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THE NUCLEAR INTERACTION OF Σ HYPERONS* **

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The analyses of the strangeness exchange (K^-,π) and the associated production (π^-,K^+) reactions are presented. They indicate — together with the observed properties of Σ atoms — that the Σ single particle potential V_Σ is repulsive inside nuclei and has a shallow attractive pocket at the nuclear surface. This conclusion is consistent with the Nijmegen model F of the hyperon–nucleon interaction. It is demonstrated how the strong-interaction shifts and widths measured in Σ atoms may be used to obtain information on the nucleon density distributions.

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1. Introduction

Our present knowledge of the Σ hyperon interaction with nuclear matter, represented by the single particle (s.p.) potential V_Σ, comes from the following sources:

— Final state interaction of Σ hyperons in the strangeness exchange (K^-,π) reactions (see, *e.g.*, [1], and [2]).

— Final state interaction of Σ hyperons in the associated production (π,K^+) reactions (see [3], and [4]).

— Free space hyperon–nucleon scattering data, to which the hyperon–nucleon interaction potential $V_{\Sigma N}$ may be fitted (see, *e.g.*, [5–8]), and with this potential one may calculate V_Σ (see, *e.g.*, [9–11]).

— Strong interaction shifts ε_a and widths Γ_a of the observed Σ^- atomic levels [12, 13].

All these sources imply that the ΣN interaction is well represented by the Nijmegen model F of the baryon–baryon interaction [6], which leads

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to V_Σ which is repulsive at densities ρ of nuclear matter of the order of the equilibrium density $\rho_0 = 0.166$ fm^{-3} and is slightly attractive at low densities encountered at nuclear surface [11, 14, 15].

Since the strong interaction shifts and widths in Σ^- atoms are sensitive to the proton and neutron density distributions ρ_n and ρ_p, we may use the Σ^- atomic data to gain information on these density distributions.

In Sec. 2, we describe how the properties of V_Σ and $V_{\Sigma N}$ follow from the analysis of the strangeness exchange and associated production reactions. In Sec. 3, we discuss the possibility of gaining information on ρ_n and ρ_p from the Σ^- atomic data. Conclusions are presented in Sec. 4.

2. Information on V_Σ and $V_{\Sigma N}$

Gaining information on V_Σ from the Σ production processes was burdened for a long time by the inaccurate early CERN results for the strangeness exchange (K^-, π) reactions [16]. The situation was clarified, when new experiments were performed at Brookhaven [17] with an order of magnitude better statistics. A simple analysis of the pion spectra measured in Brookhaven in the (K^-, π^+) reaction on the ^{9}Be target was performed in [2] in impulse approximation. The results, shown in Fig. 1, suggest that V_Σ is repulsive inside nuclei with the strength of about 20 MeV.

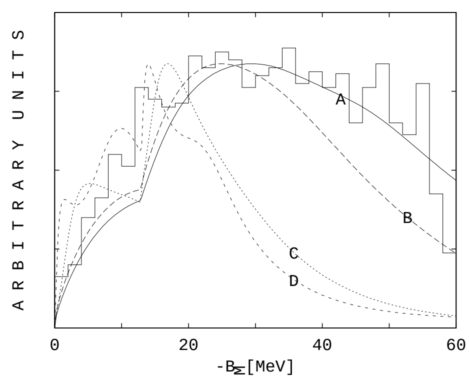

Fig. 1. Pion spectrum from (K^-, π^+) reaction on ^{9}Be at $\theta_\pi = 4°$ at $p_K = 600$ MeV/c. The curves A, B, C, D were calculated with a square well potential V_Σ with the strength 20, 10, -10, and -20 MeV, respectively.

A similar analysis of the kaon spectrum measured in KEK [3] in the associated production (π^-, K^+) reaction on the ^{28}Si target was performed in [4]. The results shown in Fig. 2 lead to a similar conclusion with a slightly stronger repulsion of V_Σ.

