УДК 539.12

AN EVIDENCE FOR THE EXCITED STATE OF THE $S = -2$ STABLE LIGHT DIBARYON

B.A.Shahbazian, T.A.Volokhovskaya, V.N.Yemelyanenko, A.S.Martynov

It has been proved that the $S = -2$ stable light dibaryon does exist in two quantum states at least: 1) in the ground state H^0, $M_{H^0} = (2146.3 \pm 1.0)$ MeV/ c^2 , $I = 0$, $J^{\pi} = 0^+$ and 2) in the excited state H_1^0, $\langle M_{H_1^0} \rangle = (2200.9 \pm 4.1)$ MeV/ c^2, $I = 0$, $|l - 1| \le J \le |l + 1|$, $\pi = (-1)^l$, or $(-1)^{l-1}$ for a 2^l-pole electric or magnetic γ-transitions, respectively.

The investigation has been performed at the Laboratory of High Energies, JINR.

Доказательство существования возбужденного состояния стабильного легкого дибариона со странностью $S = -2$

Б.А.Шахбазян и др.

Показано, что легкий стабильный дибарион со странностью $S = -2$ существует по крайней мере в двух квантовых состояниях: 1) в основном состоянии H^0, $M_{H^0} = (2146{,}3 \pm 1{,}0)$ МэВ/ c^2, $I = 0$, $J^{\pi} = 0^+$ и 2) в возбужденном состоянии H_1^0, $\langle M_{H_1^0} \rangle = (2200{,}9 \pm 4{,}1)$ МэВ/c^2, $I = 0$, $|l - 1| \le J \le |l + 1|$, $\pi = (-1)^l$, или $(-1)^{l-1}$ для 2-польного электрического или магнитного γ-переходов соответственно.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

A remarkable event was detected on the photographs of the JINR 2m propane bubble chamber (PBC) exposed to a 10 GeV/c proton beam (Fig.1). A 10 GeV/c beam proton colliding with the ^{12}C nucleus produces a four-prong star of the total $Q = +4$ electric charge, a fast and a slow V^0's and a low energy backwardly emitted γ-quantum. The black track of the star is due to a slow proton stopping in propane. Three other tracks are due to relativistic positively charged particles. The fast V^0 was unambiguously identified as a $\Lambda^0 \to p + \pi^-$ weak decay (χ^2 $(1V - 2C) = 0.268$, $C.L. = 87.5\%$).

The slow V^0 is of course the most intriguing. The positively charged weak decay particle of the V^0 in question is due to a slow proton which stopped in propane. The negatively charged heavily ionizing V^0 decay particle undoubtedly suffered weak decay emitting at 69.5° a π^--meson of an average momentum $\langle p_{\pi^-} \rangle = (192.89 \pm 2.80)$ MeV/c.

Fig.1. A four-prong $Q = +4$ star with associated fast and slow V^0-particles and a low energy γ-quantum, produced in $p^{12}C$ collision at 10 GeV/c

Table 1. Weak decay of particles unsuccessfully simulating and strong reactions failing to fit (no((2*V* – 2*C*)-fit) the event

Weak decays	Strong reactions
$\Omega^- \to \Lambda^0 + K^-$	$\pi^- + (^n_{12C}) \to (^n_{12C}) + \pi^-,\ \pi^- + (^n_{12C}) \to \pi^- + (^n_{12C})$
$\to \Xi^0 + \pi^-$	$\bar{K}^0 + n \to p + K^-,\ K^- \to \pi^0 + \pi^-,\ \pi^- + (^n_{12C}) \to \pi^- + (^n_{12C})$
$\to \pi^0 + \Xi^-$	$\to \nu + \mu^-$
$\Xi^- \to \Lambda^0 + \pi^-$	$K^- + n \to (^{\Lambda^0}_{\Sigma^0}) + \pi^-,\ \pi^- + (^n_{12C}) \to \pi^- + (^n_{12C})$
$K^- \to \pi^0 + \pi^-$	$\bar{K}^0 + n \to p + K^{*-},\ K^{*-} \to K^{*0} + \pi^-,\ \pi^- + (^n_{12c}) \to \pi^- + (^n_{12C})$
$\to \nu + \mu^-$	

