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Charge Independence in Light Hyperfragments

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The study of binding energies of light hyperfragments may provide a quantitative test of Gell-Mann's proposal to describe the Λ^0-particle as an isotopic-spin singlet. Specific predictions are that ${}_1\mathrm{H}^{4*}$ should exist with the same B_Λ as for ${}_2\mathrm{He}^{4*}$, and that B_Λ for ${}_2\mathrm{He}^{3*}$, if this exists, should not exceed B_Λ for ${}_1\mathrm{H}^{3*}$.

GELL-MANN[1] has proposed an elegant scheme for the description of hyperons and K-particles, based on the idea that the properties of these particles are closely linked with the notion of isotopic spin. To each particle there is assigned an isotopic spin T and a characteristic relationship between its charge and the component T_3. Isotopic spin $T=0$ is proposed for the Λ^0 particle, $T=1$ for the Σ particles. The former assignment is suggested by the absence of any charged hyperon with a corresponding decay mode and a Q-value close to 37 Mev. The latter assignment is now supported by some recent evidence[2] for a Σ^- particle with the same Q-value as the Σ^+ particle, and by some indications[3] that the assumption of a rapidly decaying Σ^0 particle simplifies the interpretation of some associated particle production events. For the K-particles the situation is less clear at present.

Despite the qualitative success of these notions, there is at present no direct evidence that isotopic spin is at all relevant to these particles.[4] The known charge-independence of nucleon-nucleon forces at low energies gives essentially no evidence on this point since the strong coupling of nucleons with hyperons and K-particles jointly, which is known from the evidence on associated production, will contribute to nucleon-nucleon forces only for separations of order $\hbar/M_K c$ or less. Since these forces appear to be strongly repulsive for close approach ($\lesssim 0.4\hbar/\mu c$), the low-energy nuclear phenomena are very insensitive to the charge-independence character of the forces in this region. Only for high-energy nucleon-nucleon (or pion-nucleon) scattering will this strong $(\mathfrak{N}\Lambda^0,K)$ coupling contribute appreciably—a lack of charge symmetry among the hyperons would result in differences between n-n and p-p scattering, for example. However, owing to the inaccuracies in high-energy measurements, the present degree of agreement between n-n and p-p scattering at high energies does not provide strong evidence on this point. The assumption of isotopic spin conservation also leads to quantitative relationships between various hyperon and K-particle production processes, the experimental test of which would give very direct evidence on charge-independence among hyperons and K-particles. However, these relationships generally depend on several parameters and become definite only when more specific assumptions are made or when rather detailed experiments are possible. At present it can only be said[3] that the little data available on production processes does not necessarily conflict with the possibilities allowed.

Our purpose here is to remark that this assumption of charge independence leads to several consequences for light hyperfragments (i.e., nuclei containing a bound hyperon, generally a Λ^0 particle) which should be remembered in discussing hyperfragments of low Z and which may be tested from future data. The present data on hyperfragments with $Z=1$ and 2 are collected together in the accompanying table. Several fairly well-identified events for higher Z have also been included to emphasize the following point—if the Λ^0-nucleon forces are comparable with nucleon-nucleon forces then, since the Pauli principle will not be effective for the Λ^0 particle bound in a nucleus, the Λ^0-binding energy B_Λ should be quite large compared with the binding energy B_n for a corresponding neutron, for which the Pauli effect provides an additional and strong repulsion. Since B_Λ is actually comparable with or less than B_n, it is reasonable to conclude that the Λ^0-nucleon forces are somewhat weaker,[5] on the average, than nucleon-nucleon forces. Finally, since light hyperfragments are generally observed to live for a time comparable with the Λ^0 lifetime (4×10^{-10} sec), we may assume that the hyperfragment generally reaches its ground state before the Λ^0 decay occurs, since excited states in light nuclei have gamma lifetimes short compared with this time.

