Identification of One Glue-Like Mechanism
of the $\Lambda$-Hyperon in Hypernuclei

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In order to test the predicted negative parity ground state of $^{20}\text{Ne}$, a method is proposed, in which one is to measure delayed $\gamma$-quanta in $^{18}\text{Ne}$ or $^{18}\text{F}$ resulting from the non-mesonic decay of $\Lambda$-hyperon in $^{20}\text{Ne}$.

A new era of hypernuclear research has started with a substantial refinement of experimental techniques since recently. In fact, the new production reactions allow for an extension far beyond the $p$-shell hypernuclei. Moreover, lifetime measurements and simultaneous production and taking of $\gamma$-quanta (of both hypernuclear and nuclear origin) make possible to study such tiny details as the level ordering and nuclear structure changes. In spite of a relatively weak hyperon-nucleon interaction as compared to that of nucleon-nucleon, a $\Lambda$-hyperon added to the nuclear medium often has dramatic influence on that medium. As a consequence, phenomena may be encountered, which are genuinely hypernuclear and they are not known in the ordinary nuclei. Here belong effects as, e.g., appearance of some “supersymmetric” configurations and hard (10–15 MeV) $\gamma$-quanta, hypernuclear “rearrangements” (changes of mass distributions, of deformations, of nuclear transition probabilities $B(E2)$, shape transitions oblate$\rightarrow$prolate, polarizations), changes in the characteristics of some nuclear excitation modes (fission, inter-cluster vibrations and distances, giant resonances), changes of hyperon properties (lifetime, magnetic moment) and some exotic phenomena (repulsive pairing, band reversion). It is nonetheless difficult, though highly desirable, to find conclusive signatures for demonstrating that some of the former processes really took place.

Recently, the structure of $^{20}\text{Ne}$ has been studied theoretically\textsuperscript{1)} and found to be a good candidate for deviating from a simple weak-coupling between a $\Lambda$-hyperon and the core nucleus. In $^{19}\text{Ne}$ nucleus, the positive parity $1/2^+$ state with a shell-model configuration $(sd)^3$ constitutes the ground state, while the negative parity $1/2^-$ state with a developed $\alpha$-cluster structure is at only 0.28 MeV excitation energy. These two types of structures are affected by an added $\Lambda$-hyperon in a very different way and it may result in reversing positive and negative parity bands. Thus, according to Ref. 1), the ground state of $^{20}\text{Ne}$ should be $1^-(or 0^-)$ state, in dependence on the $\Lambda N$ interaction used. In contrast, a shell model calculation\textsuperscript{2)} predicts $0^+$ ground state of $^{20}\text{Ne}$ with $1^+$ state shifted by 0.25 MeV above and $1^+$ state lying still 0.45 MeV higher. It is thus even more interesting to decide on the relative importance of cluster and weak-coupling contents.
A question now arises how one could efficiently detect such an unusual level ordering, if it is encountered at all. In Ref. 1), the use of angular distributions of outgoing particles ($\pi^-$ or $K^+$) and a comparison of ($K^-$, $\pi^-$) and ($\pi^+$, $K^+$) production strengths of various peaks have been suggested to test the parity of the ground state. Those methods, though possible in principle, are sensitive to the distances of low-lying levels (below and around 1 MeV become unreliable) and also suffer from low excitation strengths.

There is, however, a genuine hypernuclear phenomenon, namely a non-mesonic weak decay of the $\Lambda$-hyperon and subsequent (delayed) electromagnetic decays, which render possible to take the parity (and spin) of the ground (or isomeric) hypernuclear state. This method has been theoretically proposed in Ref. 3) for studying the weak decay mechanism itself, but it can be used in the present problem, as well. More explicitly, the non-mesonic weak decay of the $\Lambda$-hyperon in the medium (which prevails with increasing number of nucleons) releases a large energy of 176 MeV ($B_\Lambda + B_X$) and both resulting nucleons are emitted from the $\Lambda$-baryon system ($B_X$ stands for binding of $X$). The ($\Lambda-2$) nucleus may be produced in a baryon-stable excited state which in turn deexcites by the characteristic nuclear $\gamma$-emission, delayed by the $\Lambda$-lifetime in the particular decay channel. The pattern of such a $\gamma$-spectrum retains information on the parent-hypernuclear ground-state quantum number. In fact, some $\gamma$-lines should be present or absent in the spectrum in a straightforward dependence on $J^*$, constituting thus the signature sought.

