Review

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A Review of Σ Hypernuclear Physics

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Abstract. A concise overview of fundamental Σ hypernuclei physics and the mechanisms of hypernucleus formation and interactions are presented. Σ–Λ interaction and strong force-mediated hyperon-nucleon interaction are introduced to give an epigrammatic background and current perspective of the subject. A model phenomenological elementary Sigma-Nucleus (Σ-N) potential has been constructed and reported here as an instance of ΣN interaction. The potential incorporates both spin and isospin dependence and may be useful in calculating Hamiltonians, cross sections and decay widths in Σ hypernuclear reactions.

Keywords: ΣN potential; Σ–Λ conversion; woods-saxon potential; lane potential
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Introduction

A hypernucleus is an unstable nucleus formed *in situ* with a constituent hyperon, a baryon comprising at least one strange quark, such as a Λ, Σ or Ξ hyperon, in a nucleus, such as Helium. Since the discovery of the first hypernucleus event in 1952 at Warsaw University with the detection of a Λ-hyperon by Danysz and Pniewski, (1953a;1953b; Danysz *et al.*, 1963a; 1963b; Mladjenovic, 1992), the area of hypernuclear physics has seen a steady growth (Fig. 1). A number of further findings were made in the following years, recording more instances of hypernuclear detection, which are summarized in a detailed survey (Danysz, 1956). Nishijima (1954) predicted the Σ and Ξ particles for the first time and not only gave valuable insight into these hyperons but defined strangeness as an empirical quantum number connected to hypercharge. On the basis of this he did a complete classification of strange particles. This became one of the inspiring milestones for Schwinger (1956) to formulate his *dynamic theory of κ mesons*, as cited in his paper on this topic.

Since the Danysz and Pniewski (1953a;1953b) discovery, hypernuclei have been abundantly produced and studied at various physics laboratories in the world, most notably at the CERN in 1960's and 1970's epoch, Brookhaven (BNL) AGS during 1970's to 1990's, KEK, 1980's to 1990's, and at the BNL, KEK and US Jefferson labs (JLab) in the contemporary years, using both kaon and pion beams.

In addition to the terrestrial efforts at various laboratories, physicists turned to astronomy in order to see the presence of hyperons and strange baryonic matter in celestial bodies. It

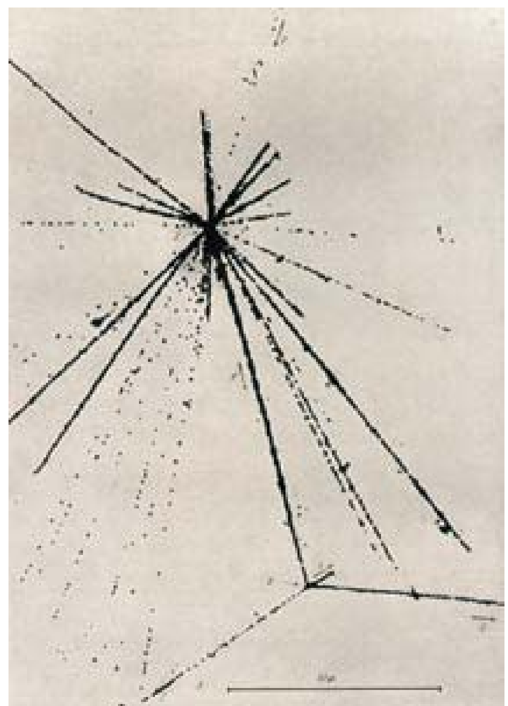

Fig. 1. The first observation of a hypernucleus. A cosmic ray coming in from the top right collides with a nucleus in the emulsion to create the star of tracks. One of the fragments from the collision disintegrates lower down the image to produce three new tracks. The faintest of these, traveling towards the lower left, is probably due to a pion. The total energy released in the disintegration is consistent with the decay of a lambda particle in the original nuclear fragment. (Courtesy and Copyrights *CERN Courier*, CERN, Geneva).

