Strangeness in Hadronic Interactions

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Strangeness has always been an important subject at all PANIC conferences as it probably constitutes the best link between particle and nuclear physics. I will thus use the theme of the conference by considering strangeness as a tourist through the world of strong interaction. During this talk we will accompany strangeness from production, to the royaume of mesons and baryons up to the complex world of nuclei.

1. Production of and by strange particles

1.1. Production of hyperons by hyperons at high energies

The production characteristics of hyperons at high energies has since long been studied. Using recent results from the hyperon beam at CERN [?] we now have a systematic set of data on differential cross sections for the production of different hyperons using beams with different strangeness (S =0,-1,-2). The resulting systematic is shown in fig 1. It shows that different production processes are at play for central production ($x_F < 0.3$) and forward production ($x_F > 0.7$). At central collisions the strange quark for the final hyperon is produced from the sea and little difference is seen if strangeness is already brought along in the beam. As is well known, the cross section drops by a factor 10 for each unit of strangeness produced without exhibiting any exhausting behavior coming from a reduction in cms-energy once 1 or 2 strange quarks have already been produced. The situation is drastically different at forward kinematics, where the final hyperon profits from a strange quark in the beam. Each additional unit of strangeness again leads to a punishment, but now in the order of a factor 100, probably due to the limited energy available in the initial collision.

1.2. Production of charm states by hyperons

In the past it had been speculated that hyperons as projectile could exhibit a larger cross section for charm production that protons or even mesons. Even in the absence of

![Figure 1. Hyperon production cross sections by WA89](image)
exotic reasons one expected the harder momentum distribution of the strange quark in the projectile to boost the cross section in the kinematic region where it strongly depends on the beam energy. The measured cross section using charmed and charmed strange mesons as well as baryons ($\sigma_{\text{tot}} = 11.3 \pm 2.4 \pm 2.0 \mu\text{barn}$) perfectly agrees with existing proton data and their predicted kinematical dependence.

As inferred from the hyperon production data the distribution for final states is altered and an efficient production of charmed strange systems is observed (as well as baryons over mesons) resulting in a strong asymmetry for $D^-/D^+$ in the forward region.

1.3. Polarization of hyperons in hadronic interactions - The case of $D_{NN}$ at low energies

Polarization of hyperons have been observed since many years. Mostly these measurements were done at high energies (many GeV beams) and different final states were studied. No complete picture of the phenomena observed yet exists. However, besides of polarization production one can also measure polarization transfer from a transversely polarized beam to a hyperon, usually called $D_{NN}$, the depolarization coefficient in the normal to the production plane. While at high energy the phenomena must be explained in a quark picture the low energy regime is the playground for meson exchange pictures concurring with descriptions on quark exchange. While threshold production in $pp$ annihilation has already been reported some time ago I would like to mention new results from Saturne. Using a transversely polarized proton beam they observed Lambda polarization in exclusive processes. The different hyperons being produced primordially could be distinguished by final state analysis and missing mass techniques. The results of the DISTO experiment show a negative polarization transfer from the proton to the Lambda of about $-20\%$ to $-50\%$, increasing with $x_F$ and decreasing with $p_T$ (see fig. 2). This can well be explained by a $K^-$-meson exchange which leads to the production of strange hadrons in the final state. (pion exchange on the other hand would predict a large and positive value for $D_{NN}$) However, if we consider the same process at higher energies the effect shows a change in sign. Clearly, the data at 200 GeV are inclusive production data but that should not lead to a change in sign.

1.4. Polarization of strange nuclei

Polarized hypernuclei are an useful tool to improve on the spectroscopy of hypernuclei, determine the magnetic moment of $\Lambda$ in the nuclear medium and to further study the dynamics of mesonic and non-mesonic decays of $\Lambda$-hypernuclei. $\Lambda$-polarization in low energy exclusive reactions can be calculated from an phase shift analysis of $K$ and $\pi$ scattering involving hyperons in the final state. In a typical hypernuclear experiment $n(\pi^+,K^+)\Lambda$ the $\Lambda$-production can be explained by phase shift analysis of $\pi$-nucleon scattering using Regge exchange and assuming intermediate baryon resonances. The underlying free process has shown to give rather large polarization of free Lambdas ($60-80\%$). Lambda Polarization
in nuclei using the \((\pi^+,K^+)\) reaction has first been observed by \[3\] using the quasi-free Lambda production in \(^{12}\text{C}\) \((P_\Lambda \sim 60-65\%)\). The results agreed very well with the calculation assuming the production on free neutrons, corrected for the Fermi-momentum effect.