The in-medium $\Lambda$-decay experiments have one additional advantage, namely a "cumulative" tendency: There may be more intermediate paths of some hypernuclear state production and its subsequent nucleon or cluster decay, all leading to the studied hypernuclear ground state. In order to measure the angular distribution of outgoing mesons in the production stage, one has to gate by a narrow $E$ window mesons under suitable angle, whereas in the advocated method of delayed $\gamma$-quanta, one collects all the $\gamma$-quanta of the energy known in advance. It should distinguish even close states ($\leq 1$ MeV).

A necessary theory may be adopted from Ref. 3) and as specified to the example of $^{20}$Ne, it reads in the lowest approximation\(^1\) as follows: The spectrum of delayed $\gamma$-quanta is determined by two factors:

1. Probability of population of levels $E_cJcTc$ of $\Lambda-2$ nucleus when one nucleon is extracted from the ground state of the hypernuclear $|j^{A-1}\epsilon N_jT_N, s_A; J\rangle$ and takes part in non-mesonic decay.

2. Weight of the triplet component $^3S_1$ in the relative part of the wave function of nucleon-hyperon pair $|js_A, J\rangle$, which dominates in the non-mesonic $\Lambda$ decay.

The first factor is given by the structure of nuclear system (thus by the corresponding fractional parentage coefficient $g$ for extraction of $(nl)jt$ nucleon):

$$
|j^{A-1}\epsilon N_jT_N, s_A; J\rangle = \sum_{Tc} \sum_{JcTc} \left( Tc \frac{1}{2} t |T_N L_N\right) \\
\times g(j^{A-1}\epsilon N_jT_N; j^{k-1}E_cJcTc, j) U(JcJ \frac{1}{2}; JN) \\
\times |j^{k-1}E_cJcTc|jt s_A, J\rangle .
$$

(1)
In Eq. (1), isospin projection \( t = \pm 1/2 \) distinguishes proton and neutron, \( t_c = t_N - t \). \( U \) is the Racah coefficient for recoupling \( J_c + j + 1/2 = \mathcal{J} \). For \( \mathcal{J} = 0 \) it holds \( U = \delta_{jn(1/2)} \delta_{jc} \). The initial and final state of the nucleus is characterized by the energy \( E_N \) and \( E_c \), respectively. The actual wave function would be a mixture of basis states and would be given by the diagonalization of a residual \( NN \) interaction.

Here, a more phenomenological procedure is adopted and the fractional percentage coefficients \( g \) are obtained by comparison with spectroscopic factors \( C^2 S \) obtained experimentally in pick-up and knock-out reactions (\( g^2(T_{tctc} \frac{1}{2} t | \mathcal{T}_N t_N) = C^2 S \)).

The second factor is yielded by \( ^3S_1 \) dominance in non-mesonic weak \( ^\Lambda \)-decay and it depends on oscillator quantum numbers of separated nucleon \( n \). The weight of the triplet component is obtained by projecting out the singlet part:

\[
1 - U \left( \frac{1}{2} \frac{1}{2} J; S = 0 j \right) = 1 - (-)^{t+1/2} \sqrt{\frac{2j+1}{2(2l+1)}} \delta_{uj}.
\]

The weight of \( 0s \) component in relative part of \( \Lambda N \) wave function is obtained from transformation:

\[
|nl(R_c - r_N)0s(R_c + r_N - r_A); l> = \sum_{N,M} T_{lM} T_{lNM}|nl(R_c - r_N - r_A)\mathcal{U}l(r_N - r_A); l>
\]

and \( T_{lM} = (1/2)^{n/2} \), with \( n = 2n_l + l \). Then the probability of populating the level \( E_{21Ne} \) of \((A-2)\) nucleus through weak non-mesonic decay of the ground state Eq. (1) (stimulated by the nucleon \( n/\bar{n} \)) is given by

\[
\Gamma_{n/\bar{n}} \sim \left( \frac{1}{2} \right)^{n} (T_{tctc} \frac{1}{2} t) T_{lNM}^2 \times \left[ \sum_{\mathcal{J}} g(N; C, j) U \left( \mathcal{J}_c \mathcal{J} \frac{1}{2} \mathcal{J}; JN \right) \left( 1 - (-)^{t+1/2} \sqrt{\frac{2j+1}{2(2l+1)}} \delta_{uj} \right) \right]^2.
\]