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has been suggested that a prospective site suitable for finding large amounts of strange matter is in the interior of neutron stars, where not only the stellar radii and masses, but even their thermal and structural evolution, are influenced by the presence of contained strange matter, such as strange quarks, hyperons, or kaon-condensates (Glendenning, 1997; Prakash *et al.*, 1997). It is believed that neutron star cores bearing strange quarks or kaon-condensates have substantially lower stellar radii and higher masses as compared to those without strange matter. It has also been reported in studies elsewhere (Pons *et al.*, 1999; Prakash *et al.*, 1994; Lattimer *et al.*, 1991) that strange matter affects the long-term thermal evolution of neutron stars and causes production of metastable neutron stars, a factor which has been suggested to affect the probability of the formation of low-mass black holes. Currently, investigations are underway to search for these effects with the help of a number of experiments and observations. These efforts include multi-wavelength photon observations of neutron stars in various experiments like ROSAT, HST, AXAF, and XMM. In addition, laboratory studies on phase-shift analyses of nucleon-hyperon, nucleon-meson and hyperon-hyperon interactions (both for many-body calculations of dense matter and for studies of superfluidity and superconductivity) are being explored.

In recent times, physicists have begun looking for a number of interesting phenomena and effects, such as different mechanisms in hypernuclei production, existence of bound states, and the appearance of narrow widths in the hypernuclear spectra. It has been proposed that an important effect in strange physics, *strangeness enhancement*, may be a signature of the creation of quark-gluon plasma in nucleus-nucleus collisions at high energies (Sibirtsev *et al.*, 1999; Sibirtsev and Cassing, 1998). One of the current aims of research pursuit in the area of hypernuclei is the search for inter-hyperonic conversion, for which a prime candidate is the Σ–Λ conversion. This report is based on an extensive theoretical, computational and experimental study carried out in the search of Σ–Λ conversion (Bukhari, 2006).

Λ and Σ Hypernuclei. The lambda hyperon (Λ) is the lightest of the hyperons, with a mass of 1115.64 MeV/c^2 and exists in the form of a charge singlet with a spin half, strangeness -1 and isospin zero. Its important parameters and quantum numbers are enumerated in Table 1. Because of its low mass, it is stable as far as the strong interaction is concerned and thus can form a stable hypernuclear system. It has a lifetime of about 2.6 x 10^{-10} s and can decay in a nucleus *via* either of two decay modes - mesonic or non-mesonic. The mesonic decay mode involves a Λ decay by meson (a pion) and a nucleon duo, whereas the non-mesonic decay involves a decay *via* a pair of nucleons (proton/neutron). A free Λ decays *via* the mesonic mode. On the other hand, if the Λ is embedded within a nucleus and the momentum of the decay proton is lower than the Fermi momentum, Pauli blocking inhibits this decay mode. In such cases, a non-mesonic decay predominates, mediated *via* the weak interaction, causing Λ decay by emission of nucleons.

The non-mesonic decay modes are less studied, but are interesting, as we can use them to obtain a knowledge of strangeness-changing, four-fermion baryon-baryon weak interac-tions. In these decays, another important applicable factor is an empirical rule, called the "ΔI=1/2 Rule" (Hungerford and Furic, 1999; Gibson and Hungerford, 1995), whereby the weak decays of hyperons predominantly occur with a change in isospin by one-half. Thus, the hyperon's interaction with nucleons is greatly dependent on spin as well as isospin. Spin-dependence of ΛN interaction in p shells have been established quite well, based on a ΛN potential model and analysis of hypernuclear data by various sources (Millener *et al.*, 1985).

The sigma (Σ) is the next hyperon after lambda in terms of mass. Unlike a Λ, a Σ hyperon exists as a charge triplet, i.e. in the form of three charge eigenstates - positive, negative and neutral sigma. They have the common quantum numbers of spin half, isospin unity and strangeness of -1. The mass of each of these is different and approximately ~ 76-80 MeV higher than the lambda.