The simulations of weak decays of Ω^-, Ξ^- and K^- particles and possible miming strong reactions listed in Table 1 were unsuccessful. The only successful hypotesis was the weak decay $\Sigma^- \to n + \pi^-$ at rest (χ^2 $(1V - 1C) = 0.32$, $C.L. = 57.4\%$). The measured decay π^- momentum $\langle p_{\pi^-} \rangle = (192.89 \pm 2.80)$ MeV/c coincides with the tabular value of the decay momentum in the Σ^- rest system $p^* =$ 193 MeV/c [1]. A crudely estimated ionization of 6.5 ± 1.8 does not contradict the expected one (6.48) as well. This is the first candidate for the neutral $S = -2$ stable dibaryon, both weak decay particles of which stopped in propane. (In the event considered in ref. [2] and events No.1 and No.2 considered in ref. [3] only decay protons stopped in propane.) This ensured the highest possible momentum measurement precision $\Delta p/p = 0.02$ in the PBC and a very precise value of invariant mass $M\ (p\Sigma^-) = (2146.3 \pm 1.0)$ MeV/c^2. The earliest quark model predictions of a light $H^0(M_{H^0} < 2M_\Lambda)$ stable $S = -2$ dibaryon of a mass of 2150 MeV/c^2 [4] and 2164 MeV/c^2 [5] meet the measured one well.

The total electric charge $Q = +4$ unambiguously proves a p^{12}C collision. But the complete absence of visible traces of nuclear disintegration at rather a violent collision resulting in six hadrons and a slow γ-quantum suggested us a qualitative «tide-attraction» scenario of the phenomenon.

At the first sight a sine qua non for stable dibaryon formation in a p^{12}C collision is the primordial existence before the collision of an intranuclear multibaryonic fluctuon target. A very low probability of its existence in cold nuclear matter drastically decreases with rising of its baryon number. Therefore an alternative explanation should be searched for. One should distinguish between collisions occurred at impact parameters larger or smaller than the nuclear radius. The approach described below made it possible to perform an exclusive multivertex kinematic analysis.

