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J.Žofka

NOTE ON HYPERNUCLEAR LIFETIMES AND PRODUCTION OF RELATIVISTIC HYPERNUCLEI

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Заметка о гиперядерных временах жизни
и рождении релятивистских гиперядер

Дан краткий обзор современного состояния исследований времен жизни гиперядер и обсуждена их физическая интерпретация. Рассмотрены перспективы проведения соответствующих экспериментов на пучках релятивистских тяжелых ионов, получаемых на ускорителях ОИЯИ.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

Сообщение Объединенного института ядерных исследований. Дубна 1986

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Note on Hypernuclear Lifetimes
and Production of Relativistic Hypernuclei

Status of hypernuclear lifetime data and their physical impact are shortly reviewed. Possibilities of measuring them using relativistic ions are briefly considered with regard to the parameters of JINR Dubna facilities.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

Communication of the Joint Institute for Nuclear Research. Dubna 1986

1. Introduction

An intensive research of hypernuclei /HY/ has started in seventieth and its scope is every year wider since. The main HY production mode, $(K^-, \pi^{\pm})$ has been used almost exclusively for that decade. It has typical virtues (low transferred momenta for K^- beams with $p_K \sim 0.4 - 1$ GeV/c ; large differential cross-sections of the order of mb/sr) for collinear production of substitutional states considered in fact long ago at JINR [1]. This technique is not directly applicable to heavy hypernuclei (gaining more interest since recently) and moreover, low momentum kaon beams are difficult to construct. There are however available other production modes, namely (π^+, K^+), (p, K^+), (A, K^+), (A, NK^+), (γ, K^+), $e, e'K^+$, etc. They differ from (K^-, π^-) reaction in the cross-sections (theirs are generally lower) and, importantly enough, in the transferred momentum. Consequently, also nonsubstitutional states (e.g. ground states in which HY weakly decay) may be populated relatively strongly. Of those were tested experimentally (π^+, K^+) and (A, XK^+).

In view of a concentrated theoretical and experimental effort, a wealth of HY data is available[2,3]. This makes possible to understand specific features of the coexistence of the strange hyperon $\Lambda (\Sigma, \Xi)$ with the nuclear medium as e.g. the YN and YA interactions and polarization of nuclear medium by the presence of the hyperon Y . There is, however, one phenomenon which has been relatively less thoroughly studied until recently, namely the lifetime of HY. Experimental data on it (as quoted in Refs. [2,3]) are old (with exception of Ref. [4]) and mutually not very consistent. It is the aim of this note to review shortly the present understanding of HY lifetime and to point at some items, which might be of experimental interest in Laboratory of High Energies of JINR Dubna.

2. Lifetime of Λ-hypernuclei

HY states, as they are produced in various reactions, are either directly ground states or excited /often very highly/ states. The latter ones undergo baryon emission, cluster emission or γ- deexcitation [5] , which bring them /succes-sively/ again into ground states. In turn, the hypernuclear ground states then decay via weak decay of implanted Λ.

Would the Λ-hyperon be free /not bound in HY/, its lifetime is $2.63 \cdot 10^{-10}$s and the main decay modes would be the mesic ones: $p\pi^-$ /64%/ and $n\pi^0$ /36%/, reminding of the fulfillment of $\Delta I = 1/2$ rule. The other weak (leptonic) decay modes are below 0.1% level. The energy release is $Q \cong 37$ MeV and c.m. momentum bite of nucleon is $q_N \cong$ $\cong 100$ MeV/c . Such a low recoil suggests an important reduc-tion of weak mesic decay of Λ inside the nucleus due to the Pauli blocking /there are few or no free states available for the nucleon resulting from the decay/ and a reduced phase space available. This is especially pronounced as going to heavier hypernuclei (beyond $^{12}_{\Lambda}C$), as all states there below the Fermi momentum (~ 270 MeV/c) are occupied.

The presence of other nucleons in the hypernucleus opens up other weak decay channels, the non-mesic ones:

$$\Lambda + p \longrightarrow n + p \quad ,$$
$$\Lambda + n \longrightarrow n + n \quad .$$

Due to a larger transfer of energy to decaying nucleons ($Q \cong 176$ MeV), this decay mode is not hindered as much as the mesic one and it will prevail in heavier hypernuclei. This will further influence the lifetime τ^A_Λ of Λ-hyperon embedded in the nuclear medium. Measurement of τ^A_Λ acquires thus importance and moreover, it yields an exclusive infor-mation on four - fermion weak interaction [6,7] .