We may now discuss the following systems:

(a) The three-particle system consisting of two nucleons and a Λ^0 particle, which may have states $T=0$ or $T=1$. The singlet state will exist only in the system ${}_1\mathrm{H}^{3*}$, while the triplet states will appear in ${}_2\mathrm{He}^{3*}$, ${}_1\mathrm{H}^{3*}$, ${}_0n^{3*}$. We cannot predict which of these states will be lowest in ${}_1\mathrm{H}^{3*}$. If the $T=1$ state lies lowest, then the binding energy of ${}_2\mathrm{He}^{3*}$ should be equal to that for ${}_1\mathrm{H}^{3*}$ (actually a little less because of the Coulomb repulsion

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[1] M. Gell-Mann, Phys. Rev. **92**, 833 (1953).

[2] Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **83**, 861 (1954); Debenedetti, Garelli, Tallone, and Vigone, Nuovo cimento **XII**, 952 (1954).

[3] Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **98**, 121 (1955).

[4] Only the conservation of charge Q and isotopic spin component T_3 are necessary to account for the strong interactions observed for K-mesons and hyperons in the Gell-Mann scheme. The conservation of total isotopic spin T^2 which has been postulated for the strong interactions has not been invoked to the present.

[5] This does not imply that the couplings responsible for the Λ_0-nucleon forces are necessarily weaker than those responsible for nucleon-nucleon forces, since the Λ_0-nucleon forces are probably of shorter range and therefore less effective in binding.

between the two protons. In the three-nucleon system this Coulomb energy difference is 0.77 Mev, but here it is presumably a good deal less since the system appears to be much less strongly bound). If the $T=0$ state lies lowest, then the $T=1$ ${}_1H^{3*}$ state will decay by γ emission rather than by Λ^0 decay and B_Λ for ${}_2He^{3*}$ will therefore be less than for ${}_1H^{3*}$. In brief, if ${}_2He^{3*}$ exists, its Λ^0-binding energy B_Λ should not exceed that for the ${}_1H^{3*}$ system, if charge independence is applicable to the Λ^0-nucleon interactions.

(b) In the four-particle systems, states of $T=\frac{1}{2}$ and $\frac{3}{2}$ are possible. In either case, from charge symmetry, the existence of a bound state ${}_2He^{4*}$ implies the existence of a bound ${}_1H^{4*}$ state. This ${}_1H^{4*}$ state should be even more strongly bound than the ${}_2He^{4*}$ state (by about 1 Mev) owing to the absence of Coulomb repulsion. Owing to the high-binding energy of the final state, the decay ${}_1H^{4*}\rightarrow {}_2He^4+\pi^-$ involves a large release of kinetic energy (about 54 Mev) and will probably be the dominant mode of decay.

(c) No five-nucleon system has bound states, owing to the repulsive effect of the Pauli principle, but the possibility of a bound system (${}_2He^4+\Lambda^0$) should be considered in discussing hyperfragments with $Z=2$. Only the singlet state $T=0$ is to be expected for this system of particles since it is the $T=0$ configuration of four nucleons which has a high-binding energy. The decay process ${}_2He^{5*}\rightarrow {}_2He^4+p+\pi^-$ will be favored since the energy release for a decay process which involves breaking up the α-particle will generally be rather low ($\lesssim 15$ Mev).

Charge independence requires that the Λ^0-neutron interaction should be identical with the Λ^0-proton interaction, but this Λ^0-nucleon interaction may still depend on the relative spin orientation of the particles. If a bound state ($\Lambda^0 p$) exists, which appears unlikely unless the Λ^0-nucleon potential has a strong spin-dependence, there would also be a bound ($\Lambda^0 n$) state—Primakoff and Cheston[6] have discussed the possibility of such a state and the decay modes it would have. Long-lived Σ fragments may also be considered, although their very existence would provide a difficulty for the Gell-Mann theory in its present form. A charged Σ particle in a nucleus would undergo a charge exchange process such as $\Sigma^-+p\rightarrow\Sigma^0+n$, and this theory suggests that a Σ^0 particle would decay to a Λ^0 particle by a very rapid γ emission. However there is now at least one hyperfragment decay[7] with an observed energy release larger than is possible for a Λ_0 hyperfragment. The existence of Λ_0 hyperfragments naturally suggests the explanation of this event as a Σ fragment; however such an event could also be due to a K-fragment in which a K^+-meson is bound to a nucleus, since the Gell-Mann theory forbids rapid absorption of a K^+-meson by a nucleon. We shall not discuss the possibilities for other types of fragments further here.