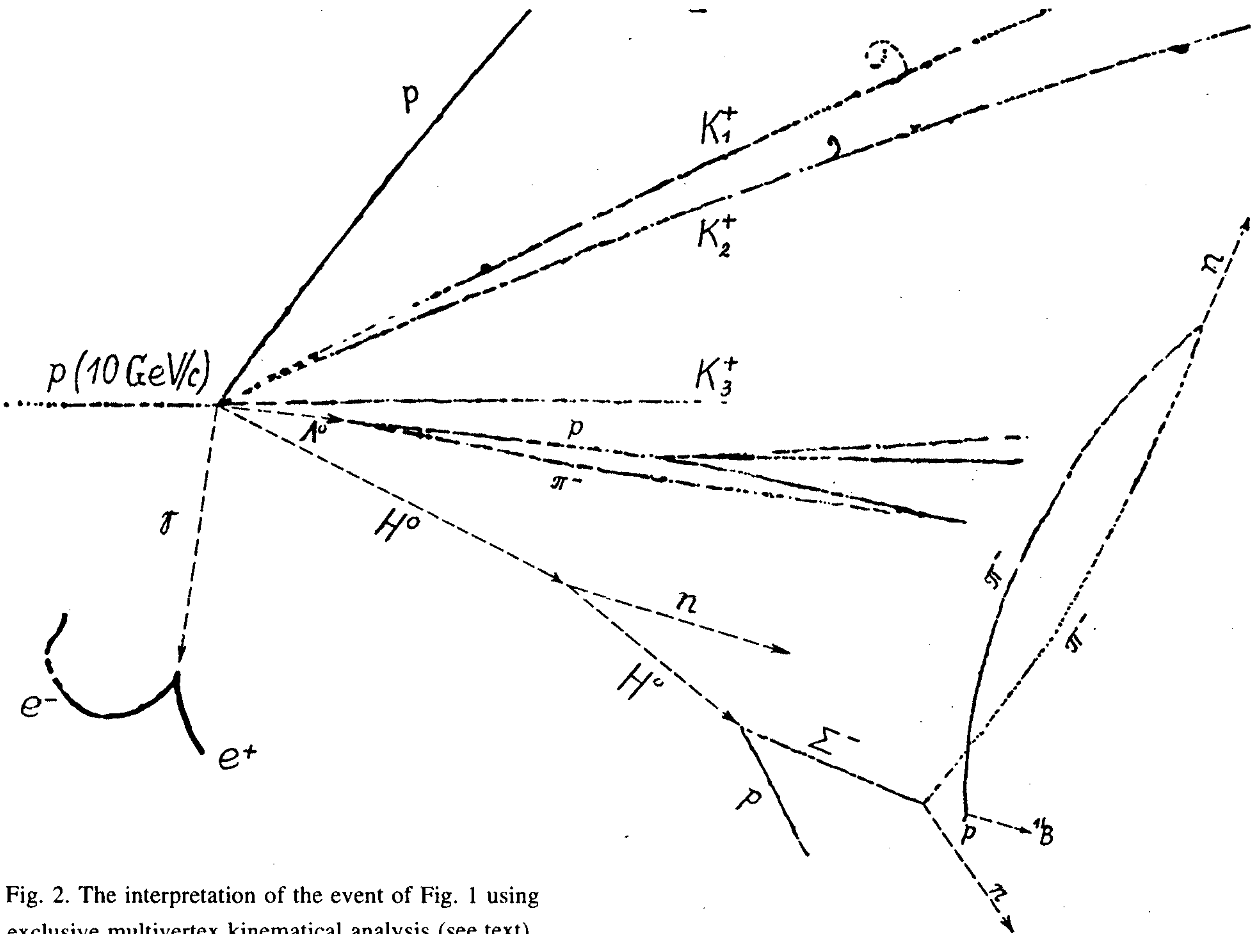

Fig. 2. The interpretation of the event of Fig. 1 using exclusive multivertex kinematical analysis (see text)

According to our scenario, in this event things were going on in the following way. A 10 GeV/c incident proton of a large impact parameter flying up to the ^{12}C nucleus already at large distances diffractively induces the formation of a peripheral tribaryon target T^{+++} of the total $Q = +3$ electric charge via multipomeron exchange. At this stage one could see on an imaginary snap-shot the deformed ^{12}C nucleus with a peripheral swellingT^{+++} reaching out for the flying up incident large impact parameter proton. Then the incident proton hits T^{+++}, fuses with it forming a highly excited four-baryon fireball B4 (perhaps a droplet of the nonstrange QGP) which however does not leave the nucleus as if being confined to it but suffers explosive phase transition to an excited light $S = -2$ dibaryon H_1^0, a Λ^0 hyperon, a proton and three K^+-mesons (Figs.1 and 2): $p + T^{+++}(3075.0 \pm \pm 100.0) \rightarrow B4 \rightarrow H_1^0\ (2203.0 \pm 5.9) + \Lambda^0 + p + K_1^+ + K_2^+ + K_3^+$ with $\chi^2\ (4V - 3C) = 2.29$, $C.L. = 51.4\%$. The best-fit effective mass of the T^{+++}, the best-fit H_1^0 and H^0 masses in MeV/c^2 and γ-quantum energy in MeV are given here and below in parantheses. The residue of the ^{12}C nucleus instantly converts to a ^{9}Li ion of a very low recoil momentum which is not sufficient to produce even if a visible blob in propane. The δ-electrons do not contradict the K_1^+ and K_2^+ hypotheses; moreover, they rule out the protonic hypotheses. Then the excited light $S = -2$ new-born H_1^0 suffers electromagnetic decay $H_1^0 \rightarrow H^0\ (2146.3 \pm 1.0) + + \gamma(41.7 \pm 3.9)$.

The average free path length of the H_1^0 amounting to $(3 - 5) \cdot 10^{-7}$ cm is well within the PBC spatial resolution which is no better than 10^{-2} cm. Therefore both the decay H^0 and γ are perceived as pointing to the vertex of the parent star (Fig.2).

