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A STUDY OF THE PRODUCTION AND LIFETIME OF THE LIGHTEST RELATIVISTIC HYPERNUCLEI

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1 Introduction

Some 20 years ago nuclei were accelerated up to the relativistic energies at Dubna and Berkeley, but the last goal of this new physics was hundreds GeV nuclei at CERN. From the very beginning of this story several proposals and ideas were announced to study the relativistic hypernuclei produced by excitation of the high energy projectile or its fragments. Indeed, the points of the production and decay of relativistic hypernuclei are separated by many centimeters (instead of some μm in the emulsion experiments) and this goal offered many advantages: to give a possibility to observe and study independently the production, interactions, decay of hypernuclei, excited states of daughter nuclei, angular distribution of the polarized hypernuclei etc. It seemed that the experiments would be very simple because some naive estimates predicted high production rates. Nevertheless there was one attempt only to realize the idea: a short experiment at Berkeley [1] in the ^{16}O beam. More than 20 suggested $^{16}_{\Lambda}$O events were observed but without a trusty identification. Maybe the main problem was to invent a good trigger. As soon as we realized a trigger sensitive to hypernuclei pionic decay we started experiments in Dubna synchrophasotron beams (^{3}He, ^{4}He, ^{6}Li, ^{7}Li) generally at 9xZ_1 GeV/c momentum (Z_1 is the charge of the projectile). One experiment was performed at a lower momentum as an attempt to investigate the energy dependence of the production cross section. The study of the production cross sections was natural for the initial program because at least one must know the range of the values of cross sections before planning experiments. But we had also an interesting theoretical issue to prove - the coalescence model [2-5] calculations and predictions of H.Bandō, M.Sano, M.Wakai, and J.Žofka.

2 The experimental details: trigger, identification, background

The trigger system including three blocks of scintillation counters was tuned to trigger the streamer chamber under the following conditions: the target was struck by a beam nucleus with charge Z_1— fixed by the first block of the counters, a particle with charge Z (eventual hypernucleus $^{A}_{\Lambda}(Z)$) was registered in the second block of the counters installed between the target and the chamber, a daughter nucleus with charge Z+1 hits the third block of the counters downstream the fiducial volume of the chamber . So the trigger had to discriminate a Z→Z+1 bump, a characteristic signature of the mesonic (π^-) hypernuclear decay.

The main detector was a streamer chamber with a track sensitive volume 2x1x0.6 m^3. The chamber filled with pure Ne at atmospheric pressure was placed in a magnetic field of 0.9 T. Events in the chamber were recorded with three cameras .

The only background process that could simulate the hypernucleus decay was the charge exchange reactions of beam nuclei or their fragments on the Ne gas in the chamber volume: Z+Ne→(Z+1) +π^-+... The hypernuclei decays and charge exchange events were identified at a high confidence level by the criteria used in film and data processing. The strongest criterium was the effective mass of the system—the daughter nucleus and the pion—this value must be in limits of the spectrometer resolution (2–3 MeV). Additional criteria were chosen in the measurements of the daughter nuclei momenta. In the film scanning process it was found that all charge exchange events are marked by some extra tracks (target nucleus fragments) or a bright streamer at the vertex due to the target (Ne) recoil.

At the same time the charge exchange reactions were used as monitoring processes for an additional control of the detector efficiency. For example, let us analyze the production of ${}^{4}_{\Lambda}$H hypernuclei in the reaction ^{4}He+C→${}^{4}_{\Lambda}$H+... with a subsequent decay in the fiducial volume of the streamer chamber, ${}^{4}_{\Lambda}$H→^{4}He+π^- , and the the corresponding background charge exchange reactions: ^{4}He+C→^{3}H+... (in the target) and ^{3}H+Ne→^{3}He+π^- (in the fiducial volume). Using the values of fragmentation cross sections [6] for ^{4}He→^{3}H , the charge exchange cross sections we have measured in the ^{3}H beam [7], and the calculated values of the detector efficiencies, we have estimated that 46±6 charge exchange events may be expected during the experiment on hypernuclei production (^{4}He→${}^{4}_{\Lambda}$H) at 2.2 GeV/nucleon. 53 events observed in the real experiment have confirmed our estimation of the efficiency. It must be stressed that among these 53 events there are only 20 2-prong events than can simulate hypernuclear decay. Really the number of 2-prong events is of the same order as the number of hypernuclei in all our high energy (more than 3.0 GeV/nucl.) experiments. For example, there were 22 ${}^{4}_{\Lambda}$H events observed at the 3.7 GeV/nucl. energy and about 20 2-prong charge exchanges in the same experiment. So we once more see that the background level is low and conditions for unambiguous identification of the hypernuclei are quite well.