TABLE I. Binding energies of light hyperfragments.

Reference	Z	Interpretation proposed	B_Λ(Mev)	B_n(Mev)
Bonetti *et al.*[a]	1	${}_1H^{3*}\rightarrow {}_2He^3+\pi^-$	1 ± 1	6.3
DeBenedetti *et al.*[a]	1		0.24 ± 4	6.3
Baldo *et al.*[a]	1		0.8 ± 1	6.3
Yagoda[b]	1	${}_1H^{3*}\rightarrow n+p+p+\pi^-$	3.2 ± 1	6.3
Hill *et al.*[c]	2	${}_2He^{4*}\rightarrow {}_2He^3+p+\pi^-$	2.8 ± 1.3	20.6
Naugle *et al.*[d]	2 or 3		2.8 ± 1	20.6
Fry *et al.*[e]	2		0.9 ± 0.5	20.6
Crussard and Morellet.[f]	2 or 3	${}_2He^{4*}\rightarrow {}_2He^3+p+\pi^-$	8 ± 4	20.6
		${}_3Li^{7*}\rightarrow {}_3Li^6+p+\pi^-$	8 ± 4	7.1
Baldo *et al.*[a]	2	${}_2He^{4*}\rightarrow {}_2He^3+p+\pi^-$	2.0 ± 1.3	20.6
		${}_2He^{6*}\rightarrow {}_2He^4+d+\pi^-$	3.9 ± 1.3	1.9
Fry *et al.*[g]	2	${}_2He^{4*}\rightarrow {}_1H^3+p+\pi^0$	3.9 ± 1	20.6
		${}_2He^{3*}\rightarrow {}_1H^2+p+\pi^0$	5.9 ± 1	7.7
Freier *et al.*[h]	$3<Z\leqslant 7$	${}_7N^{14*}\rightarrow p+p+{}_5B^{12}$ $({}_5B^{12}\rightarrow {}_6C^{12}+e^-)$	20 ± 11	10
Fry *et al.*[g]	$\geqslant 5$	${}_6C^{11*}\rightarrow {}_3Li^7+{}_2He^3+p$	13.0 ± 6	12.1
Fry *et al.*[g]	4	${}_4Be^{7*}\rightarrow {}_2He^4+p+p+n$	5.9 ± 8	8.7

[a] See reference 8.
[b] See reference 9.
[c] See reference 10.
[d] See reference 11.
[e] See reference 14.
[f] See reference 12.
[g] See reference 13.
[h] Freier, Anderson, and Naugle, Phys. Rev. **94**, 677 (1954).

It must next be considered whether, in view of the uncertainties in the mass measurements of hyperfragments and their decay products, the interpretations given in Table I may conflict with or exemplify these remarks. The event of Bonetti *et al.*[8] could be interpreted as ${}_1H^{4*}$ decay, for example, but the value of B_Λ then obtained would be rather large (about 15 Mev), which seems unlikely on the basis of the evidence from heavier hyperfragments mentioned above. Yagoda's event[9] is less clear cut, but with the interpretation proposed its B_Λ is not inconsistent with the value of Bonetti *et al.* for a ${}_1H^{3*}$ fragment. It is also possible that this event may be an example of ${}_1H^{4*}$ decay, ${}_1H^{4*}\rightarrow d+p+n+\pi^-$, giving a B_Λ of -0.1 (±1.5) Mev.

The events of Hill *et al.*,[10] Naugle *et al.*,[11] and Baldo *et al.*[8] could equally well represent ${}_2He^{5*}\rightarrow {}_2He^4+p+\pi^-$, with $B_\Lambda\sim 3$ Mev. In this decay, the initial nuclear configuration is rather little changed, so that the value of B_Λ is rather insensitive to the mass of the fragment—the uniqueness of the fit generally depends on the accuracy with which the direction and length of the short recoil track are determined, since a good measurement of the hyperfragment mass is rarely possible. For this reason, the example of Crussard and Morellet[12] also allows several interpretations which lead to $B_\Lambda=8(\pm4)$ Mev.