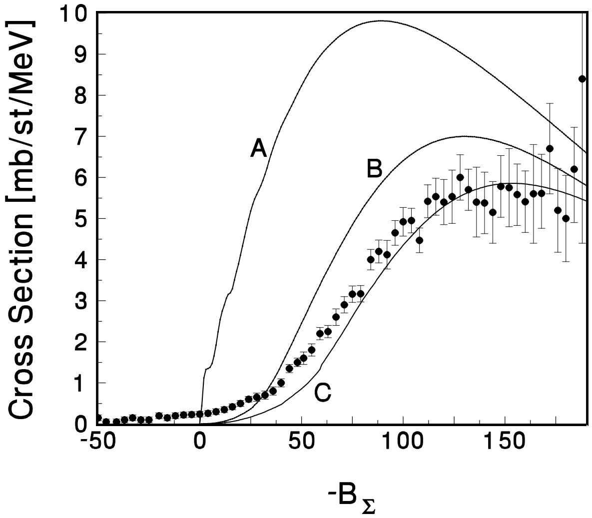

Fig. 2. Kaon spectrum from (π^-, K^+) reaction on ^{28}Si at $\theta_K = 6°$ at $p_\pi = 1.2\,\mathrm{GeV}/c$. See text for explanation. The curves A, B, C were calculated with a square well potential V_Σ with the strength -20, 20, and 40 MeV, respectively.

An important feature of V_Σ is its isospin dependence [14]. For a $\Sigma^\pm$ moving with momentum k_Σ in nuclear matter of density ρ with neutron excess $\alpha = (N - Z)/A$, we have:

$$V_{\Sigma^\pm}(\rho, k_\Sigma) = V_0(\rho, k_\Sigma) \mp \frac{1}{2} V_\tau(\rho, k_\Sigma)\alpha\,. \tag{1}$$

As discussed in [14], the π^- spectrum observed in the Brookhaven (K^-, π^-) experiments [17] indicates that the final state interaction of the Σ hyperon is here less repulsive than in the (K^-, π^+) reaction. This suggests a sizable strength of the Σ Lane potential V_τ, consistent with the value of $V_\tau|_{\rho=\rho_0} \sim 80\,\mathrm{MeV}$ estimated in the phenomenological analysis [12] of Σ^- atoms.

We may exploit our information on V_Σ to find the most reliable version of the Σ-nucleon interaction potential $V_{\Sigma N}$. In the present discussion, we consider the Nijmegen models of of the baryon–baryon interactions: models D [5], F [6], soft-core (SC) model [7], and the new soft-core (NSC) model [8]. Within the Brueckner theory, one may obtain with these models the corresponding effective interactions in nuclear matter. This was done by Yamamoto *et al.* [11], and we use here their effective YNG interaction. It is a configuration space representation of the G-matrix calculated in the low order Brueckner (LOB) theory. With the help of the YNG interaction, we calculate V_0 and V_τ, by applying the expressions derived in [14].

Our results obtained for $V_0(\rho, k_\Sigma = 0)$ and $V_\tau(\rho, k_\Sigma = 0)$ are shown in Fig. 3 and 4[1]. We notice that at densities ρ of the order of the nuclear matter densities ρ_0, only model F leads to a repulsive $V_0 \sim 20$ MeV, in agreement with the results of the analyses of the (K^-, π) and (π, K^+) reactions described above, whereas all the remaining models lead to an attractive V_0. At the same time, the attractive character of V_0 at low densities (relevant in Σ^- atoms) revealed by model F guaranties that it leads to

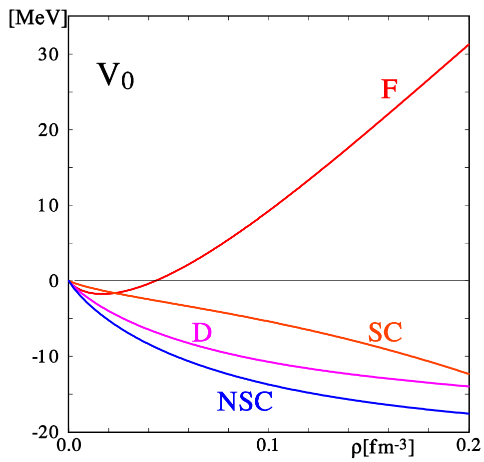

Fig. 3. Potential $V_0(\rho, k_\Sigma = 0)$.

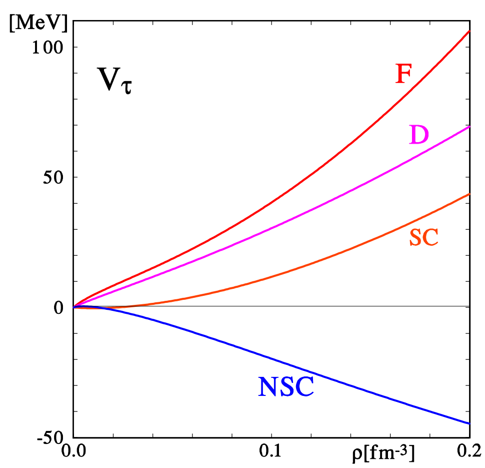

Fig. 4. Potential $V_\tau(\rho, k_\Sigma = 0)$.

