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SHORT STORY OF Σ HYPERNUCLEI — A PERSONAL ACCOUNT* **

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Around 1979, two realistic Nijmegen models of the baryon–baryon interaction were available: the elder model D and the improved new model F. Only model F led to the semiempirical value of the Λ binding in nuclear matter. When the first CERN observation of Σ hypernuclei was announced, model F was used to calculate V_Σ, the potential felt by Σ in nuclear matter. The result, a repulsive V_Σ, was unreconcilable with the CERN observation, and prompted theoreticians to use model D which led to an attractive V_Σ. To explain the existence of narrow Σ hypernuclear states at a relatively high energy, the theoreticians came forward with such ideas as the 'bound states embedded in continuum', or $V_\Sigma(r)$ with a repulsive barrier at the hypernuclear surface. A possible inaccuracy in the CERN experiments was not considered. The first empirical indication that V_Σ may be repulsive inside the nuclear core came from the analysis of strong interaction shifts and widths of Σ^- atoms, which could be explained with the help of model F of the baryon–baryon interaction. Final evidence of the repulsiveness of V_Σ was supplied by the new (K^-, π) experiments performed at Brookhaven with an order of magnitude better statistics than the old CERN experiments. In the Brookhaven experiments the narrow states of Σ hypernuclei observed at CERN disappeared. The pion spectra measured in these new experiments are consistent with V_Σ repulsive inside nuclei and with model F of the baryon–baryon interaction.

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1. Λ hypernuclei and the baryon–baryon interaction

Although the observation at CERN by Bertini *et al.* [1] of pion spectra from the (K^-, π^-) reaction on ^{9}Be, interpreted as the discovery of Σ hypernuclei, took place in 1979, let me go still a few years earlier when we together with Jacek Rożynek looked for a solution of the so called overbinding problem of Λ hypernuclei.

This problem concerns the binding energy $B_\Lambda(A)$ of a Λ particle in a hypernucleus with mass number A. When we go to the limit $A \to \infty$, we obtain $B_\Lambda(\infty)$, the semiempirical value of Λ binding in nuclear matter (NM), which according to the most recent estimates by Millener, Dover, and Gal [2] is equal 28 MeV. All attempts to calculate $B_\Lambda(\infty)$ with ΛN potentials fitted to Λp scattering and to Λ binding in $A = 3$, 4 hypernuclei led to $B_\Lambda(\infty)$ values about 10 MeV larger than the semiempirical value. It was Bodmer [3] who suggested the suppression of $\Lambda\Sigma$ conversion ($\Lambda N \to \Sigma N'$) in NM as a possible explanation of this overbinding problem.

To take into account the suppression of $\Sigma\Lambda$ conversion in calculating $B_\Lambda(\infty)$, we have to introduce explicitly the Σ channel (in addition to the Λ channel), and we need a hyperon–nucleon interaction potential $\hat{v}$ which is a 2×2 YN potential matrix ($Y = \Lambda, \Sigma$) which contains a coupling between the two channels.

A realistic form of such two channel YN potential $\hat{v}$ has been worked out by the Nijmegen group which at that time worked out two models of $\hat{v}$: model D [4] and model F [5]. The authors apply the OBE model and assume SU(3) relations for the coupling constants. The short-range behavior of the resulting local $\hat{v}$ is represented by phenomenological hard cores. Free parameters are determined from a combined analysis of the available NN and NY scattering data , up to the pion production threshold. The model D consists of potentials due to exchanges of members of pseudoscalar and vector meson nonets and the scalar meson ϵ taken as a unitary singlet. The breaking of SU(3) in model D is kinematical and also dynamical via different hard cores. The newer model F differs from D by including exchanges of the whole nonet of scalar mesons, and by having the same hard cores within the same irreducible representation. Consequently the breaking of SU(3) in model F is purely kinematical. Important for hypernuclear physics is the improvement in the values of the ΛN scattering lengths. No doubt, model F was an improvement in constructing $\hat{v}$ compared with the elder model D.