The data on τ^A_Λ are summarized in Tab. 1 and Fig. 1.

Table 1

Experimental Λ- hypernuclear lifetimes (from Ref. [2])

HY	τ_Λ (psec)	remarks
$^{3}_{\Lambda}H$	95 ± 20	
	$90 {+220 \atop -40}$	
	274 ± 110	
	232 ± 45	
	128 ± 35	
$^{4}_{\Lambda}H$	$180 {+250 \atop -70}$	
	200 ± 80	
$^{5}_{\Lambda}He$	$140 {+190 \atop -50}$	
	274 ± 60	
$^{9}_{\Lambda}Be$	201 ± 30	Refs. [4,18]
$^{11}_{\Lambda}B$	192 ± 22	Ref. [4]
$^{12}_{\Lambda}C$	211 ± 31	Ref. [4]
$^{16}_{\Lambda}O$	86 ± 33	relativist. HI Ref. [15]

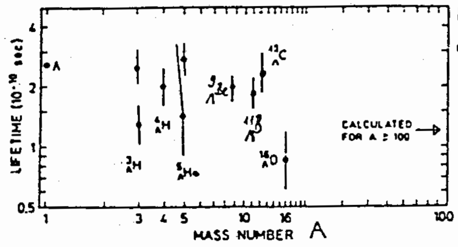

Fig. 1. Observed lifetimes of Λ-hypernuclei (Refs. [2,3,8,18])

The only piece of new data comes from Refs. [4,8], which revealed in addition an important source of τ_Λ^A information, namely the baryon emission and subsequent weak hyperon decay. (This makes possible to measure more HY species - and thus more τ_Λ^A - in a single experiment. This remark is pertinent to all productions with population of excited HY resonances[18].) Ref. [8] has mentioned also a measurement on ${}^5_\Lambda He$ and ${}^4_\Lambda He$, not analyzed as yet.

Another quantity of interest is the measure of competition of various channels. As is shown in reviews [2,3], the ratio Q^-, $Q^- = \frac{\Gamma_{NM}}{\Gamma_{\pi^-}}$, of non- mesic to mesic decay modes /see Tab. 2/ rapidly increases with increasing A so that already in the region of carbon, the non-mesic decays largely prevail over mesic ones by a considerable factor (5-6 in Ref. [2], 22 in Ref. [8]). Starting from oxygen, the mesic decays may be thus neglected and non-mesic ones constitute the full decay width /or lifetime/. Two remarks are due here: The A dependence of Q^- as seen in Tab. 2 does not imply the A dependence of the mechanism of the process itself, but reflects the A-dependent interference of the nuclear medium. Thus the lifetime of heavier hypernuclear species need not be quantitatively similar to the free value for Λ-decay.

Table 2

Ratio Q^- of non mesic to π^- mesic decays

	$Q^- = \Gamma_{NM} / \Gamma_{\pi^-}$
${}^4_\Lambda H$	0.26 ± 0.13
${}^4_\Lambda He$	0.52 ± 0.10
	0.70 ± 0.19
${}^{4,5}_\Lambda He$	1.01 ± 0.12
${}^5_\Lambda He$	1.29 ± 0.10
	1.21 ± 0.19
${}_\Lambda Li$	2.55 ± 0.66
${}_\Lambda Li$, ${}_\Lambda Be$	2.4 ± 0.7
${}_\Lambda Be$	4.3 ± 0.1
≥ ${}_\Lambda Be$	6.6 ± 1.4
${}^{11}_\Lambda B$	4.8 ± 1.1
≥ ${}^{11}_\Lambda B$	5.3 ± 1.3
${}^{12}_\Lambda C$	22^{+43}_{-12}
${}_\Lambda B$, ${}_\Lambda C$, ${}_\Lambda N$	5.9 ± 1.2
	5.5 ± 0.5
40 < A < 100	100 ÷ 200

To distinguish between different non-mesic decay modes "the Λ-neutron stimulation fraction n " is introduced to express whether Λ hyperon prefers neutrons or protons to "stimulate" its decay:

$$n = \frac{\Gamma^{n}_{NM}\,(\Lambda n \longrightarrow nn)}{\Gamma^{tot}_{NM}\,(= \Gamma^{n}_{NM} + \Gamma^{p}_{NM})}\,.$$

Again, n reveals some A dependence, as seen in Tab. 3, although the data available are not numerous.