[1] The dependence on k_Σ, which is rather weak (especially in case of V_τ), is discussed in [18].

a strong-interaction energy shifts in Σ^- atoms towards increased binding of the atomic levels, in agreement with experiment (see [13]). As far as the Lane potential is concerned, we see that at $\rho \sim \rho_0$, model F leads to $V_\tau \sim 80\,\mathrm{MeV}$, in agreement with the previously mentioned estimates, whereas models D and SC lead to a weaker V_τ, and model NSC leads to negative value of V_τ.

We conclude that among the Nijmegen baryon–baryon interaction models, only model F appears to be a realistic representation of the ΣN interaction.

3. Information on ρ_n and ρ_p

If we know the complex Σ s.p. potential in nuclear matter (its imaginary part may be directly related to the cross section for the $\Sigma\Lambda$ conversion process $\Sigma + N \to \Lambda + N$) and apply the local density approximation, we may follow [13] and calculate the strong-interaction shifts ε and widths Γ of Σ^- atomic levels [12,13], provided we know the neutron and proton density distributions ρ_n and ρ_p. Here, we want to hint at a possibility of exploiting the sensitivity of the calculated values of ε and Γ to the form of ρ_n and ρ_p (especially in the peripheral region of the nucleus) to gain information on ρ_n and ρ_p.

We consider the case of the Σ^-Pb atom because of the relatively high accuracy of the three data points measured in [19]: the energy shift ε and the width Γ of the lower level with the principal and orbital quantum numbers $n = 9$, $l = 8$, and the width Γ^u of the upper level with $n = 10$, $l = 9$. We want to find nucleon densities in ^{208}Pb, $\rho_n(r)$ and $\rho_p(r)$ which lead to the best agreement between the measured values of ε, Γ, and Γ^u and these values calculated with model F of the Nijmegen interaction.

Let us consider model F and, *e.g.* model D. We start with HF densities ρ_n and ρ_p calculated by Skalski [20] with the Skyrme interaction SkM*. Values of ε, Γ, and Γ^u calculated with these densities lead to $\chi^2|_D = 7.9$ and $\chi^2|_F = 65.2$, respectively, for model D and F. The fact that the wrong model D leads to a better agreement with experiment than the correct model F indicates that the HF densities require corrections. The steps in which these corrections are introduced, are described in detail in [21]. They lead to the modified proton density distribution $\tilde{\rho}_p$ with the unchanged root-mean-square radius (with the neutron distribution unchanged). The energy shift and widths ε, Γ, and Γ^u calculated with these densities give: $\tilde{\chi}^2|_D = 22.7$ and $\tilde{\chi}^2|_F = 7.6$. Thus the corrected densities lead to the desired situation in which the realistic model of the ΣN interaction leads to the best agreement with the Σ^-Pb atomic data. The essential features of the corrected densities are visualized in Fig. 5 which shows $\alpha(r) = [\rho_n - \rho_p]/[\rho_n + \rho_p]$. Whereas with the HF densities the nuclear periphery consists mainly of neutrons, with the corrected densities the neutron to proton ratio at the nuclear periphery is approximately equal N/Z.

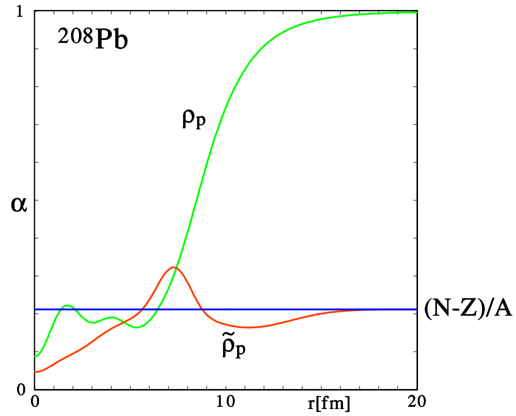

Fig. 5. The local neutron excess $\alpha(r)$ calculated with the HF density ρ_p and with the modified density $\tilde{\rho}_p$.

4. Summary

— The analysis of the new strangeness exchange and associated production data indicates that the Σ s.p. potential V_Σ inside the nuclear core is repulsive.

— Among the Nijmegen models of the ΣN interaction only model F leads to a V_Σ repulsive at nuclear densities appearing inside nuclei.

— Assuming that model F is a realistic picture of the ΣN interaction, the analysis of the Σ atomic data may lead to information on ρ_n, ρ_p at the nuclear periphery.

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