The (1678.1 ± 147.8) MeV/c H^0 at a distance of 9.2 cm from the parent star vertex suffered elastic scattering on a peripheral neutron of the ^{12}C nucleus $H^0(2146.3 \pm \pm 1.0) + n$ ($\chi^2(1V - 1C) = 0.02$, $C.L. = 88.7\%$), lost its momentum to (618.5 ± 10.1) MeVc and, passing 5.25 cm, suffered weak decay $H^0 \rightarrow p + \Sigma^-$ ($\chi^2(1V - 1C) = 1.08$, $C.L. = 29.8\%$), both p and Σ^- stopping in propane. The weak decay at rest of the Σ^--hyperon, $\Sigma^- \rightarrow n + \pi^-$, ($\chi^2(1V - 1C) = 0.32$, $C.L. = 57.4\%$) was considered above in detail. The decay π^--meson after backward scattering on a peripheral neutron of the ^{12}C nucleus $\pi^- + n \rightarrow \pi^- + n$ ($\chi^2(1V - 1C) = 0.725$, $C.L. = 39.5\%$) was slowed down to a stop in propane and concluded its existence with capture via the reaction $\pi^- + {}^{12}C \rightarrow p + {}^{11}B$. Again, the recoil momentum of the ^{11}Be ion is not sufficient to produce even if a visible blob in propane. Note that the processes of elastic scattering $H^0 + {}^{12}C \rightarrow H^0 + {}^{12}C$ and $\pi^- + {}^{12}C \rightarrow \rightarrow \pi^- + {}^{12}C$ on ^{12}C nuclei as a whole did not fit the event.

The underlying hypotheses of the above scenario were checked in the following way. Using the fitted parameters, we succeeded in fitting the event by the hypothesis on the reaction $p + {}^{12}C \rightarrow H_1^0 + \Lambda^0 + p + K_1^+ + K_2^+ + K_3^+ + {}^9Li$ ($\chi^2(1V - 1C) = 0.157$, $C.L. = 69.2\%$).

Table 2. Strong reactions possibly miming the event

No.	Sequence of reaction	The result of fit
1.	$nn \to p\Sigma^- K^{*0}$, $\Sigma^- \to n\pi^-$, $\pi^- n \to \pi^- n$	no(3V – 3C)-fit
2.	$\Lambda^0 n \to p\Sigma^- M^0$, $\Sigma^- \to n\pi^-$, $\pi^- n \to \pi^- n$	no(3V – 3C)-fit
3.	$\Lambda^0 n \to \mathrm{H}^0 K^{0*}$, $\mathrm{H}^0 \to p\Sigma^-$, $\Sigma^- \to n\pi^-$, $\pi^- n \to \pi^- n$	no(4V – 4C)-fit
4.	$\Lambda^{0\,12}\mathrm{C} \to p\Sigma^{-\,11}\mathrm{C}$, $\Sigma^- \to n\pi^-$, $\pi^- n \to \pi^- n$	no(3V – 4C)-fit
5.	$\bar{K}^0 n \to pK^{-*}$, $K^{-*} n \to \Sigma^- M^0$, $\Sigma^- \to n\pi^-$, $\pi^- n \to \pi^- n$	no(4V – 4C)-fit
6.	$\bar{K}^0 n \to M^+\Sigma^-$, $M^+ n \to pM^0$, $\Sigma^- \to n\pi^-$, $\pi^- n \to \pi^- n$	no(4V – 4C)-fit
7.	$\bar{K}^0(2n) \to \mathrm{H}^0 K^{0*}$, $\mathrm{H}^0 \to p\Sigma^-$, $\Sigma^- \to n\pi^-$, $\pi^- n \to \pi^- n$	no(4V – 4C)-fit
8.	$\bar{K}^0\,{}^{12}\mathrm{C} \to p\Sigma^{-\,10}\mathrm{C}$, $\Sigma^- \to n\pi^-$, $\pi^- n \to \pi^- n$	no(3V – 3C)-fit

For masses of the M^0, M^+, K^{0*}, $\bar{K}^{0*}$, K^{-*}-mesons see S = 0 and S = ± 1 Meson Summary Tables [1]. $M_{2n} = 2M_n$

The best-fit recoil momentum of the ^{9}Li ion equal to (282.5±54.4) MeV/c is indeed insufficient to produce even if a visible blob in propane. One can say that the «tide-attraction» mechanism ensures quasi-diffractive production of the H_1^0 dibaryon.