Table 3

Λ-neutron stimulation factor $n = \Gamma^{n}_{NM}/\Gamma_{NM}$ (where $\Gamma_{NM} = \Gamma^{n}_{NM} + \Gamma^{p}_{NM}$).

	n
${}^{4}_{\Lambda}He$	0.3 ± 0.1
	0.4 ± 0.06
${}^{11}_{\Lambda}B$	$0.51 {+0.11 \atop -0.15}$
${}^{12}_{\Lambda}C$	$0.57 {+0.14 \atop -0.23}$
${}_{\Lambda}B$, ${}_{\Lambda}C$, ${}_{\Lambda}N$	0.37 ± 0.06
$A > 10$	$0.68 {+0.04 \atop -0.03}$
$A \sim 40 - 100$	$0.6 \div 0.9$
	0.85
	0.9

There were various theoretical attempts to understand those weak Λ-decays, starting with pioneering works of Dalitz and coworkers [9] up to investigations of Dubach [6] and Bandō and collaborators [7]. They all show variety of information contained in HY lifetime data. In view of that and some contradictions in various data sets on one hand and between theory and experiment on the other, the lifetime measurements are worth of effort.

3. Relativistic hypernuclei

For measuring HY lifetimes, reactions at high energies using "heavy" ion projectiles have a special appeal [10] as HY are produced in projectile frame, which makes the detection easy and the lifetime longer. Background effects may be efficiently suppressed, although non-mesic decays may be essentially traced only.

For the production of HY to be efficient, the recoil momentum q_{tr} of the produced Λ should be small /comparable with the Fermi momentum in the nucleus $k_F \sim 270$ MeV/c/, so that Λ sticks to the nucleus. The dependence of q_{tr} on the incident ion momentum is depicted in Fig. 2. From that it

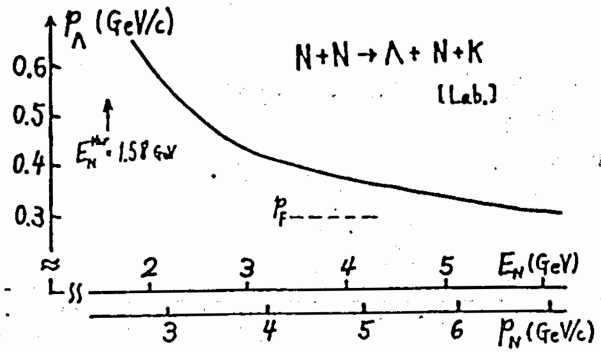

Fig.2. The recoil momentum of Λ in the N+N→Λ+N+K reaction as a function of the incident nucleon energy /or momentum/ [10].

follows that the energy per nucleon should be of the order of 5 GeV/N and higher. Another limitation is a reasonable cross--section. For the elementary process $N + N \rightarrow \Lambda + N + K^+$, the threshold lies at 1.6 GeV and around $p_p = 4$ GeV/c, the cross-section $\sigma(pp \rightarrow p\Lambda K^+)$ reaches a saturation value $\sim 60\ \mu b$ (see Fig. 3, [10]). Thus, the maximum energies per nucleon available at JINR / $\lesssim 4.5$ GeV/ seem well suited for the purpose of relativistic hypernuclear production.

Theoretical estimates [11-14] suggest the cross-sections for the HY production of the order of 1 μb/ target nucleon. The only experiment with the energy of 2.1 GeV /nucleon using ^{16}O ions (beam of 3×10^5 ions / burst, low momentum K^+ furnishing the signature for trigging) [15] gave $2 \pm 1\ \mu b$ / N .

An example of a rough estimate of the rate of hypernuclear production events for a thick carbon target ($1 g/cm^2$) and the beam intensity of 10^8 ions/sec (upper mean of JINR beams) would yield some 60 HY events per second. Number of all events (geometrical cross section) is by some 4 orders of magnitude larger, thus an efficient triggering would be an essential task.