In a paper with Rożynek published in 1979 [6], we have used models D and F of the Nijmegen interaction to calculate $B_\Lambda(\infty) = -(V_\Lambda + V_R)$, where V_Λ is the single particle (s.p.) Λ potential in NM, and V_R is the rearrangement potential. We applied Brueckner theory in calculating V_Λ, and the expression [7] $V_R = -\kappa V_\Lambda$, where κ is the ratio of the correlation volume to the volume per nucleon in NM. For a reasonable range of κ: $0.15 > \kappa > 0.1$ the result was: $32.0 < B_\Lambda(\infty) < 33.8$ MeV for model D, and $26.7 < B_\Lambda < 28.3$ MeV for model F of the interaction. We see that model F leads to $B_\Lambda(\infty)$ which agrees with the semiempirical value of 28 MeV, in contradistinction to model D which leads to an overbinding of about 4–6 MeV.

Our conclusion was that model F was the best representation of the YN interaction.

2. The CERN experiments

In March 1979 Bertini [8] reported at the Meson-Nuclear Physics Conference in Houston the CERN observation of Σ hypernuclei, and at that time I was asked by A. Bouyssy about the model F value of Σ well depth V_Σ. This prompted us with Jacek Rożynek to apply our scheme of calculating V_Λ to the Σ problem. There are certain complications here connected with the energy conserving $\Sigma N \to \Lambda N'$ transitions which lead to a complex V_Σ. Our provisional result obtained with model F: a repulsive potential V_Σ, which I mentioned at the International Conference On Hypernuclear and Low Energy Kaon Physics in Jabłonna in September 1979 [9], was unreconcilable with the CERN observation which implied an attractive $V_\Sigma \sim -21$ MeV[1].

At that moment the possible inaccuracy in the CERN experiment was not considered at all, and the expert's suggestion was to go back to the old model D. Being aware that the arguments favoring model F may not be absolutely convincing, and not being aware of possible shortcomings of the CERN experiments, we followed this suggestion, and indeed obtained [11] with model D an attractive V_Σ in agreement with Bertini's estimate [8].

What really should have raised some doubts about the CERN measurement of the pion spectra from the (K^-, π) reactions on ^{9}Be [1], as well as on ^{12}C [12] and ^{16}O [13], was the narrowness of the observed Σ hypernuclear levels $\Gamma \sim 5$ MeV, although their positive energies were relatively high, up to about 10 MeV. Obviously one should expect a quenching of the $\Sigma\Lambda$ conversion in nuclear matter [11], but even in the absence of the $\Sigma\Lambda$ conversion the small values of Γ would be hard to understand. Nevertheless a number of explanations was offered, and let me mention two of them.

1. We may describe a Σ hypernucleus with the help a wave function Ψ of the Σ hyperon moving in the optical potential $V_\Sigma(r) + iW_\Sigma(r)$ of the nuclear core, where W_Σ is due to the $\Sigma\Lambda$ conversion. The Schrödinger equation for Ψ with the complex potential leads to complex energy eigenvalues $\mathcal{E} = E - i\Gamma/2$, and the corresponding momentum eigenvalues $k = (2\mu\mathcal{E})^{1/2}/\hbar = k_R + ik_I$ (μ is the Σ-nuclear core reduced mass), with $k_R < 0$ and $k_I > 0$. We

[1] This result was consistent with the value of $V_\Sigma \sim -26$ MeV suggested by Batty *et al.* [10] in their analysis of the early Σ^- atomic data.

have: $E = \hbar^2(k_R^2 - k_I^2)2\mu$, $\Gamma = -2\hbar^2 k_R k_I/\mu$. If $|k_R| > k_I$, the asymptotic wave function $\Psi \sim \exp(ikr)/r$ is an exponentially decaying, normalizable state with $E > 0$, *i.e.*, a *bound state embedded in the continuum* (BSEC). The possible explanation of the narrow resonances found by Bertini *et al.* in the CERN experiments was discussed in detail by Gal *et al.* [14][2]. The idea of identifying peaks in pion spectra from (K^-, π) reactions with BCES's was given up when Morimatsu and Yazaki [16] did not find in their calculations any effect of BCES's on these pion spectra.

