}$-shell and $1d\frac{3}{2}$-shell are the same in the present analysis, the levels of the states for the quark excitations to the $1p\frac{3}{2}$-shell and $1d\frac{3}{2}$-shell are completely degenerate. The parities of the upper three levels in each k shown here are of the states for the excitation to the $1d\frac{3}{2}$-shell.

Fig.2: The color configurations of the $q^k\bar{q}^k$ states with chain structure for $k = 3, 4$ and 5. The white and black circles (squares) represent q and $\bar{q}$ (ϕ and $\bar{\phi}$), respectively. The lines represent either of the 3 and 3* color states.

Fig.3: Some examples of the $q^{h+3}\bar{q}^h$ states with chain color structure. ($h = 1, 4$ and 5) The two quarks in the left-hand end of configuration (a) form a diquark. When the diquark is a ϕ the system becomes a spurious state by virtue of the color-SU(3) symmetry.

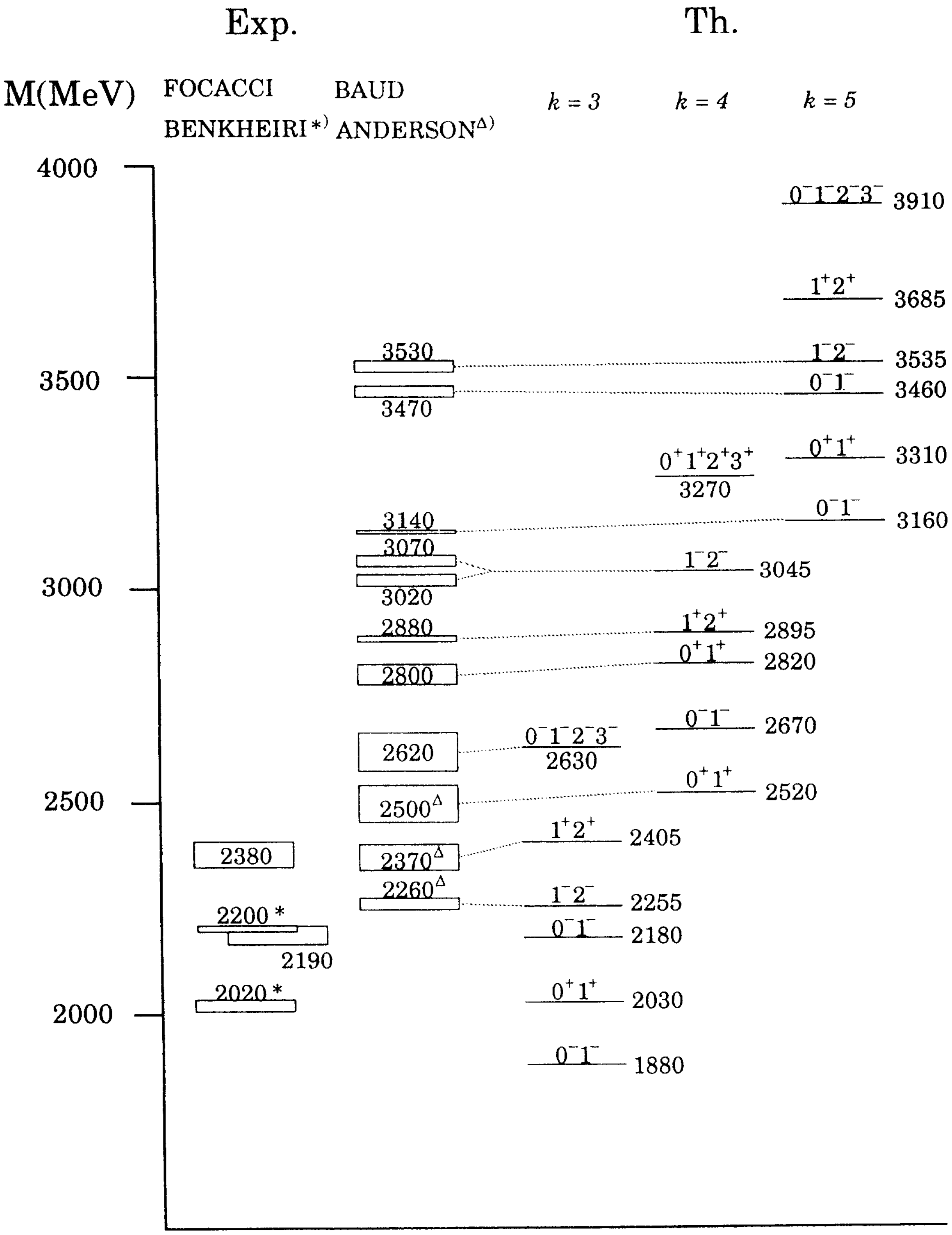
Exp.
Th.
M(MeV)
FOCACCI
BENKHEIRI *)
BAUD
ANDERSON$^{\Delta)}$
$k = 3$
$k = 4$
$k = 5$
4000
3500
3000
2500
2000
3530
3470
3140
3070
3020
2880
2800
2620
2500^{Δ}
2380
2370^{Δ}
2260^{Δ}
2200 *
2190
2020 *
$0^-1^-2^-3^-$ 3910
1^+2^+ 3685
1^-2^- 3535
0^-1^- 3460
0^+1^+ 3310
$0^+1^+2^+3^+$ 3270
0^-1^- 3160
1^-2^- 3045
1^+2^+ 2895
0^+1^+ 2820
0^-1^- 2670
$0^-1^-2^-3^-$ 2630
0^+1^+ 2520
1^+2^+ 2405
1^-2^- 2255
0^-1^- 2180
0^+1^+ 2030
0^-1^- 1880