All the three flavours of sigma have their individual decay modes and interaction channels with the nucleons.

Table 1. Λ and Σ Hyperon characteristics.

Hyperon (structure)	Mass (M, MeV)	Charge (Q)	Spin (J)	Isospin (T and T_3)	Strangeness (S)	Mean Life (τ, s.)
Λ^0 (uds)	1115.64	0	½	0, 0	-1	2.63 x 10^{-10}
Σ^0 (uds)	1192.5	0	½	1, 0	-1	7.0 x 10^{-20}
Σ^- (dds)	1197.43	-1	½	1, +1	-1	1.5 x 10^{-10}
Σ^+ (uus)	1189.37	+1	½	1, -1	-1	0.8 x 10^{-10}

The Σ^0 has an extremely short lifetime $<\tau> \sim 7 \times 10^{-20}$ s. (making it the shortest-lived particle in the triplet). It can also decay electromagnetically by forming a Λ and emitting a single gamma photon (~100% B.R.) or a Λ with a pair (<3% B.R.) of gamma photons. Though Σ^0 and Λ^0 share the same quark constituents, their difference of isospin quantum number implies a structural difference and relevant symmetries between the two. An in-depth study of the conversion of Σ into Λ could help resolve this structure.

The Σ^- has the highest mass in the triplet. It has only one significant decay channel (99.84% B.R.) through which it decays (weakly) to a neutron and a pion (π^-) with a mean life of ~1.5×10^{-10} s.

In the case of the Σ^+, this eigenstate has the lowest mass in triplet. There are two decay channels available to it, both weak and mesonic, one with a proton and a neutral pion (51.57%) and one with a neutron and a positive pion (48.3%), and has a mean life of 0.8×10^{-10} s.

Interactions of a Σ with a nucleon are known as *Σ N interactions*. Owing to a stronger spin and isospin dependence, this interaction is not only richer and more complicated than a ΛN interaction, it has farther-reaching implications. For instance, it can play a significant role in the Σ-nucleus dynamics and production of narrow Σ states.

While residing in a nucleus, a Σ has a number of interaction channels available, by the virtue of which it can undergo a strong interaction with any of the nucleons, leading to its conversion into a lambda (Λ^0) and an accompanying particle. These conversion pathways include five distinct channels, favoured by conservation laws and kinematics;

1. $\Sigma^- p^+ \rightarrow \Lambda^0\, n^0$
2. $\Sigma^- p^+ \rightarrow \Sigma^0 n^0$
3. $\Sigma^0 n^0 \rightarrow \Lambda^0\, n^0$
4. $\Sigma^0 p^+ \rightarrow \Sigma^+ n^0$
5. $\Sigma^+ n^0 \rightarrow \Sigma^0 p^+$

In the case of Σ interaction with the nucleus, through the channel ΣN−ΛN, a large width is exhibited, recorded on the order of ~25MeV (Batty *et al.,* 1978). Though some studies (Bertini *et al.,* 1980) suggested the existence of bound nuclear states, they were later on disproved by more accurate measurements. Thus to date, all the searches for narrow or bound states for this hyperon have been negative, except one case, the ${}^4_\Sigma$He, which has a reported bound state (Nagae *et al.,* 1998). The reasons cited for the unavailability of any bound states in Σ have mainly been due to the shallow Σ-N potential and the process of Σ−Λ conversion. Thus the conversion is an important process in hypernuclear physics.

Hypernucleus formation. In studies of hypernuclei, efforts have mainly been focused on the investigations of hypernuclei decay modes and hypernuclei spectroscopy. Both of these rely, in most cases, on one common theme - the knowledge of hypernuclear formation and decay. Hypernuclei are unstable, short-lived systems and the hyperons embedded within them, whether bound or quasi-free, have very short lifetimes and decay *in situ* within the nucleus. Hence, the only way to study these interactions is by indirectly measuring their decay products. Both production and decay have a number of possible mechanisms, ranging from simple modes to intricate ones.