These calculations of the free Lambda polarization has to be adapted for nuclear effects, which can lead to a depolarization by gamma-emission or particle emission \[3\]. It was pointed out that \(^5\Lambda\text{He}\) is an ideal system to study the polarization and test the model predictions. In a recent experiment at KEK \[6\] this system was produced by the \(^6\text{Li}(\pi^+,K^+p)^5\Lambda\text{He}\) reaction, a strangeness exchange reaction on Lithium with subsequent proton emission at \(p(\pi) = 1.05\) GeV/c. Owing to the low nuclear mass number the decay of the hypernucleus shows a strong mesonic component with large decay asymmetry from the free \(\Lambda\) decay. A polarization of 25\% \((0.247\pm0.082)\) was observed at small angles (transverse momenta) and of 40\% \((0.393\pm0.094)\) at larger angles. The results are well reproduced by the calculations giving 18\% and 37\%, respectively. Considering the complex production mechanism this results gives confidence that the polarization of other hypernuclei may be extracted from theory and may be used to study other phenomena (as mentioned above).

2. Strangeness in Hadrons (interaction with the host)

2.1. The size of strange baryons

The structure of hadrons is closely connected to the question of their size. We can define hadronic and charge radii for mesons and baryons, as they can be measured by elastic scattering and electron scattering \[8\] and which can be explained in different models. Here we shall only deal with the more familiar concept of charge radii. Assuming an effective size of a constituent quark which scales with the mass of the quark Povh et al. have predicted the radii for all different hadrons. While most of the hadronic radii have been determined, electromagnetic radii for hyperons are still missing. This field has recently seen important progress. Using the method of electron scattering in reverse kinematics (scattering charged hyperons off the electrons in a target) which has been used for the determination of the \(\pi\) and \(K\) radii data on the charge radius of the \(\Sigma^-\) could be obtained. The first measurement by WA89 \[9\] establishing the method which showed large statistical and systematic errors was recently superseded by a more precise result from the SELEX \[10\] group at FNAL. The mean square charge radius is determined by the slope of the elastic form factor at \(q^2=0\). The SELEX experiment has cross checked their results by a simultaneous measurement of the pion and proton radii. The results are
depicted in fig. 3 together with a number of predictions. As for the meson system ($\pi$-K) the strange counterpart of the proton shows a smaller radius than the charged nucleon confirming the predictions of many models. The key measurement to expect in the future is a measurement of $\Sigma^+$ charge radius which should be larger than the proton one owing to the different charge of u and d-quarks. Many other models exist and most of them predict the $\Sigma^+$ to be smaller than the proton, just as the $\Sigma^-$.