Note that this mechanism works well for the first light [6] and second heavy (event No.2 in [3]) $S = -2$ dibaryons. Let us remind that dibaryons in both these events were emitted from two-prong stars of the total electric charge $Q = +2$ without visible traces of nuclear disintegration. Thus visually these events mimed the proton-proton collision, whereas the *pp* kinematics failed to fit them. As it was shown in ref.[3] the light dibaryon first published in [6] was produced in a quasi-diffractive reaction of the incident proton with an intranuclear $Q = +1$ dibaryonic target D^+ dynamically induced at the moment of collision. Its effective best-fit mass was $M_{D^+} = 1250^{+500}_{-76}$ MeV/c^2. The second heavy $S = -2$ stable dibaryon [3] was shown to be created quasi-diffractively on a dynamically induced $Q = +1$ intranuclear dibaryionc target D^+ of the best-fit effective mass $M_{D^+} = 1700^{+176}_{-76}$ MeV/c^2. In this case we succeeded even in fitting the event by the hypothesis on coherent production $p + {}^{12}\mathrm{C} \to \mathrm{H} + K_1^+ + K_2^+ + {}^{11}\mathrm{B}$ ($\chi^2(4V - 5C) = 7.41$, $C.L.$ = = 19.2%). Again, the ^{11}B recoil momentum was too low to produce even if a visible blob in propane.

Note, that M_{D^+}, $M_{T^{+++}}$ were treated as effective masses, because at the moment of collision they still formed parts of the ^{12}C nucleus.

Perhaps, among the three events the largest impact parameter did occur in the first [6] event and the smallest one in the event which this article is devoted to. But intranuclear cascades were generated in none of these three events.

At impact parameters smaller than the nuclear radius intranuclear cascades rule out a successful exclusive multivertex kinematic analysis. This took place in the event of ref. [2] and in H^+ event No.1 of ref. [3].

Strong reactions possibly miming the event, unsuccessfully tried for all potentially possible «primary» vertices on the frame, are listed in Table 2. The importance of quasi-diffractive and coherent processes is taken into account in this list.

Special care was taken of electromagnetic decays possibly miming the event.

Firstly, even in the worst case the measured invariant masses $M(p\gamma) = 983.3 \pm 1.0$, $M(\Lambda\gamma) = 1296.0 \pm 16.3$, $M(K_1^+\gamma) = 584.0 \pm 31.0$, $M(K_2^+\gamma) = 590.0 \pm 12.4$, $M(K_3^+\gamma) = 699 \pm 10.0)$ MeV/c^2 are more than six standard deviations distant from the masses of the known particles subject to electromagnetic decays: $\Sigma^+ \to p + \gamma$, $\Sigma^0 \to \Lambda^0 + \gamma$, $K^{+*} \to K^+ + \gamma$ [1]. No wonder that the $(2V\text{-}6C)$-fit for $\Lambda^0\gamma$ and $(1V\text{-}3C)$ fits for other combinations were unsuccessful.

Then we failed to associate the γ-quantum with the fast Λ^0 via its radiative decay mode $\Lambda^0 \to p + \pi^- + \gamma$ (no $(2V - 6C)$ fit).

Secondly, no successful fits were found for the following reaction sequences $p + T^{+++} \to H^0 + \Lambda^0 + p + K_1^+ + K_2^+ + K_3^+ + \begin{cases} \gamma_m + \gamma_u \\ \pi^0 \to \gamma_m + \gamma_u \end{cases}$. The subscripts m and u mean «measured» and «unknown».

Thirdly, we explored the inclusive momentum spectrum of γ-quanta from a sample of 2348 events $p + \binom{^1H}{^{12}C} \to \binom{\Lambda^0}{K^0} + m\gamma + X$, $m = 1,2,...$ at 10 GeV/c and did not find any significant enhancement which could be responsible for the observed γ-quantum by analogy with the π^0-meson case [7].