There are a number of different production mechanisms by which hypernuclei are produced. These mainly include strangeness exchange and associated production (photoproduction, electroproduction and double-strangeness-exchange) reactions. In order to form hypernuclei, in general, charged kaon beams are used to produce a strange quark inside a nucleus. A beam of incoming particles with a strange quark in them has to be incident with a momentum in an appropriate range, in order to satisfy the criteria of *'momentum matching'* and *'sticking probability'* (Bandõ *et al.,* 1990). The sticking probability is related to the momentum transfer which allows the produced hyperon to remain in the nucleus after the interaction (The lower the momentum of the hyperon, the higher is this probability.) This momentum optimizes the sticking probabi-lity, and in general is higher than the Fermi momentum and lower than the threshold momentum required to disintegrate the nucleus into its constituent nucleons. This maximizes the probability of a projectile's interaction with the nucleus to form a hyperon. When an incident projectile with this momentum interacts with one of the nucleons in the s or p shells, it can form a hyperon in the shells available to it, undergoing a strangeness exchange reaction.

A general hypernuclear production reaction is written as:

$$a + A = {}_AY + b$$

where ***a*** is the incident projectile which interacts with nucleus ***A*** and creates a hypernucleus ${}_A\boldsymbol{Y}$, comprising of a hyperon and a nucleon system. A by-product meson ***b*** is emitted from the process as one of output products of reaction. The ${}_A\boldsymbol{Y}$ hypernucleus forms the recoil system left over from the nucleus.

For instance, in the production of a hypernucleus by means of a stopped-kaon reaction, an incident projectile, such as a kaon, takes a position into the atom's Bohr orbitals on its interaction with the atom. By traversing and cascading down through these orbitals, when its radius becomes small, and it is in the proximity of the nucleus, it interacts with the nucleons and forms a hyperon, within the nucleus. It is in sharp contrast to the production of hyperons in Quasi-Free (QF) form where they are produced in a scattering state with high values of momenta (enabling them to escape capture by a nucleus) and do not lead to the formation of hypernuclei.

Stopped projectile reactions are often employed for hypernucleus production. These offer benefits as efficient production of hyperons, complete absorption of incident projectiles at the nuclear surface, large formation probability of hypernuclei and the population of non-substitutional states (such as the ground and low-lying states). These can also lead to the formation of "*Stretched States*", which are stretched-spin states with large momentum transfer values. An example is the production of Λ hypernuclei in the ^{4}He($k^-_{stopped}$, π^0)X reaction, where non-substitutional stretched-spin states are excited preferentially by substantial transfer of momenta.

Contemporary hypernuclear production is facilitated by a number of mechanisms. These include processes as in-flight reactions and stopped incident particle reactions, which can lead to either recoilless production or recoil production of hypernuclei. In all these, recoilless production using the in-flight reaction (K^-,π^+) is a special case of in-flight reactions and is important and relevant in this context.

In a kaon-induced strangeness exchange reaction, the strange quark in the kaon substitutes for an up or down quark in the nucleon and directly converts the nucleon into hyperon – it is possible to have very little amount of momentum transferred from the projectile to the nucleus and the collision remains recoilless. The momentum of the incoming particle (in *lab* frame) is borne almost entirely by an out-going projectile (in this case, a pion), which is emitted in the same direction as the kaon (in *lab* frame) and this whole process can result in a recoilless *in-flight* reaction. The reaction involves no change in quantum numbers (*n*, *l* or *m*). Owing to the constancy of linear momentum as a result of the involved kinematics, it does not induce any angular momentum change and the overall state of the system remains the same. These are thus referred to as *"substitutional states"*, as the incoming projectile with its specially-tuned momentum matching causes a preferential excitation of only the substitutional states, causing $\Delta L = 0$. These kinds of reactions are *exothermic*, i.e. they yield a positive Q-value, liberating the energy from the reaction while producing a hypernucleus. The ^{3}He(k^-, $\pi^\pm$)ΣNN reactions are an example of this case, using a projectile momentum range of 400 to 800 MeV/c and cross section on the order of 10^3μb/sr.