2.2. The role of strangeness in meson and baryon spectroscopy

As we know from the constituent quark model and the many more 'realistic' models derived from it later on the binding forces inside a hadron can be derived from a series of potentials. A central potential and higher order terms like spin-orbit or spin-spin interaction. At short distances the interaction of quarks proceeds analog to e.m. via the 1-gluon exchange. Similarly we can define a spin-spin splitting where the couplings are assumed to be proportional to the color magnetic moments of the hadrons. Since the magnetic moment of a constituent quark scales with its mass we have an effective flavor breaking of the quark-quark interaction. Negative parity states show a richer structure particularly in the baryon sector. In the quark model description two orthogonal degrees freedom which are defined combining only two quarks or the axis of the third quark moving around the other two. In equal mass systems these two systems are degenerate but introducing a different quark flavor breaks this symmetry and the system splits into $\Lambda$ and $\Sigma$-type states (symmetric and anti-symmetric in the exchange of two equal mass quarks) [11]. This becomes more interesting if angular momentum is involved as these two coordinates can be distinguished more easily (fig. 4). While for l=0 the $\Lambda$-states are lighter than the $\Sigma$ states the particular symmetry leads to a partial inversion of this order for $l \geq 1$. For $\Lambda$-type baryons we expect the angular momentum to be mostly within the qq-coordinate, thus increasing their distance and decreasing the spin-spin force, while for the $\Sigma$-type system the angular momentum is mostly in the orthogonal coordinate of the quark with unequal mass. Replacing the strange quark by a charm quark reduces the $\frac{3}{2}^+ - \frac{1}{2}^+$ splitting in the $\Sigma$-system.
(because of the heavy charm quark mass) but increases the \( \Lambda-\Sigma \) splitting. Adding a strange quark to the charm quark almost reestablishes the \( \Lambda-\Sigma \) situation because the repulsion in the \( S=1 \) \( qs \)-system is reduced and compensates the lack of spin-spin interaction of lighter and charm quark. Also the spin \( \frac{3}{2}^+ \) state is moved down for the same reason (see also fig.6). New results are now available for the \( l=1 \) system, particularly in the \( csq \)-sector. For these states in the \( csq \)-sector the spin-spin interaction is reduced to the minimum for the \( \Lambda \)-type system, as the two lighter quarks are now at larger distances due to the angular momentum between them. We expect the \( \Lambda \frac{1}{2}^- \) and \( \frac{3}{2}^- \) state to be almost degenerate, which still shows a small separation in the \( qqc \) system. Indeed, the \( \Lambda \frac{1}{2}^- \) system of the \( \Xi_c \) has not yet been found. CLEO \([12]\) has recently reported the observation of a new \( \Xi_c \)-state, interpreted as \( \frac{3}{2}^- \), decaying via \( 2\pi \)-emission into the ground state \( \Xi_c \) (fig.7). The extreme narrow width of this state and the particular decay pattern (via an intermediate \( \Xi_c^* \)) supports the spin assignment and the baryon picture drawn above, using arguments too long to be outlined here.

2.3. Lifetimes of heavy strange hadrons

Including strangeness into charmed baryons results in a rich pattern of lifetime observed for various charmed strange baryons. This result is caused by an interference of the \( s \)-quark stemming from the \( c \)-quark decay and the one present in the parent baryon. While short distance physics puts lifetimes of all charmed hadrons to about 1 ps, long range correlations lead to a variety spanning a factor of 20 with the \( \Omega_c \) being the shortest one.

3. Hypernuclei (Strangeness visiting nuclei)

The pioneering work in this field was done using recoiless production of \( \Lambda \)-hypernuclei \((K^-,\pi^-)\) at 700-800 MeV/c, which established the existence of hypernuclei and allowed a clear assignment of hypernuclear states from where the \( \Lambda-N \) potential was derived and first estimates on \( \Lambda \) spin-orbit potential were obtained. Comparing the features to heavy baryons we can see similar and very different features. a) While the confinement potential is flavor independent (and thus the central constituent quark potential) the \( \Lambda-N \) interaction is weakened as compared with the \( NN \) to about \( 3/5 \) leading to a potential depth of 30 MeV as compared to 50 MeV for the \( NN \) case. b) As is the case for heavy quarks the \( \text{‘intruder’} \) is hardly sensitive to the spin interaction (LS and SS) which results in a quasi degeneration of states of the new system. c) The heavy visitor is well distinguishable from the ordinary population (light quarks and nucleons) as the many body system can be described as a core coupling to the \( \text{‘tourist’} \) which mainly behaves as an independent single particle system acting as a static source of attraction.

Lately the development has shifted to the \((\pi^+K^+)\) reaction pursued at KEK and BNL. Owing to its large recoil (350 MeV/c) this reaction allows to populate also the low lying ground states of hypernuclei. The population favors maximum angular momentum (spin-stretched states) of the core/\( \Lambda \) system.

The virtue of this reaction can be seen in the \( ^{89}\Lambda Y \) spectrum (see fig.8) where the core nucleus mainly stays in a \( g_{9/2} \) state and the excitation spectrum clearly unravels the single particle spectrum of Lambda’s in a nucleus. It has since been the textbook example of a single particle spectrum within a strongly interacting multi-body system. However, not
all nuclei can be treated with the same success (see $^{40}$Ca) when several closely spaced neutron hole states can be excited.

