Hypernuclear Physics at TJNAF*

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The strangeness electroproduction experiments, just starting to take data at TJNAF, are very promising for giving very useful information to understand the nuclear and nucleonic structure and reaction mechanism. The experimental program on hypernuclei already approved concerns few body, light nuclei and heavy nuclei. It will be possible to investigate these hypernuclear systems for the first time by photo- and electro- induced reactions, allowing to obtain very useful information such as Λ -N interaction and weak interaction in the nuclear medium in a complementary way with respect to what can be done with hadron probes.

1. INTRODUCTION

One of the basic studies of strangeness nuclear physics is the study of hyperon-nucleon and hyperon-hyperon interaction which is one important place to check the QCD based models recently constructed to understand the nuclear force. The hyperon-nucleon interaction can be studied by hyperon-nucleon scattering experiments and also by spectroscopy of hypernuclei. Hypernuclei, resulting from bound hyperons, offer new degrees of freedom (flavour) so adding a new dimension to the evolving picture of nuclear physics[1–3]. They provide a laboratory in which properties of Λ -N interaction in the nuclear medium can be explored. Moreover one can treat the hyperon like a controlled "impurity" and employ it as a probe of the nuclear structure; in contrast with the nucleon the hyperon is not restricted by the Pauli principle and can penetrate deep inside the nucleus. It has been speculated in the past that changes from conventional predictions of such structure due to partial deconfinement of the quarks in the Λ may occur. Our present knowledge of hypernuclear states comes essentially from the strangeness exchange reactions induced by hadron probes. The advent of TJNAF beam and detectors allows for the first time the possibility of studying photo- and electro-production of hyperons both in elementary and nuclear processes. In the following sections we will briefly describe the hypernuclear

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physics program at TJNAF trying to show the advantages of this new experimental approach. A lot of experiments have been approved on electroproduction of strangeness at TJNAF. Many of them concern the elementary reaction on proton or its modification in the nuclear medium and will be the subject of other contributions. We will outline the approved experiments on bound states. We will start with one experiment on electroproduction on light nuclei (we have already some preliminary data), then we will speak about hypernuclear spectroscopy experiments and finally about the lifetime measurement of heavy hypernuclei.

2. ELECTROPRODUCTION OF KAONS AND LIGHT HYPERNUCLEI

Several experiments will study the $(e,e'K)$ reaction on proton; the “next step” is the investigation of this reaction in few body systems. In fact the study of two-body and few-body systems limits the complexity of possible interactions and offers the best chance to understand the features of hyperon-nucleon interaction in the nuclear medium and whether it is possible to calculate the physical properties of few body systems in terms of phenomenological hyperon-nucleon interaction without including explicit quark-gluon degrees of freedom.

These problems will be addressed by the PR-91-016 experiment[4] in Hall C. A careful study of electroproduction of kaons on deuterium will provide important information about the K -nucleon- Y coupling constants (Y is either Λ or Σ) and a unique method for studying the Y -neutron interaction which is poorly understood.

The measurement scans the cross section of the $D(e,e'K)$ reaction as a function of missing mass in the region between the Λ and the Σ_0 . Here the amplitudes for production of the two hyperons are expected to interfere, producing a cusp that has been predicted[5] and seen in $D(\pi^+, K^+)$ and $D(K^-, \pi^-)$ reactions [7]. The electromagnetic study of the shape of the cusp will possibly give information about the relative phase of the production amplitudes. Another goal of the experiment is to look for narrow structures predicted near Σ - N threshold [7]. There have been attempts to interpret the bumps seen in the experiments involving hadronic production as dibarions [8].

The experiment will look also at bound hypernuclear states that can be produced by $(e,e'K)$ reactions on ^3He and ^4He . There are two bound states in $^4\text{He}_\Lambda$ hypernucleus: a 0^+ ground state, Λ binding energy of 2.04 MeV, that should be very weakly excited in $(e,e'K)$ reactions and sensitive to variation in the elementary amplitudes and a 1^+ state at an excitation energy of 1.04 MeV that is expected to have a relatively large cross section [2]. Investigations of the bound state angular distributions in the previously unstudied $\text{He}(e,e'K)$ reactions should provide tests of the wave functions used to describe these states. Since the location of the unbound $3/2^+$ state is important in evaluating model calculations, the missing mass spectrum for the hypertriton will be examined carefully to see if there is evidence for low-lying unbound states [9].