In most of the other cases, a recoil mechanism takes place in hypernucleus production, and a substantial amount of momentum is transferred to the hypernuclear system.

This study was based on and discussed reactions of the first type, i.e. recoilless production of Λ and Σ hypernuclei in s-shell by means of an in-flight reaction, ^{3}He (κ^-, π^+)Σ^-NN involving excitation of non-stretched, substitutional states. A study by Barakat and Hungerford (1992) contributes valuable insight into understanding this reaction.

Σ-N interaction and potentials. An essential step in the understanding of hyperon-nucleon interaction is the understanding of nuclear and nucleon-nucleon potential. This knowledge is relatively well-understood after decades of theoretical and experimental investigation. In contrast, the hyperon-nucleon potential and consequent interaction has yet to achieve the same footing, as it is difficult to obtain hyperon beams to study Y-N scattering. Besides, the extremely short hyperon lifetimes and their inter-conversion processes can also pose problems in studying these interactions. Nevertheless, this interaction offers a rich spectrum of knowledge and countless new vistas to explore.

When it comes to expressing the potential of any spin-vector particle or system, spin is an important degree of freedom, not just limited to hypernuclei but in ordinary nuclei as well. It is a well-established fact that the nuclear potential is spin-dependent, due to the two-body tensor force which induces a strong one-body spin-orbit potential experienced by the nucleus. A similar tensor force must prevail for a hypernucleus, where spin and orbital angular momentum should couple to a collective spin-dependent nuclear potential. It has been reported by Dover *et al.* (1989) that the coupling strength of Σ-N spin-orbit interaction is about one-half of its N-N counterpart, whereas the ratios of the strengths of the averaged NN, Λ-N and Σ-N potentials were proposed to exist in proportion:

$$NN / \Sigma N \sim 3/1,$$
$$NN / \Lambda N \sim 3/2$$

In the ΛN and ΣN interactions, there are two more degrees of freedom – strangeness, by the virtue of the strange quark embedded into a hyperon, and isospin, because of the isospin-coupling and the strong isospin-dominant symmetries involved with the hyperonic structure. These, as well as the unstable nature of the hyperons, make it more difficult, and at the same time interesting, to define quantitatively or illustrate qualitatively a hyperon-nucleon interaction.

In particular, spin and isospin play an intertwined role in the interaction of a hyperon with a nucleon and consequently on the potential formed by their combination. The strong spin–isospin dependence in ΣN interaction is evidently because of the exchange of both isoscalar (ω, η) and isovector (π, ρ) mesons, which presents a wide spectrum of coupling states.

One dimension of this problem is understanding the isospin structure, as the nuclear potential itself depends significantly on the isospin. A further dimension enters in this problem from the fact that the hyperons are distinguishable from nucleons in terms of their quantum numbers, specifically in terms of the strangeness. Thus, Pauli blocking does not apply and the hyperons inhabit their own individual nuclear shells, following the same shell model scheme as the nucleons.

The ΛN interaction (Dalitz *et al.,* 1972) is relatively well known as compared to ΣN interaction, as a Λ within a nucleus forms bound states with the nucleons and enables studies to probe this potential. However, the ΣN interaction is not understood very well and requires a lot of experimental data to quantify its core potential. Hence the ΣN potential is a crucial piece of information.