However, this reaction seems an ideal tool to study light nuclei with high precision. Here, mostly nuclei are studied with simple shell structure of the hypernucleus or the core nucleus ($^4$He, $^6$Li, $^8$Be, $^{12}$C, $^{16}$O). Achievements of the past have been first estimates of the $\Lambda$ LS-coupling, the $\Lambda$-N SS-coupling and the study of core excitation of Lambda-hypernuclei. Since then the main aim of many groups is the precise determination of the LS coupling, SS-strength and the study of hypernuclei using polarization.

3.1. Determination of the SS-coupling
The determination of the $\Lambda$-N spin-spin coupling is very difficult as it is expected to be very small. Since usually the experimental energy resolution of a spectrometer system is in the order of 2 MeV (close to the size of spin-spin splitting in the NN case) we may only detect this splitting using $\gamma$-spectroscopy of $\Lambda$-hypernuclei. A good candidate is $^7\Lambda$Li where the $^6$Li core may be described in the cluster model as $\alpha$+d (or $^3$He + t, the latter one for higher excitation). We may obtain a first estimate of the SS-coupling, being typically very short ranged, assuming the interaction to proceed via $1^-$ exchange, analog to the 1-photon or 1-gluon exchange. In this case we may just scale the SS-splitting ($0^+ - 1^+$) of $^6$Li (3.56 MeV) with the ratio of magnetic moments of Lambda and nucleons.

Taking the average of $\Lambda$-p and $\Lambda$-n interaction (p and n being parallel in spin) we obtain $(\mu_\Lambda \cdot \mu_N \sim -0.65 \ast (2.8 - 1.9)$ as compared to $\mu_p \cdot \mu_n \sim -1.9 \ast 2.8)$ which gives a factor -0.6/-5.5, thus a factor 9.

In a very nice experiment employing a Ge-ball (with BGO Compton shield) surrounding the hypernuclear production target $^7\Lambda$Li Tamura et al. have observed two gamma-transitions tagging the production of bound hypernuclei using the $(\pi^+, K^+)$ reaction (see fig. 6). They attribute the line at 690 KeV to the M1 transition $\frac{1}{2}^- \rightarrow \frac{3}{2}^-$, thus the SS-coupling. It is about a factor 5 smaller than in the NN case. Using an OBE model for the underlying $\Lambda$-N interaction this value could be reproduced theoretically by Motoba et al. This value is also compatible with the results from light hypernuclei ($^4$He and $^3$H). The other line at 2.05 MeV is attributed to the $\frac{5}{2}^+ \rightarrow \frac{1}{2}^+$ transition.

3.2. Determination of the LS-coupling
$^{13}$C is since long considered to be the best candidate for a determination of the LS coupling of Lambdas. This state can be seen as a Lambda coupled to a $^{12}$C core. We can populate
the $p_{\Lambda}$ state and try to observe the $\frac{1}{2} - \frac{3}{2}$ gamma-transition. This is subject of an ongoing experiment at BNL. In the meanwhile the group at KEK, again using the $(\pi^+, K^+)$ reaction with the superconducting Kaon spectrometer, has observed the $p_{3/2-s_{1/2}}$ splitting to be $9.92 (\pm 0.13 \pm 0.5)$ MeV [15]. Using the $p_{1/2-s_{1/2}}$ gamma transition ($10.95 \pm 0.1 \pm 0.2$ MeV) observed at BNL [16] many years ago the LS splitting can be determined to $1.03 (\pm 0.23 \pm 0.7)$. This should be compared to an LS-splitting of $0.72 (\pm 0.5)$ MeV observed by the same group in $^{16}$O and previous results from BNL, limiting the LS splitting to $0.35 (\pm 0.3)$ MeV [17]. Using the fact that the LS-coupling increases with L a KEK group has investigated $^{89}$Y$_{\Lambda}$ with high resolution allowing to observe the LS-splitting for the $f_{9/2}$ level (see fig.8) [13].