2. Narrow resonances could occur at a relatively high energy if the potential $V_\Sigma(r)$, in which the Σ hyperon moves, had a barrier near the surface of the nuclear core. The presence of such a barrier was suggested by Myint, Tadokoro, and Akaishi [17] (see also [18]) whose effective ΣN interaction $v_{\Sigma N}$ consists of a short range repulsion and a long range attraction. Inside the nuclear core the two parts of $v_{\Sigma N}$ contribute fully to the resulting attractive V_Σ. Close to the nuclear surface, the full short range repulsion but only a diminished fraction of the long range attraction contributes to the resulting V_Σ, which turns out to be repulsive. This leads to the appearance of a surface repulsive barrier in $V_\Sigma(r)$. If one applies this type of $V_\Sigma(r)$ to calculate the pion spectrum from the (K^-, π) reaction, one may reproduce the results of the CERN experiments [19].

3. Σ^- atoms

The first empirical indication that the s.p. Σ potential in nuclear matter V_Σ may be repulsive came from the improved analysis of the strong interaction shifts ϵ_a and widths Γ_a of Σ^- atoms [20].

Since the Σ^- hyperon spends most of the time in the far periphery of the Σ^- atomic nucleus, it is difficult here to obtain definite information on the behavior of $V_\Sigma(r)$ inside the nucleus. The sign of ϵ_a indicates that the strong interaction increases the binding of Σ^- hyperons in Σ^- atoms, which certainly means that $V_\Sigma(r)$ is attractive in the periphery of atoms. Consequently the early analyses of Σ^- atoms [10], in which $V_\Sigma(r)$ was assumed to be proportional to the nuclear density $\rho(r)$, suggested that $V_\Sigma(r)$ is attractive also inside nuclei, in agreement with Bertini's interpretation of the CERN (K^-, π) experiments.

The situation changed when new precise data on ϵ_a and Γ_a in Σ^-Pb atoms were available [21]. In their recent comprehensive phenomenological analysis of all the existing 23 data points (ϵ_a's and Γ_a's), including the Pb data, Batty, Friedman, and Gal [20] obtained the best χ^2 fit with $V_\Sigma(r)$

[2] It appears that Σ hyperon eigenvalues with positive energy were first noticed in [15]. Wycech, the coauthor of [15], was always skeptical about the idea of BSEC.

which is repulsive inside the nucleus and has an attractive pocket at the periphery of the nucleus.

At that moment I became interested in the possibility of explaining the Σ^- atomic data with the Nijmegen baryon–baryon interaction [22]. Looking at Σ potential in NM of density ρ, obtained (via Brueckner theory) with the help of model D, model F, and also the soft core (SC) [23] and the new soft core (NSC) [24] model of the Nijmegen interaction, one finds that only model F has the desired feature: it leads to repulsive V_Σ at ρ encountered inside nuclei, and to attractive V_Σ at lower ρ encountered in the nuclear surface. That indeed model F leads to the best description of the 23 Σ^- atomic data, was supported by detailed calculations [25].

We determined ϵ_a and Γ_a in [25] by solving the Schrödinger equation for the Σ^- wave function with the Coulomb interaction $V_{\mathrm{C}}(r)$ and the strong interaction $V_\Sigma(r)+iW_\Sigma(r)$ between Σ^- and the nucleus. The Σ^- atom was treated at each point as Σ^- moving in NM with the local density of protons and neutrons in the Σ^- atom. The s.p. potential V_Σ of Σ^- moving with momentum $\hbar h_\Sigma$ in NM has the form [26]: $V_{\mathrm{NM}} = V_0(k_\Sigma,\rho) + \frac{1}{2}\alpha V_\tau(k_\Sigma,\rho)$, where $\alpha = (N-Z)A$. In calculating the V_{NM}, we applied the effective $\Sigma^- N$ interaction in NM, $\mathcal{K}$, obtained with the Brueckner theory in [27] and [24] (the so called YNG interaction). The Lane potential V_τ was calculated in an approximation applied a long time ago [28] in the pure nuclear case. The absorptive potential $W \approx W_{\mathrm{NM}}$ was expressed through the cross section σ for the $\Sigma^- p \to \Lambda n$ process (this is equivalent to applying the optical theorem to the Brueckner $\mathcal{K}$ matrix). For σ we used here the parametrization given by Oset *et al.* [29].