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[6] H. Primakoff and W. Cheston, Phys. Rev. **93**, 908 (1954).

[7] W. F. Fry and M. S. Swami, Phys. Rev. **96**, 809 (1954).

[8] Bonetti, Levi, Setti, Panetti, Scarsi, and Tomasini, Nuovo cimento **11**, 210, 330 (1954). Similar events have now been reported also by deBenedetti, Garelli, Tallone, and Vigone [Nuovo cimento **12**, 466 (1954)] and by Baldo, Belliboni, Ceccarelli, Grilli, Secchi, Vitale, and Zorn [Nuovo cimento **1**, 1180 (1955)]. See Table I.

[9] H. Yagoda, Phys. Rev. **98**, 153 (1955).

[10] Hill, Salant, Widgoff, Osborne, Pevsner, Ritson, Crussard, and Walker, Phys. Rev. **94**, 797 (A) (1954). (*Note added in proof.*—The data on this event have now been shown to fit the interpretation of ${}_2He^{5*}$ decay somewhat better, leading to a B_Λ of 2.6 ± 1.3 Mev.)

[11] Naugle, Ney, Freier, and Cheston, Phys. Rev. **96**, 1383 (1954).

[12] J. Crussard and D. Morellet, Compt. rend. **236**, 64 (1953).

If the event which Fry *et al.*[13] have described represents $2\mathrm{He}^{3*}$ decay, the B_Λ obtained conflicts with the remarks (a) made in the aforementioned since it is then considerably larger than the B_Λ obtained for ${}_1\mathrm{H}^{3*}$ by Bonetti *et al.*—however the alternative hypothesis of ${}_2\mathrm{He}^{4*}$ decay is possible and fits equally well. For this event, the assumption of ${}_2\mathrm{He}^{5*}$ decay is not permitted since the resulting B_Λ would not be positive. Now since B_Λ for this $2\mathrm{He}^{4*}$ decay is 3.9 ± 1 Mev, it is most natural to accept the interpretations given in the table since all four B_Λ values given for ${}_2\mathrm{He}^{4*}$ are then in reasonable agreement.[14] At present there is no evidence which requires the existence of the ${}_1\mathrm{H}^{4*}$ fragment—however, the range of this fragment will be about four times greater than for a ${}_2\mathrm{He}^{4*}$ fragment of the same energy, and the probability for observation of its decay may therefore be rather less.

A discussion of hyperfragments $Z>2$ may be given on similar lines and the Gell-Mann theory suggests the possibility of mass numbers (for given Z) for hyperfragments different from those for the corresponding stable nuclei. For example, the existence of ${}_6\mathrm{C}^{11*}$, suggested by Fry *et al.*,[13] would imply that the hyperfragment ${}_4\mathrm{Be}^{11*}$ be bound. If each hyperfragment is represented by a point on a plot of N (number of neutrons) *versus* Z, the Bell-Mann scheme requires that these points be distributed symmetrically with respect to the line $N=Z$, B_Λ being the same at corresponding points, at least up to $Z\sim10$ where the Coulomb forces begin to play an important role. In fact all the heavier hyperfragments for which an interpretation has been suggested have $Z\geqslant N$. One possible reason for this is that, for $N>Z$, the nonmesonic decay processes possible generally lead to emission of one or more neutrons. These cases either cannot be identified with certainty or may happen to allow an interpretation with a smaller value of N. For example, the event of Fry *et al.* for which the interpretation of ${}_4\mathrm{Be}^{7*}$ decay proves possible (see Table I) could equally well represent ${}_4\mathrm{Be}^{8*}\rightarrow{}_2\mathrm{He}^4+p+p+n+n$, with a binding energy B_Λ given by $(22.3(\pm8)-T_n)$ Mev, where T_n is the total kinetic energy of the two neutrons seen in their relative c.m. system. The fact that measurement of the energy release is considerably less accurate in these more complex events also contributes to the uncertainty in the interpretation of heavier hyperfragments.