Another goal of the experiment is the eventual confirmation of the controversial narrow Σ state peak that has been seen with hadronic probes, both for ^3He and for ^4He [10]. The experiment is started, data have been taken on proton and deuterium; ^3He and ^4He parts will be done later on, when the target will be available. Some very preliminary data on deuterium is already available (figure 1); the Λ (~ 2.1 GeV) and Λ (~ 2.2 GeV) are

Figure 1. (a) Cross section for the $D(e, e'K)$ reaction (see [5]); (b) very preliminary data (see [6]). The Λ (~ 2.1 GeV) and Σ (~ 2.2 GeV) are clearly visible.

clearly visible as well as, at this very preliminary stage, some “shoulder” around 2.14 and 2.17 GeV. The experiment is being done in Hall C. Electrons and kaons will be detected by HMS and SOS: the flux of virtual photons is maximized at forward angles since the minimum HMS angle (12.5 deg) will be used for electrons and kaons (kaons detection in the same direction of virtual photons). The kaons angular distribution will be measured by changing the SOS angle.

3. HIGH RESOLUTION HYPERNUCLEAR SPECTROSCOPY

One of the most important aims of the spectroscopic studies is the investigation of the hyperon-nucleon interaction through the structure of Λ hypernuclei [10]. Important information on the spin dependence of the effective Λ -N interaction can be obtained from the energy splitting of hypernuclear spin doublets. In fact the energy spectrum can be calculated from the effective Λ -N interaction potential which can be written as a sum of five terms: a central part, a spin-spin interaction term, Λ - and N-spin-orbit interactions and a tensor part. The doublet splitting is mainly determined by the spin-spin, Λ -spin-orbit and tensor terms, while the N-spin-orbit part mainly affects the spacing between doublets. The doublet splitting are expected to be very small, so energy resolution is essential. In the (K^-, π^-) , (π^+, K^+) the energy resolution of both processes is typically of the order of 2 MeV, a value which is much greater than characteristic spin doublet splitting. The $(e, e'K^+)$ reactions are expected to provide a useful alternative to these reactions since it excite both natural and unnatural parity hypernuclear states with comparable strength. Although many theoretical predictions have been carried out

for hypernuclear production by the $(e, e'\text{K}^+)$ and (γ, K^+) reactions, no experimental data have been reported so far. Only the electromagnetic (electro- and photo-) production of strangeness on the electron beam of TJNAF quality (high intensity and very good energy resolution) affords the possibility to obtain the high resolution (some hundredth of keV) data on hypernuclear spectra. Moreover the electromagnetic production of $\text{K}^+\Lambda$ pair is on the proton not on the neutron as in the hadronic production, making possible to study the hypernuclei non available otherwise (${}^7\text{He}_\Lambda, {}^9\text{Li}_\Lambda$).

Two experiment have been proposed (and approved) at TJNAF on hypernuclear spectroscopy: the 89-009 in Hall C [11] and the 94-107 in Hall A[12] The physics is essentially the same but the experimental technique to maximize the cross sections and the energy resolution is different.

The PR-89-009 experiment plans to use a 1.8 GeV electron beam and a dedicated Enge split pole magnet to detect low energy scattered electrons at zero degrees and the SOS spectrometer with about 1.2 MeV resolution for kaons. A “splitting magnet” will be used at the target to peel off the electrons and kaons to large enough angles to enter the spectrometers. A recent better evaluation of the Hall C spectrometer optics seems to show that it will be possible to get missing mass resolutions as good as ~ 650 keV [17].

The PR-94-107 experiment will make use of the Hall A HRS2 high resolution spectrometers. To obtain maximum cross-section one has to keep the electron scattering angle as small as possible (large virtual photon flux) and kaon scattering angle close to the virtual photon direction $\theta_K = \theta_\gamma$. To keep $\theta_\gamma < 10$ deg and $|\theta_K - \theta_\gamma| < 10$ deg, $\theta_\gamma < 10$ deg is a crucial requirements (6° is sufficient). Moreover, to first produce and then keep a reasonable kaon survival fraction, the particles momenta have to be fairly high (~ 1.8 GeV/c for the electrons and ~ 2 GeV/c for the kaons). The angular acceptance should be ~ 4.5 mrad to keep the solid angle of the spectrometer reasonable. The doublet splitting is very narrow, good resolution in missing mass is needed, so the momentum resolution should be as small as possible ($1. \times 10^{-4}$). For this reason two septum magnets have been designed to allow experiments using scattering angles as low as 6° , while keeping the performance of the HRS2 spectrometers essentially unchanged [13,14]. This, along with the quality of the TJNAF beam [14], will make possible to identify bound hypernuclear levels with an energy resolution of the order of ~ 350 keV. In figure 2 we report the projected CEBAF data for the ${}^{12}\text{C}(e,e'\text{k}){}^{12}\text{B}_\Lambda$ reaction. A comparison with the spectrum recently obtained at KEK [15] is also given where two more peaks appear in the spectrum with respect to the previous mesurement with lower energy resolution (4 MeV). The figure shows clearly the much greater reachness of information achievable in Hall A at CEBAF.