Σ-N potentials. One existing model which describes a Σ-N potential is the *Nijmegen Model,* comprising two variations, models I and II (Maessen *et al.,* 1989; Nagels *et al.,* 1978). It proposes an elementary potential for the interaction of a Σ with a nucleon, in form of a *one-boson-exchange (OBE)* model. In quantum hadrodynamics, these models are also termed as *one-pion-exchange (OPE)* or *one-meson-exchange (OME)* models and are very useful in understanding the interaction at the level of exchange particles. The Nijmegen model is largely based on $SU(3)_f$ symmetry and uses the existing nucleon-nucleon data in order to determine its parameters. The spin splittings predicted in the model for Λ hypernuclei were later measured in an experiment at Brookhaven (Dover *et al.,* 1989). Nevertheless, investigations are still underway to validate the model's applicability to the ΣN potential. It has been suggested (Alberico and Garbarino, 2002) that the Σ-N interaction exhibits a long range *One-Pion-Exchange (OPE)* component, with the central part weaker than the Λ-N part. Thus, investigations of this interaction within the framework of One-Boson-Exchange (OBE) models, is a viable approach.

Harada *et al.* (Harada and Akishi, 1996; Koike and Harada, 1996; Harada, 1992; Harada *et al.,* 1990), using the Nijmegen model, proposed an effective Σ-nucleus potential derived from this model and based on many-body calculations. In a *Mean Field Model* (Walecka, 1995; Jaminon and Mahaux, 1989), they assumed that the hyperon is embedded in a collective mean field of nucleons where it retains its individual structure and undergoes interactions with nucleons in the form of Nijmegen potentials. This model is considered a reasonable formulation of an effective potential to explain the interaction of a hyperon in the effective potential created by the surrounding nuclear medium. It uses a Lane potential (Lane, 1962) and incorporates an isospin mixing term $\boldsymbol{\tau}_N.\mathbf{t}_\Sigma$ to describe isospin mixing of Σ and N.

In connection with actual observations of Σ-N potentials, there have been a few studies which attempted to quantify these potentials on the basis of experimental data. Some quantitative estimates of the sigma-nucleus potential were established from the analysis of Σ^--atom X-ray data by Batty (1979), who reported estimates of the sigma-nucleus potential at the center of the nucleus to be -(25-30) MeV for the real part and -(10-15MeV) for the imaginary part, with a form proportional to the nuclear density.

In addition to isospin and spin degrees of freedom, there is one more important factor in the quest for finding this potential, i.e., the continuum – which is represented by quasi-free states which do not have a discrete sets of states and lie in the continuum. The continuum plays an important role in both hypernuclear production and the potential. Studies by Tang *et al.* (1988) and Chrien *et al.* (1987) have highlighted the effects of the continuum in $^{16}O(k^-,\pi^+)X$, $^{12}C(k^-,\pi^+)X$ and $^6Li(k^-,\pi^+)$ reactions. As the Σ potential is shallower than that of a Λ, fewer states can be expected in the bound regions of the spectrum, in turn manifesting a more profound role of the continuum.

In view of the paucity of available experimental data and intricacies involved in the understanding of the underlying processes, the subject of the Σ-N potential remains intriguing and controversial. However, one thing remains paramount- as suggested by Bandõ *et al.* (1990) as well, *"The strong isospin-spin dependence of the Σ-N interaction should generally play an important and characteristic role in the Σ-nucleus dynamics"*. An exhaustive review, which discusses the Σ-nucleus potential, spin-isopin role and consequent interactions in A=3,4 systems (Barakat and Hungerford, 1992), presents various important aspects of this problem in further detail.

Here, to illustrate a general form of a Y-N potential, an attempt has been made to construct a simple elementary Σ-N potential which is in its class similar to an optical potential and incorporates both spin and isospin dependence.