3.3. Lifetimes of hypernuclei

$\Lambda$ in nuclei can decay in two different ways, via mesonic decays just like a free $\Lambda$ ($\Lambda \rightarrow p\pi^-$, $n\pi^0$) or via non-mesonic two body reactions $N\Lambda \rightarrow NN$. Thus we expect hypernuclei to live shorter than free $\Lambda$, depending on the importance of the latter process. Fig. 8 summarizes the presently known lifetimes of hypernuclei as function of the nuclear mass number [18]. As can be seen, lifetimes drop at small values of A due to the onset of n.m. decays but stay constant for nuclei with $A \geq 10$. The saturation of n.m. decays may reflect the saturation of nuclear density and thus the average number of nucleons seen by the $\Lambda$.

3.4. $\Sigma$-hypernuclei (are $\Sigma$-baryons welcome in nuclei?)

Since the first observation of $\Sigma$-hypernuclei at CERN in Be, C and O many years ago [20] much effort has gone into the study of Sigma hypernuclei. The big puzzle had been the narrow width of the observed states while theory predicted large widths owing to the $\Sigma$-$N \rightarrow \Lambda$-$N$ quenching mechanism. However, until day, these states could not be observed again neither using stopped kaons nor the in flight reaction with kinematics similar to the CERN one by BNL [21] (E887). However, the search for
a confirmation of these states finally resulted in the observation of bound $\Sigma$'s in He using stopped $K^-$. This measurement had been mentioned time and again since its publication in 1989. Recently these states have been confirmed using the ($\pi^+, K^+$) reaction at BNL \[22\] at $B(\Sigma^0) = 4.4 \pm 0.3 \text{(stat.)} \pm 1 \text{(sys)}$ MeV (see fig. 10). The width is measured to $\Gamma = 7 \pm 0.7 \text{(stat)} \pm 1 \text{(sys)}$ MeV. This should be compared to the KEK results obtained with stopped kaons extracting a binding $B_{\Sigma^+} = 2.8 \pm 0.7$ MeV and $\Gamma = 12.1 \pm 1.2$ MeV \[19\]. Theoretical calculations by Harada et al.\[23\] give $B_{\Sigma^-} = 4.6$ MeV and $\Gamma = 7.9$ MeV using meson exchange potentials. The non-observation of a similar state in $(K^-, \pi^+)$ producing a $\Sigma^-$ in the nucleus is remarkable. Also a large isospin dependence of the $\Sigma$-N force could be confirmed since no bound states were observed for $\Sigma^-$ from the reaction $(K^-, \pi^+)$.  

3.5. Double strange systems (group tourism)

$S=-2$ systems have since long attracted attention for two reasons. Ever since the famous paper of Jaffe \[24\] on the existence of a double strange dibaryon experimentalists have searched for such systems in various experiments (pp-collisions, heavy ion collisions, hyperon-collisions). The technique has mostly been to look for structures in the spectra of invariant mass investigating all possible final states, allowing for strong decay to weak decay of the H. Owing to the exotic wave function of this object no reliable predictions of the production cross section could be given and thus the non evidence for such a state could not disprove its existence. More recently the investigations have focused on the low energy approach, inherited from hypernuclear physics. Most of the effort is now spent on $(K^-, K^+)$ double strangeness exchange reaction leaving $S=-2$ in the target. This reaction also offers the possibility to look for doubly strange hypernuclei, a necessary prerequisite for ideas on strange nuclear matters, so called strangelets. So far, only 3 candidates for $\Lambda\Lambda$-hypernuclei have been found in emulsion, in part not uniquely identified, which however set a lower limit to the mass of the H by the apparent absence of the fusion mechanism $\Lambda\Lambda+X \to H+X$ of $M(\Lambda\Lambda)-30$ MeV. 

The following reactions can be investigated:

1. $K^- \ 12^C \to K^{+12}\text{Be}_\Xi$
2. $K^- \ 12^C \to K^{+11}\text{Be}_{\Lambda\Lambda} + n$ (via intermediate $^{12}\text{Be}_\Xi \to ^{11}\text{Be}_{\Lambda\Lambda} + n$)
3. $K^- \ 12^C \to K^{+}\Xi^- X (\Xi^- 12^C)\text{atom} \to ^{11}\text{Be}_{\Lambda\Lambda} + n$
4. $K^- \ 12^C \to K^{+}\Xi^- X (\Xi^- p(12^C))\text{atom} \to H + X$
5. $K^- \ 12^C \to H + X$
6. $K^- \ p \to \Xi^- K^+$ (via intermediate $\Xi^- D \text{atom} \to H + n$)
observed. As for $\Sigma$ an exothermic reaction exists in nuclei, $\Xi^- + p \rightarrow \Lambda\Lambda$ which is more the probable process for low binding energies (reaction 2). At low $K^+$ momenta (large momentum transfers) we produce a $\Xi^-$ beam, which subsequently interacts with the target, slows down, forms $\Xi^-$-atoms and by the strangeness exchange reaction again leads to 2 Lambda which may form a H-dibaryon or double $\Lambda$-hypernucleus (reaction 3 and 4). Several events have been identified for the production of doubly strange hypernuclei without a clear identification and a determination of the binding energy. Also production of 2 strange hypernuclei was observed. The experimental technique employed is a hybrid system of emulsion and scintillating fibers (SciFi) to link in- and out-going tracks to the emulsion pictures. At BNL one has employed high density carbon targets surrounded by SciFi arrays to track the decay of the strange states. In a new experiment at BNL one uses a set of cylindrical wire chambers within a solenoid to determine the momenta of possible decay products of light double strange hypernuclei produced in a $\Lambda\Lambda$ target (assuming $\Lambda\Lambda+$core undergo fission to produce $^6$He$\Lambda\Lambda$ or $^5$He$\Lambda\Lambda$) with an energy resolution of 1.7 MeV FWHM. The mass of the double strange hypernucleus can either be inferred from the $K^-$ spectrum (reaction 1), from the recoil spectrum of n (reaction 2) or from the spectroscopy of the decay chain of the $\Lambda\Lambda$-hypernucleus.

Results:

1. For the H-production KEK experiment E224 reported an excess in events in the $\Lambda\Lambda$ invariant mass spectrum using a scintillating fiber target.
2. No structure could be observed in the neutron energy spectrum from E885 for $\Lambda\Lambda$Be.
3. E885 has repeated E224 with 10 times higher statistics (no results yet) for the H-search
4. E885 sees excess of events for large binding energies of $\Xi^-$ in Carbon using a CH$_2$ target, as compared to calculated cross section. Comparing with two calculations assuming different $V^0_{\Xi}$ potential shows a favoring of $V^0_{\Xi} -16$ MeV.
5. No evidence for structures in the neutron spectrum could be found in experiment E813 (BNL) using reaction 6.
6. No evidence for structures in n TOF spectrum from reaction 7 at E836 (BNL)
7. No evidence for structures using $^6$Li target (E836) or $^{12}$C target (E224 KEK)
4. Future plans:

In the near future I expect further progress in the field of charm baryon spectroscopy, charge radii of hyperons and hypernuclear physics. In particular the various efforts to extract the spin-orbit interaction from data to be taken on $^{13}$C is very promising. Also the role of $\Xi$ in nuclei shall be cleared during the next years hopefully leading to a first identification of the ground state. In addition to these topics mentioned already above other measurements are expected to be done in the context of the COMPASS experiment at CERN. They address the polarizability of the kaon and the role of strange quarks in the nucleon on what concerns the total spin of the nucleon. Continuing efforts at GSI on bound mesons in nuclei we may expect the study of mass modifications of the kaon in nuclear matter, in analogy to the recent experiment with bound pions using heavy nuclei, an effect related to the restoration of chiral symmetry.

In the more distant future we may think of implanting charmed hadrons into nuclei, using new facilities currently under discussion (like a $\Xi$ storage ring at GSI).

5. Conclusions

We have seen that the reaction of a well known system to a strange or heavy intruder shows many similarities for hadrons and nuclei, even if the underlying physics may be very different. This is true concerning the single particle picture, the masking of particular parts of the usually very complex interaction (e.g. spin-spin (hadron) or spin-orbit interaction (nucleus)) or the modification of the properties of the ‘tourist’ like its lifetime which can be caused by additional reaction channels only possible in the new surrounding.

These effects can now be studied in detail owing to new and precise data coming from many laboratories around the world, both in high energy physics and in nuclear physics. The similarities of the phenomena observed in the two systems is remarkable.

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