Fig. 1

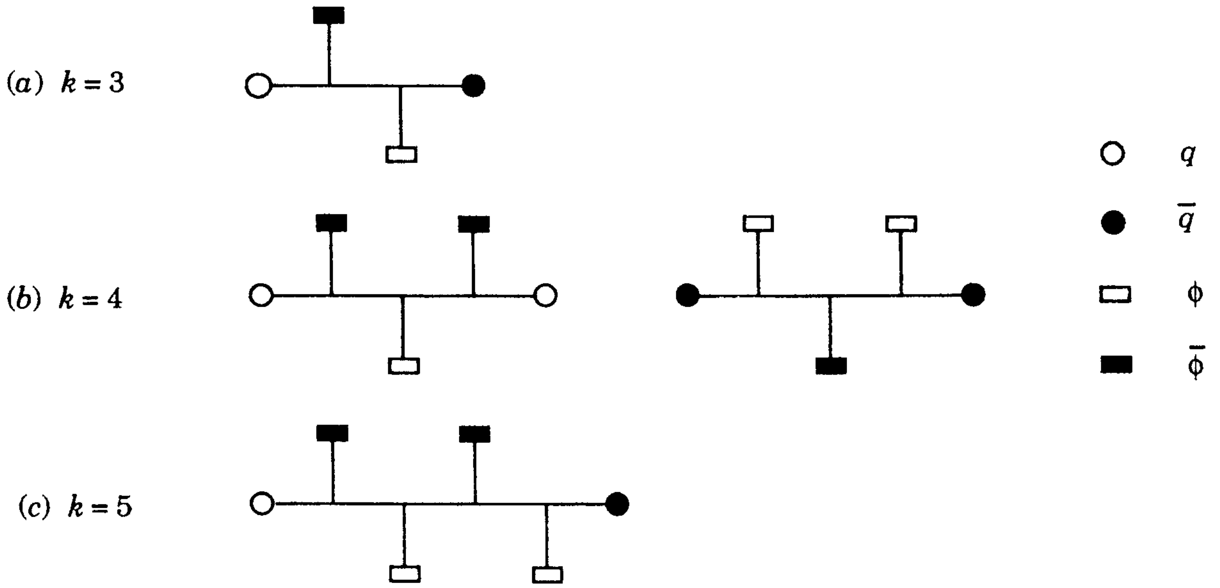

Fig. 2

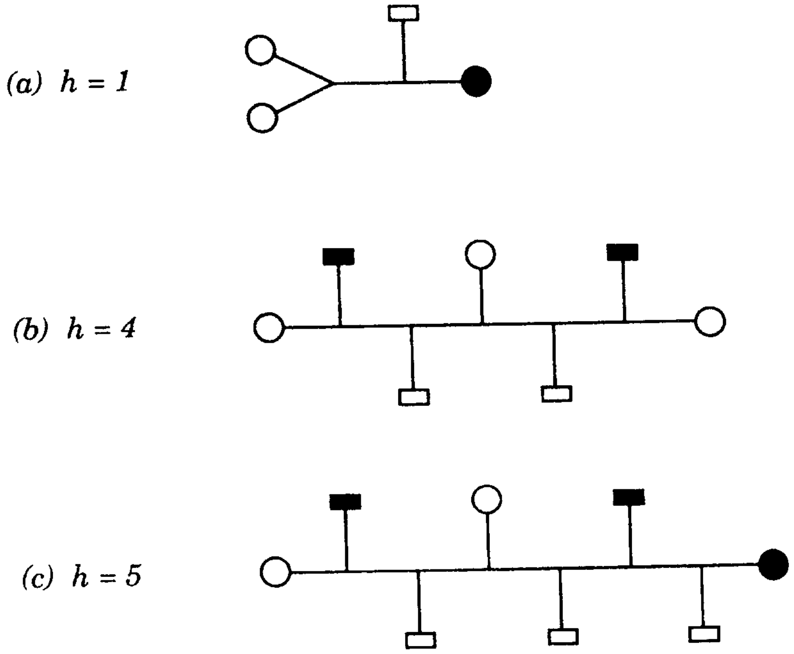

Fig. 3