Population of levels of \( ^{18}\text{F} \) differs substantially in dependence on whether the non-mesonic decay proceeds from the state \( \left| s^4 p^{12} 0^+ 0(sd)^3 \frac{1}{2}^+ \frac{1}{2} E_N = 0, \frac{1}{2}^+ \frac{1}{2}, s_N; \mathcal{J}^+ \right> \) or from the state \( \left| s^4 p^{12} \frac{1}{2}^- \frac{1}{2} (sd)^3 0^+ 0 E_N = 0.28, \frac{1}{2}^- \frac{1}{2}, s_N; \mathcal{J}^- \right> \).

In Fig. 1, the upper part displays the experimental excitation function (spectroscopic factors \( C^2 S \)) for the reaction \( ^{19}\text{F}(1/2^+) (p, d)^{18}\text{F} \) (see Table 18.20 in Ref. 4) by a full line. For the negative parity, the spectroscopic factors are calculated (based on the assumption of \( p_{1/2} \) hole in \( ^{20}\text{Ne} \) structure for \( \frac{1}{2}^- \frac{1}{2} \) state of \( ^{18}\text{F} \)). In Fig. 1, only low-lying states are plotted (<5 MeV) which correspond to the particle-stable part of \( ^{18}\text{F} \) spectrum. The \( ^{20}\text{Ne} \) structure is that of \( ^{18}\text{F}(T=1) \) combined with appropriate \( C^2 S \).

It is seen that states \( 1^+ 0 \) (1.70 MeV) and \( 2^+ 0 \) (2.52 MeV) are populated exclusively from negative parity \( ^{20}\text{Ne} \) ground state. On the contrary, the state \( 3^+ 0 \) (0.94 MeV) may be populated only from the positive parity.

In fact, Table 18.12 of Ref. 4) giving branching ratios suggests the state \( 3^+ 0 \) to be strongly populated from electromagnetic decays of higher levels. The \( 1^+ 0 \) state prevailingly (70%) decays by a cascade onto \( 0^+ 1(1.04 \text{ MeV}) \) state. Moreover, \( 2^+ 0 \)
state deexcites mainly (75%) to the ground state of $A=18$ nucleus and higher states populate it electromagnetically only to a negligible extent. All that is visualized in the middle insertion of the cascade pattern.

Would the ground state of $^{20}\text{Ne}$ be $1^-$ (instead of $0^-$), the weight of the triplet component would be decreased by $1/3$ and the main features of the spectrum would be kept. It means that the definite signature for the negative parity of $^{20}\text{Ne}$ ground state is the appearance of 2.52 MeV $\gamma$-quanta.

There are other differences in $\gamma$-spectra, corresponding to proton- (neutron-) stimulated weak $\Lambda$-decays and reflecting their relative importance. (Neutrons are distinguished by $n$ in Fig. 1.) The positive parity $^{20}\text{Ne}$ ground state would yield $\gamma$-spectrum dominated by 0.94 MeV $\gamma$(proton stimulated). Negative parity causes dominance by 1.9 MeV $\gamma$-quanta (neutron stimulated). Neutron contribution is less influenced by branching due to simplicity of $^{18}\text{Ne}$ spectra. Those detailed differences become, however, of importance when the parity is known or when the first delayed nuclear $\gamma$-emission is extracted and identified.

It is to be emphasized that the method of the detection of the delayed $\gamma$-quanta is
a genuinely hypernuclear method, which is very powerful and selective and has no analog in the usual nuclear spectroscopic procedure. The implanted hyperon decays in the nuclear medium, but the decay is strongly influenced by properties of the medium. Subsequent measurement of the deexcitation pattern of the changed medium reveals clearly properties of the original parent hypernucleus (and of the decay mechanism, as well).

It would be thus highly desirable and helpful, when experimental verification of the above scheme makes it a real tool for studying the hypernuclei and the response of nuclear medium to the added strangeness. It may then be used to study not only the structure of hypernuclei, as proposed here, but also the weak decay mechanism and other phenomena.

3) L. Majling, J. Žofka, V. N. Fetisov and R. A. Eramzhyan, Preprint Orsay IPNO/TH 87-40; to be published in Phys. Lett. B.