4. DIRECT MEASUREMENTS OF THE LIFETIME OF HEAVY HYPERNUCLEI AT TJNAF

The free Λ hyperon lifetime is determined by its pion-mesonic decay. This decay mode is characterized by a small pion momentum (~ 100 MeV/c), which is smaller than the typical nuclear Fermi momentum: thus the pionic decay modes are severely inhibited by Pauli blocking in the final-state nucleons in all but the lightest hypernuclei. On the other hand, non-mesonic weak decays can occur in the nuclear medium via a two-body weak interaction with a nucleon, $\Lambda + n \rightarrow n + n + 176$ MeV and $\Lambda + p \rightarrow n + p + 176$ MeV.

Figure 2. (a) Recent KEK data taken from [15]; (b) CEBAF proposed experiment on $^{12}\text{C}(e, e'K)^{12}\text{C}_{\Lambda}$ together with the projected experimental uncertainties

One should note that nonmesonic Λ decay, a strangeness changing weak interaction, takes place only in the nuclear medium and provides a unique opportunity to investigate the weak four-fermion vertex and that the large momentum transfer involved implies that the decay probes short distances associated with explicit subnucleonic degrees of freedom [1]. The lifetime of heavy hypernuclei can depend strongly on the behavior of this nonmesonic decay mode; in turn this nonmesonic decay mode in nuclear matter is strongly related to the effective Λ -N interaction range. The relative contributions of these two extremely different decay modes of the Λ in nuclear matter can depend on A , hence hypernuclear lifetimes can have an observable A dependence.

In a simple and naive picture, one would expect that the hypernuclear lifetime is smaller than the lifetime of a free Λ : the lifetime should decrease slowly as the atomic number increases (due to the suppression of the mesonic decay channel). If the Λ -N interaction has a very short effective range (relative to nuclear size) then one should observe a saturation effect in the A dependence of the hypernuclear lifetime. Most importantly, such a saturation effect will strongly appear in the region of heavy hypernuclei, where explicit quark effects may also appear. The partial width of the different decay mode channels as well as the A dependence of their parameters have been predicted by many theoretical models [17]. Very precise measurements of the mean lifetime of many hypernuclei are needed. The aim of the experiment 94-101 in Hall C [18] is to carry out a measurement of the lifetimes of different Λ hypernuclei (^{197}Au , ^{209}Bi , ^{64}Cu , ^{195}Pt and ^{238}U) produced in the (γ, K^+) reaction using virtual photons from forward scattering of unobserved outgo-

ing electrons. Kaons will be detected at small angles (12.5 deg) in the kinematical region corresponding to the high energy part of the photon spectrum (to keep hypernuclear excitation energies as low as possible). The lifetime of the produced hypernuclei will be measured directly from the time delay between the electron beam pulses (tagged by K^+ mesons) and the nuclear fission fragments. The unique time structure of the TJNAF beam (1.67 ps bunch width and ~ 2 ns bunch spacing) will provide the time-zero information and is very suitable for the hypernuclei lifetime range (0.1–1 ns). A low pressure multiwire proportional chamber (LPMWPC), which is only sensitive to the fission products with Z much higher than alpha particles, will be utilized to detect the so-called delayed fission fragments produced by the decay of heavy hypernuclei. The accuracy will be ~ 20 ps.

5. CONCLUSIONS

The hypernuclear physics experiments with electromagnetic probe are possible for the first time due to the TJNAF beam quality and spectrometer expected performances. This will allow for the first time access to hypernuclear levels difficult or impossible to reach by pseudoscalar mesons induced reactions. One should note that the different production mechanisms are complementary and are required for a complete study of hypernuclear spectra. Important information will be available soon from TJNAF experiments about the $A-N$ interaction in the nuclear medium from electro and photo-production on light nuclei and from a “complete” study of high resolution 1p shell hypernuclear spectroscopy. Important information on weak interactions in the nuclear medium will be obtained by studying the mesonic versus non mesonic decays in heavy nuclei.

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