For the 23 data points, we obtained for the four models of the Nijmegen interaction the following χ^2 values: $\chi^2|_{\mathrm{F}} = 19.5$, $\chi^2|_{\mathrm{SC}} = 33.3$, $\chi^2|_{\mathrm{D}} > 129.9$, $\chi^2|_{\mathrm{NSC}} > 903.6$. Thus the Σ^- atomic data clearly favor model F of the Nijmegen interaction, and indicate, similarly as the phenomenological analysis of Ref. [20], that the s.p. potential of the Σ hyperon is repulsive inside the nucleus. Notice that the Σ^- atomic data favor $V_\Sigma(r)$ with a substantial Lane potential, as is the case with $V_\Sigma(r)$ derived from model F of the ΣN interaction (see [26]).

4. The Brookhaven experiments

The problem how to reconcile the contradictory conclusions of the analysis of Σ^- atoms (and also of the Λ overbinding problem) with the CERN experiments was solved when new (K^-,π) experiments on ^{9}Be were performed at Brookhaven [30] with an order of magnitude better statistics than the old CERN experiments. The first results of this experiments were reported by Sawafta [31] at the same 1994 Vancouver Conference at which Batty [32] reported the new results of the analysis of the Σ^- atomic data. In the new accurate π^- spectrum measured at Brookhaven the narrow peaks observed at CERN disappeared. It appears then that the narrow peaks present in the old CERN experiments were simply results of poor statistics.

There are two features of the pion spectra measured at Brookhaven: *(i)* The π^+ spectrum is shifted towards higher Σ energies, compared with the quasi-free model, which obviously suggests a repulsive V_Σ inside the nucleus [33, 34]. *(ii)* The π^+ spectrum is shifted towards higher Σ energies compared to the π^- spectrum, which indicates an substantial Lane component in $V_\Sigma(r)$ (see, *e.g.*, [26]). Both features clearly favor model F of the Nijmegen interaction.

Let us mention that the recent measurement at KEK [35] of the K^+ spectrum from the associated Σ production reaction (π^-, K^+) on Si also leads to the conclusion that $V_\Sigma(r)$ is strongly repulsive inside the nucleus[3].

5. Final comments

We come to the following conclusions:

- The ΣN interaction is well represented by the Nijmegen model F which leads to the s.p. Σ potential which is repulsive inside the nucleus and has an shallow attractive pocket at the nuclear surface.
- Consequently, we do not expect Σ hypernuclear bound states[4] or narrow resonance states.
- We could have reached this conclusion more than twenty years ago, if not for the misleading results of the (K^-, π) experiments at CERN, and also the early analysis of the Σ^- atomic data.

Finally let us mention the astrophysical consequences of the character of the potential V_Σ felt by Σ in NM. At high densities hyperons appear in NM, and the potential felt by the hyperons affect the equation of state of NM. Particularly important is here the Σ^- hyperon. With increasing repulsion in V_Σ the equation of state becomes stiffer. This in turn leads to the increase of the expected mass of neutron stars. (See *e.g.*, [37].)

REFERENCES

[1] R. Bertini *et al.*, *Phys. Lett.* **B90**, 375 (1980).

[2] D.J. Millener, C.B. Dover, A. Gal, *Phys. Rev.* **C38**, 2700 (1988).

[3] A.R. Bodmer, *Phys. Rev.* **141**, 1387 (1966).

[3] However, the 150 MeV strength of the repulsion suggested in [35] appears suspiciously high.

[4] The observed [36] ${}^{4}_{\Sigma}$He bound state is an exception, connected with the special structure of this system.

[4] N.M. Nagels, T.A. Rijken, J.J. de Swart, *Phys. Rev.* **D12**, 744 (1975); **D15**, 2547 (1977).