3 The Production Cross Sections. Results and Discussion

We have measured the production cross sections of the lightest hypernuclei ${}^{3}_{\Lambda}$H and ${}^{4}_{\Lambda}$H as well as their lifetimes. In table I we accumulated all our data (experiment) and theoretical predictions calculated in [2-5]. The carbon target was used almost in all experiments.

Beam	Hyper-nuclei	Energy (GeV/nucleon)	Cross Sections (μb)	
			Theory	Experiment
^{3}He	${}^{3}_{\Lambda}$H	5.14	0.03	$0.05^{+0.05}_{-0.02}$
^{4}He	${}^{3}_{\Lambda}$H	3.7	0.06	<0.1
	${}^{4}_{\Lambda}$H	2.2	0.08	<0.08
		3.7	0.29	$0.4^{+0.4}_{-0.2}$
^{6}Li	${}^{3}_{\Lambda}$H	3.7	0.09	$0.2^{+0.3}_{-0.15}$
	${}^{4}_{\Lambda}$H	3.7	0.2	$0.3^{+0.3}_{-0.15}$
^{7}Li	${}^{7}_{\Lambda}$Li	3.0	0.11	<1
	${}^{6}_{\Lambda}$He	3.0	0.25	<0.5

We can see there are no contradictions between two sets of the values. Sometimes only the first test run was performed and only the upper limit of the production cross section was available. Nevertheless we present them here, because the limit values as compared to the calculated ones are quite reasonable. Two results need some additional comments. The production cross section of ${}^{3}_{\Lambda}$H is so low that it was impossible to obtain good statistics during some "realistic" accelerator run time (300 h) and only few events were registered.

Concerning the 2.2 GeV/nucleon experiment, we expected to observe at least few ${}^{4}_{\Lambda}$H events (this number was evaluated from emulsion experimental data [8], new calculations [9] by M.Sano and M.Wakai, showing dramatic energy dependence in the 2–5 GeV band not available at the time of experiment) but only one discussible event was observed. The effective mass value of this event exceeds the value of the ${}^{4}_{\Lambda}$H hypernucleus by 6±1 MeV. It means that this event can be neither a hypernucleus nor a charge exchange event ! Indeed, at a low energy all momenta are measured considerably better than at 3.7 GeV/nucl., and we cannot regard the 6 MeV discrepancy as an accidental error of measurements. But the same accurate momentum measurements prove that the probability to simulate ${}^{4}_{\Lambda}$H by charge exchange reaction ^{3}H+Ne→^{3}He+π^- is less then 10^{-5}. Another criterium (a "pure vertex") also contradicts the charge exchange version. So we have the only interpretation: there is an event of ${}^{4}_{\Lambda}$H→^{4}He+π^- decay, but the effective mass value is spoiled by a rescattered pion (the probability is about 10^{-3}). But we cannot prove this hypothesis, therefore the upper limit is accepted as a result of this experiment.

4 Lifetimes

We want to point out that the method is very powerful for the lifetime measurements. We have obtained the lifetime values for hydrogen hypernuclei:

$\tau(^4_\Lambda H) = 220^{+50}_{-40}$ ps, $\tau(^3_\Lambda H) = 240^{+170}_{-100}$ ps.

The first result was published in 1989 [10] and was based only on 22 events. Recently Outa et al. [11] used the picosecond technique and obtained $\tau(^4_\Lambda H) = 195^{+25}_{-30} ps$. Nevertheless they had to accumulate about 700 events during four weeks to reach an error level twice as lower as in our case. The main difference was the circumstance that we had no calibration and stability problems. The ^{3}H lifetime result is rather crude, but nevertheless it allows us to eliminate some of previous measurements [12-14] with very low τ values.

5 Summary

Though one can see that experimental and theoretical values of the hypernuclear production cross sections do not contradict each other it is clear that new experiments are needed, because the model [2-5] is really tested only at one point –for the production of the lightest hypernuclei in the light ion beams. Generally the model takes into account two production mechanisms depending on the projectile A number, on A , Z numbers of hypernuclei and on the projectile energy. So we should obtain some set of measurements at different A and Z as well as different energies. Also it is necessary to improve the accuracy of the experiment. More sophisticated detectors and new efficiency calculations together with precise knowledge of cross sections of charge exchange reactions allow us to reduce systematic errors. On the other hand, in the beams of the new accelerator NUCLOTRON the statistic can be improved more than ten times.

So we can say that we have for the first time elaborated the method adequate to detect and to identify unambiguously the hypernuclei produced in the beams of relativistic ions. The production cross sections and the lifetimes were measured. Future experiments in the NUCLOTRON beams will provide an approach for a full-scale test of the coalescence model of hypernuclear production.

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