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In conclusion, I am pleased to thank Dr. M. Gell-Mann and Dr. C. N. Yang for their comments on this note.

Note added in proof.—An event which has the interpretation

$$ {}_1\mathrm{H}^{4*}\rightarrow{}_2\mathrm{He}^4+\pi^- \qquad \text{(i)} $$

has recently been observed by Menon, Friedlander, and Keefe.[15] The binding energy of the Λ_0 in ${}_1\mathrm{H}^{4*}$ is then found to be 1.2 (±0.8) Mev. Also, a further event which may be due to ${}_1\mathrm{H}^{4*}$ has been reported by Hornbostel and Salant,[16] a possible interpretation being

$$ {}_1\mathrm{H}^{4*}\rightarrow{}_2\mathrm{He}^3+n+\pi^- \qquad \text{(ii)} $$

with a B_Λ of 4.7 (±3.1) Mev. However interpretation of this event as a Σ^--capture star is also possible. Several further ${}_1\mathrm{H}^{4*}$ events have recently been reported at the Pisa conference (1955) but full details are not available at present.

Comparison of B_Λ for ${}_1\mathrm{H}^{4*}$ and for ${}_2\mathrm{He}^{4*}$ suggests that indeed the Λ_0N and Λ_0P forces are rather closely equal.

The origin of the Λ_0-nucleon forces is not well known at present. The interaction $P\rightarrow\Lambda_0+K^+$ is known to be strong and can lead to an exchange force between Λ_0 and nucleon, thus

$$ \Lambda_0+P\rightarrow(P+K^-)+P\rightarrow P+\Lambda_0, \qquad \text{(iii)} $$

with a range close to $\hbar/M_kc$. However interactions through the pion field are not excluded by considerations of "conservation of strangeness." Double pion exchange between Λ_0 and nucleon could result from an interaction

$$ \Lambda_0\rightarrow\Lambda_0+\pi^++\pi^- \qquad \text{(iv)} $$

which is allowed both by "strangeness" considerations and by isotopic spin conservation, and would lead to ordinary forces of range $\hbar/2\mu c$.

The single pion interaction

$$ \Lambda_0\rightarrow\Lambda_0+\pi^0 \qquad \text{(v)} $$

also conserves the strangeness number $(Q-T_3)$ and would lead to a Λ_0-nucleon force of range $\hbar/\mu c$. Since the interaction of π^0 meson with neutron is opposite to that with proton, according to charge independence (τ_3 coupling), the Λ_0-nucleon force resulting from (v) would have opposite sign for Λ_0-N and for Λ_0-P. Since this Λ_0-nucleon force would have a much longer range than the other forces which could be effective and which may be attractive, the existence of this force would show clearly in the binding energy data for hyperfragments, especially in the comparison of hyperfragments with the same $(N+Z)$. The fact that the binding energies B_Λ of ${}_1\mathrm{H}^{4*}$ and ${}_2\mathrm{He}^{4*}$ are actually very close indicates that the interaction (iv) can at most be very weak. The most direct way in which the interaction (v) may be forbidden is by the assignment of isotopic spin $T=0$ to the Λ_0 particle, since total isotopic spin cannot then be conserved in this interaction. This is, of course, the situation in the Gell-Mann theory so that this event (i) provides some considerable support to the linking of strangeness with isotopic spin as postulated in this theory.

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[13] Fry, Schneps, and Swami, Phys. Rev. **97**, 1189 (1955).

[14] *Note added in proof.*—A decay of this type, well identified as a ${}_2\mathrm{He}^{4*}$ hyperfragment since the hypothesis of ${}_2\mathrm{He}^{5*}$ decay gives a very poor fit, has been observed by Fry, Schneps, Snow, and Swami and leads to a B_Λ of 0.9 ± 0.5 Mev. I am much indebted to Dr. W. Fry for preliminary details of this event.

[15] I am much indebted to Professor F. C. Powell for information concerning this event.

[16] J. Hornbostel and E. O. Salant, Phys. Rev. **98**, 218 (1955). I am much indebted to Dr. Hornbostel for more detailed information on this event.