Constructing an elementary Σ-N optical potential. The interaction of a Σ inside a nucleus can be modeled as an incident particle interacting with a complex optical potential formed by the nucleons in a nucleus. If this optical model is devised on the lines of a Woods-Saxon type potential in the shell model paradigm (Jensen, 1963; Mayer and Jensen, 1955; Mayer, 1950; 1949; 1948), one can construct a form:

$$U(r) = -[V(r) + iW(r)] + V_{S.O.} \quad (1)$$

where *V(r)* is the real part of the potential and *W(r)* the imaginary part, and $V_{S.O.}$ is the spin-orbit coupling term. The imaginary part here corresponds to absorption, which manifests its effects in the form of inelastic scattering, as well as in the form of Σ-N isospin mixing and Σ–Λ conversion channel. Both of these parts have a scaling behavior in energy, i.e. they depend on the energies involved.

In an approach similar to one taken by Eder *et al.* (1977), in which a potential for the neutron-nucleus interaction was constructed, one can formulate a Σ-N phenomenological potential within the framework of the shell model, and express it as:

$$U(r) = -V_0 f(x) - i\left(Wf(x) - 4W_s \frac{d}{dx} f(x)\right) + 2\zeta m^2 V_{S.O.}\left(\frac{\vec{\sigma}\cdot\vec{L}}{\hbar}\right)\frac{1}{r}\frac{d}{dx} f(x),$$
$$f(x) = \frac{1}{e^x + 1}, x = \frac{r-R}{a}, R = r_0 A^{1/3} \quad (2)$$

Here, r is the nucleonic separation, R the nuclear radius, *a* the diffusivity, and σ and L the spin and orbital momentum vectors, whereas W, W_s and ζ are shell parameters calculated from the energy tables (Perey and Perey, 1974).

The potential is incomplete yet, because of a lack of isospin dependence. Here, one can incorporate a suitable potential with embedded isospin dependence, such as the one introduced by Lane (1962) to describe inter-nucleonic potentials. If the depths of the nucleon potentials are known, this potential can be determined conveniently and can be used to construct a suitable nuclear potential.

If a Lane term (Harada and Akishi, 1996; Koike and Harada, 1996; Lane, 1962) is assumed in the real part of this potential and isospin dependence is introduced, we obtain a complete potential which describes the Σ-N interaction. This kind of Σ-N potential is also suggested by Harada *et al.* (1990) in the Harada model. It has a form:

$$U_{C\Sigma}(R) = U^0(R) + U^\tau(R)(T_C \cdot t_\Sigma) \quad (3)$$

Here, C and Σ denote the nuclear core and Σ hyperon, respectively. The first term describes the usual central nuclear potential and the second term is the 1/A Lane Term, including a dot product of the isospin operators for the two entities. This potential is illustrated in Fig. 2 (Harada and Akishi, 1996; Koike and Harada, 1996), featuring an A=4 ΣNNN system for the two Σ-N system isospin states, T=1/2 and T=3/2. Here, Σ hypernucleus potentials for the T=1/2 and T=3/2 states in the four-body ΣNNN system, as calculated by Harada (1992) and Harada *et al.* (1990) are shown. In the T=1/2 state, the real part is attractive and has a small contribution from a repulsive part, but has an imaginary part. This imaginary part corresponds to absorption and is attributed to the isospin mixing and Σ–Λ conversion processes. Based on Harada's work, it can be surmised that two processes are going on in the nuclear core nearly simultaneously– first, a Σ is being absorbed into the nucleon(s), and second, this absorption goes on inversely proportional to the potential depth. On the other hand, in the T=3/2 state, these trends are unavailable. This seems to agree with the findings (Albercio and Garbarino, 2002) in some models supported by experimental data, which have shown the Σ-N effective potential to be strongly repulsive at short distances.