Fourthly, the ratio of the probability of the bremsstrahlung quantum emitted in the elementary solid angle defined by the parameters and their errors of the observed γ-quantum to the probability of the inelastic collsion in question [8] proved to be $1.14 \cdot 10^{-8}$.

Thus we failed to find any possible source of a low momentum γ-quantum other than the excited stable dibaryon H_I^0.

On the other hand, the average of the best-fit masses of the two previously detected light $S = -2$ stable dibaryons,(2172.7 ± 15.2) [6] and (2218.0 ± 12.0) MeV/c^2 [2], equal to (2195.4 ± 9.7) MeV/c^2, coincides with the mass of the new-found excited state $M_{H_I^0} = (2203.0 \pm 5.9)$ MeV/c^2. The weighted average over the three masses gives $M_{H^0} = (2200.9 \pm 4.1)$ MeV/c^2.

Thus, we come to the following conclusions. The light $S = -2$ stable dibaryon does exist at least in two quantum states.

1. The ground state H^0: $M_{H^0} = (2146.3 \pm 1.0)$ MeV/c^2, most probably $I = 0$, $J^{\pi} = 0^+$.

2. The excited state H_1^0: $M_{H_1^0} = (2200.9 \pm 4.1)$ MeV/c^2, $I = 0$, $|l - s| \leq J \leq |l + s|$, $s = 1$ being the spin of the γ-quantum, l its orbital angular momentum, $\pi = (-1)^l$ or $(-1)^{l-1}$ for a 2^l-pole electric or magnetic γ-transitions respectively [9]. The transition energy is $E = (53.7 \pm 4.2)$ MeV.

3. The time of flight before the weak decay of the H^0 dibaryon was 1.03 ns.

4. The effective cross section of H^0 production in $p^{12}C$ collisions at 10 GeV/c crudely amounts to 60 nb.

5. Most probably the stable $S = -2$ dibaryons can serve as unique signatures of transient formation of dibaryonic droplets of nonstrange QCP [3].

As to the limits set on H^0 binding by the existence of double hypernuclei, we agree with the critical analysis of the three controversial events [10, 11, 12] performed by Quinn [13, 14]: each experiment yielded a single candidate, despite differences of orders of magnitude in flux.

On the other hand, Lipkin suggested that double hypernuclei might be long lived even if H^0 is tightly bound because a long range repulsion between two Λ^0's resulting from one-quark exchange was indicated by lattice QCD calculations and this repulsion might keep the Λ^0's from fusing to an H^0 before their weak decay [13, 14, 15]. The process of double hypernuclei formation itself at different stages of the intranuclear cascade conduces to this situation.

We always investigate and try new reactions which are able to mime all the candidates for light H^0 and heavy H, H^+ stable dibaryons observed up to now [2, 3, 6]. In 1994 the following was done in this direction.

a) Both decay particles of the second candidate for H^0 ([2], Fig.1) produce kinked tracks, the positive one of them being a proton stopping in propane. Therefore of all hypotheses on two-body weak decays, not associated with the parent star, only $V^0 \equiv \Lambda^0 \to p\pi^-$ should be checked. The invariant mass M_{V^0} is unmeasurable because so is the negative particle momentum $p_{\pi^-}^{\Lambda^0}$. For the above hypothesis one has $p_{\pi^-}^{\Lambda^0} = 144.0$ MeV/c which is significantly smaller than the pion momentum after the kink $p^{\pi^-} = (316.9 \pm 33.9)$ MeV/c. Thus, the hypothesis $V^0 \equiv \Lambda^0 \to p\pi^-$ not associated with the parent star should be rejected.

b) The same hypothesis for the first candidate for heavy H dibaryon ([3], Fig.1) should be rejected because of (i) a significant inequality $p_{\pi^-}^{\Lambda^0} = 151.0 < (269.0 \pm 13.1)$ MeV/c, (ii) the maximum sagitta of the presumed decay pion, $\delta = 0.86$ cm, which is much larger than the observed one, (iii) the expected ionization of the decay pion $I/I^0 = 1.86$ against the observed minimum ionization, (iiii) the invariant mass of the V^0 for the $V^0 \to p\pi^-$ hypothesis equal to (1828.5 ± 97.2) MeV/c^2 [3].

c) For the second heavy H dibaryon ([3], Fig.2) one has (i) $p_{\pi^-}^{\Lambda^0} = 124.0 <$ $< (262.3 \pm 17.1)$ MeV/c, (ii) $\delta = 0.82$ cm against the one imperceptible by eye, (iii) the expected $I/I^0 = 2.3$ against 1.0.