[5] N.M. Nagels, T.A. Rijken, J.J. de Swart, *Phys. Rev.* **D20**, 1663 (1979).

[6] J. Rożynek, J. Dąbrowski, *Phys. Rev.* **C20**, 1612 (1979).

[7] J. Dąbrowski, H.S. Köhler, *Phys. Rev.* **136**, B162 (1964).

[8] R. Bertini, in *Meson–Nuclear Physics-1979 (Houston)*, Ed. E.V. Hungerford III, AIP Conference Proc. No. 54, N.Y. 1979, p. 703.

[9] J. Rożynek, J. Dąbrowski, *Nukleonika* **25**, 604 (1980).

[10] C.J. Batty *et al.*, *Phys. Lett.* **B74**, 27 (1978).

[11] J. Dąbrowski, J. Rożynek, *Phys. Rev.* **C23**, 1706 (1981).

[12] R. Bertini *et al.*, *Phys. Lett.* **B136**, 29 (1984).

[13] R. Bertini *et al.*, *Phys. Lett.* **B158**, 19 (1985).

[14] A. Gal, G. Toker, Y. Alexander, *Ann. Phys.* **137**, 341 (1981).

[15] W. Stępień-Rudzka, S. Wycech, *Nucl. Phys.* **A362**, 349 (1981).

[16] O. Morimatsu, K. Yazaki, *Nucl. Phys.* **A435**, 727 (1985).

[17] K.S. Myint, S. Tadokoro, Y. Akaishi, *Progr. Theor. Phys.* **82**, 112 (1989).

[18] S. Tadokoro, Y. Akaishi, *Phys. Rev.* **C42**, 2591 (1990).

[19] J. Dąbrowski, J. Rożynek, *Phys. Lett.* **B323**, 99 (1994); *Nucl. Phys.* **A585**, 317c (1995); *Acta Phys. Pol. B* **27**, 985 (1996).

[20] C.J. Batty, E. Friedman, A. Gal, *Phys. Rep.* **287**, 385 (1997).

[21] R.J. Powers *et al.*, *Phys. Rev.* **C47**, 1263 (1993).

[22] J. Dąbrowski, *Nucl. Phys.* **A691**, 58c (2001).

[23] P.M.M. Maessen, T.A. Rijken, J.J. de Swart, *Phys. Rev.* **C40**, 2226 (1989); *Nucl. Phys.* **A547**, 245c (1992).

[24] T.A. Rijken, V.G.J. Stoks, Y. Yamamoto, *Phys. Rev.* **C59**, 21 (1999).

[25] J. Dąbrowski, J. Rożynek, G.S. Anagnostatos, *Eur. Phys. J.* **A14**, 125 (2002).

[26] J. Dąbrowski, *Phys. Rev.* **C60**, 025205 (1999).

[27] Y. Yamamoto, T. Motoba, H. Himeno, K. Ikeda, S. Nagata, *Progr. Theor. Phys. Suppl.* **117**, 361 (1994).

[28] K.A. Brueckner, J. Dąbrowski, *Phys. Rev.* **134**, B722 (1964).

[29] E. Oset, L.L. Salcedo, R. Brockmann, *Phys. Rep.* **188**, 79 (1990).

[30] S. Bart *et al.*, *Phys. Rev. Lett.* **83**, 5238 (1999).

[31] R. Sawafta, *Nucl. Phys.* **A585**, 103c (1995).

[32] C.J. Batty, *Nucl. Phys.* **A585**, 229c (1995).

[33] J. Dąbrowski, J. Rożynek, *Acta Phys. Pol. B* **29**, 2147 (1998).

[34] Y. Shimizu, Ph.D. thesis, University of Tokyo, 1996 (unpublished).

[35] H. Noummi *et al.*, *Phys. Rev. Lett.* **89**, 072301 (2002).

[36] T. Nagae *et al.*, *Phys. Rev. Lett.* **80**, 1605 (1998).

[37] M. Baldo, F. Burgio, *Lecture Notes in Physics* **578**, 1 (2001).