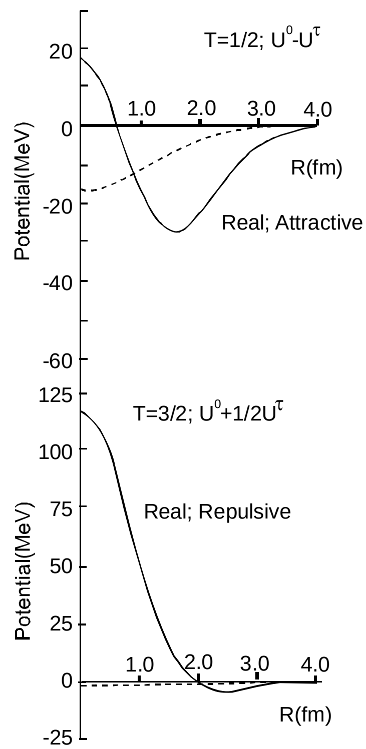

Fig. 2. ΣN potentials as calculated by Harada (Image courtesy of Harada, 1996).

As the Σ is an isospin vector with total isospin of unity, in a $_\Sigma^4$He hypernucleus, the sigma-nucleon system has two available isotopic spin states; the T=1/2 and T=3/2. In contrast, a Λ with its scalar isospin, can exist in only one isotopic spin state, T=1/2. For instance, the ^{4}He(k^-,π^-)ΣNNN reaction populates both of these states for ΣNNN, while the ^{4}He(k^-,π^+)ΣNNN reaction populates only the T=3/2 state (Afnan and Gibson, 1993). The reaction investigated in this study, the ^{3}He (k^-,π^+)ΣNN reaction, leads to a total T=1 state for the Σ^--^{2}H system, as deuteron has a (J=1, T=0) state, whereas a Σ^- has the state (J=1/2, T=1).

The Lane-term-modified potential term for isospin is then substituted in the potential in equation 2, and a suitable form for a phenomenological Σ-N potential can be constructed, as given below in the equation 4. The potential has both spin-dependence and isospin dependence in the form of spin-orbit coupling and isospin coupling, respectively. A Coulomb interaction between the hyperon and the nucleus has been included (which was not included in the equation 2). The Coulomb interaction being a long-range force is difficult to handle in the short-range potentials, but it has been added for completeness.

$$U(r) = -U^0 f(x) + U^{\Sigma N}_{coul} - U^{\tau} f(x)(\vec{T}_C \cdot \vec{T}_{\Sigma}) - i[Wf(x) - \xi f'(x)] + 2\zeta m^2 V_{S.O.}\left(\frac{\vec{\sigma}\cdot\vec{L}}{\hbar}\right)\frac{1}{r} f'(x) \qquad (4)$$

Here, the symbols ξ and ζ have been arbitrarily chosen to represent the energy-dependent shell parameters, which replace W_s and ζ in the equation (2), and can be determined from the experimental data. The form of the coulomb potential is taken as a uniformly charged sphere of a radius R_c which can be expressed as;

$$U^{\Sigma N}_{coul}(r) = Ze^2/r \Rightarrow r > R_c$$
$$U^{\Sigma N}_{coul}(r) = a + br^2 \Rightarrow r \le R_c \qquad (5)$$

where, *a* and *b* are given by:

$$a = \frac{3Ze^2}{2R_c}$$
$$b = -\frac{Ze^2}{2R_C^3} \qquad (6)$$

and the values for the constant parameters r_0, a_0 and R_c can be chosen from the studies described earlier.

The potential expressed in equation 4 is a complete and physical expression for a Σ-N potential, incorporating both the spin and isosopin dependence. It can be used to formulate a suitable Hamiltonian or Lagrangian for the ΣN hypernuclear interactions, and possible solutions could be determined in the available degrees of freedom.

Conclusion and Discussion

This report presents a general overview of Σ and Λ physics and presents the development of an elementary ΣN phenomenological potential as a model. The report primarily deals with the formation, decay and interaction of a Σ hyperon with a nuclear medium. A detailed report in this connection has appeared elsewhere (Bukhari, 2006), including detailed development of the potential, and in particular, a study of the mechanics of the Σ conversion into a Λ hyperon. Another useful study, reported in recent years (Saha *et al.*, 2005) based on some theoretical work and experimental data collected at the KEK proton synchrotron, presents an overview of the ΣN potential and decay widths in a p-shell system.

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