At energies of 2.5 ÷ 4.5 GeV per nucleon, the mean decay length varies between 19 ÷ 36 cm, which again shows that working at higher energies would be advantageous. The direct detec-

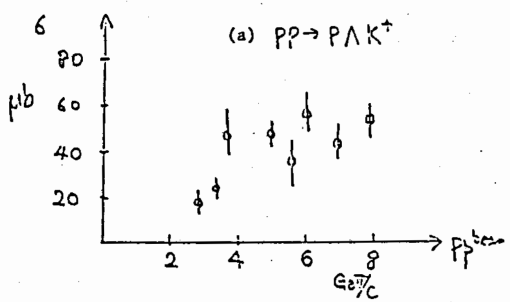

Fig. 3. Elementary pp strangeness production cross-section σ [10] .

tion of secondary particles from the decay star is difficult due to kinematics and the low multiplicity of secondary particles. Thus, a tracking of the sudden change of dE/dx (energy loss on the trajectory) at the vertex point seems more promising [10], especially when not very heavy ions are used and $(\Delta Z)^2$ is large. The trigger for starting the clock would be K^+ emission, the energy loss might be sampled in some ionozation chamber, length resolution of few cm would be sufficient (at $E \sim 4.5$ GeV).

In fact, the detection of mesic Λ-decays though difficult in relativistic production of ions, it is nonetheless possible if leading to unstable nuclei as e.g.:

$$^{6}_{\Lambda}Li \rightarrow \left.\begin{matrix} \pi^- + p \\ \pi^0 + n \end{matrix}\right\} + {}^{5}Li \longrightarrow {}^{4}He + p$$

$$^{9}_{\Lambda}Be \rightarrow \left.\begin{matrix} \pi^- + p \\ \pi^0 + n \end{matrix}\right\} + {}^{8}Be \longrightarrow \alpha + \alpha .$$

Then, products of secondary decays might be detected. In Ref. [10] , ^{6}Li incident on ^{12}C reaction was considered as a useful testing example, but certainly ^{12}C on ^{12}C and other reactions leading to HY and especially to heavy hypernuclei /A $\gtrsim 100$/ are highly interesting. As concerns very light incident nuclei, (p,d) or (d,p) reactions would probably not lead to $^{3}_{\Lambda}H$ with appreciable cross section. The reason is that a binary reaction $p + d \rightarrow {}^{3}_{\Lambda}H + K^+$ is kinematically less suitable than a ternary one /with at least one outgoing nucleon/, as was pointed out in Ref. [13] . On the other hand, an attempt to produce three-body $S = -1$ hypernuclei $^{3}_{\Lambda}H$, $pp\Lambda$ or $nn\Lambda$ is worthwhile [16] and it would moreover shed new light on the role of three-body ΛNN force. (The lightest experimentally known HY is ${}^{3}_{\Lambda}H$ with $B_{\Lambda} = 0.13 \pm 0.05$ MeV and its τ_{Λ} is not well established./

For the sake of completeness, it should be noted that a measurement of g-factor of the hypernucleus would be useful. As was discussed in Ref. [17] , a deviation in anomalous g-factor of the hypernucleus heaving Λ hyperon in the deep lying states could serve a measure of a partial deconfinement of that Λ-hyperon. An indication of a possibility of such a measurement would be an observed asymmetry of π^{-} emission with respect to the K^{+} direction [10] , if detectable.

The reasons for relativistic heavy ion Λ- HY production and subsequent hypernuclear lifetime measurements might be thus collected and summarized again as follows:

i/ precision and taking of new cross-sections not well known and difficult for extrapolation

ii/ new insight into the weak component of the baryon--baryon interaction [19]

iii/ test of $\Delta I = 1/2$ rule

iv/ new tool for studying nuclear short-range correlations [20]

v/ parameters extraction for H^{weak} in terms of quark degrees of freedom and its competition with standard /meson/ picture [19]

vi/ test of pion renormalization in nuclear medium (increased importance of Γ^{mesic}) [7,21] .

4. Conclusion

A need for and physical interest of Λ-hypernuclear lifetime data have been sketched and the applicability to it of relativistic ion reactions has been reviewed and specified to JINR facilities. Performing those experiments with the use of relativistic ions would constitute a source of complementary data, which would not only check and improve on the existing old ones, but it would open an access to heavier species, as well. To virtues of hypernuclear production via relativistic "heavy" ions belong notably a high detection efficiency and in-flight determination of lifetime of high precision. It is thus worthwhile to consider those experiments in full detail and to test the available instrumentation with view of performing Λ-hypernuclear lifetime measurements in the near future.

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