We have enlarged the sample of the hypotheses on production reactions by the following ones $pB^+ \to HK_1^+K_2^+$ $(4V-7C)$, $A^0(S=-3)K_1^+K_2^+K^{*0}(4V-7C)$ each followed by reaction sequences $H \to p\Sigma^-$, $A^0 \to p\Xi^-$, $p^{12}C \to p^{12}C$, $\Sigma^- \to n\pi^-$, $\Xi^- \to \Lambda^0\pi^-$, $K_1^+ \to \mu^+\nu$. Both failed to fit the event. For B^+ see Baryon Summary Tables [1].

Then the candidates for light H^0 dibaryons [6, 2] and for heavy ones H (No.1 and 2, [3]) were tried for the possibly miming reactions No.5 and 6, Table 2 of the present paper, with negative results.

Two suggestions for the H^+ No.1, [3] were made by Peaslee [16]. The hypothesis $H^+ \to p\Xi^0$, $\Xi^0 \to \pi^0\Lambda^0$, $\Lambda^0 \to p\pi^-$ failed to fit the event observed. Instead, the possible decay mode $H^+ \to \Sigma^+\Lambda^0$, $\Sigma^+ \to p\gamma$, $\Lambda^0 \to p\pi^-$ has led to the best-fit mass $M_{H^+} = (2368.0 \pm$ $\pm 8.0)$ MeV/c^2 coinciding within the errors with the previous result [3] with an extra probability factor of 3.68 ± 10^{-4}

We are very much obliged to Academican A.M.Baldin for his support of this work. Thanks are due to Prof. D.C.Peaslee for his suggestions and discussions. This work has been performed with a partial financial support of the Russian Foundation for Fundamental Research, Grant No.93-02-03923.

References

1. Montanet L. et al. — Review of Particle Properties, Phys. Rev., 1994, D50, vol.3, Part I.
2. Shahbazian B.A. et al. — Phys. Lett., 1990, B235, p.208.
3. Shahbazian B.A. et al. — Phys. Lett., 1993, B316, p.593.
4. Jaffe R.L. — Phys. Rev. Lett., 1977, 38, p.195.
5. Mulders P.J.G., Aerts A.T., de Swart J.J. — Phys. Rev., 1980, D21, p.2553.
6. Shahbazian B.A. et al. — JINR Rapid Communications, N3-84, Dubna, 1984, p.42; Shahbazian B.A. et al. — Z. Phys., 1988, C39, p.151.
7. Carlson A.G., Hooper J.E., King D.T. — Phil. Mag., 1950, 41, p.701.
8. Feinberg E.L. — JETP, 1949, 19, p.1098.
9. Alpha-, Beta-, and Gamma-Ray Spectroscopy, v.3, ed. Kai Siegbahn, N.-H.Publishing Co., Amsterdam, 1965.
10. Danysz M. et al. — Nucl. Phys., 1963, 49, p.121.
11. Prowse D.J. — Phys. Rev. Lett., 1966, 17, p.782.
12. Aoki S. et al. — Prog. Theor. Phys., 1991, 85, p.1287.
13. Quinn B. et al. — Proc. Int. Conf. «Baryons'92», June 1—4, 1992, Yale University, ed. Moshe Gai, p.278.

14. Quinn B. et al. — Talk given at Int. Conf. on Hypernuclear and Strange Particle Physics, July 4-8, 1994, Vancower, Canada.
15. Lipkin Harry J. — Paper contributed to Int. Conf. «Baryons'92», June 1—4, 1992, Yale University, p.89.
16. Peaslee D.C., private communication.

Received on December 30, 1994.