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Nuclear Physics A 914 (2013) 23–33
NUCLEAR PHYSICS A
www.elsevier.com/locate/nuclphysa

Structure and production of medium-mass hypernuclei

T. Motoba

Laboratory of Physics, Osaka Electro-Communication University, Neyagawa, Osaka 572-8530, Japan

Received 31 December 2012; received in revised form 30 January 2013; accepted 31 January 2013

Available online 16 February 2013

Abstract

Based on the recent progress in high-resolution spectroscopy using electromagnetic hypernuclear production, the prospects for medium-heavy hypernuclear spectroscopy are discussed. Updated theoretical excitation spectra calculated in the DWIA framework are presented for the typical medium-mass targets ^{19}F, ^{28}Si, ^{40}Ca, and ^{52}Cr. Because the spin-flip interaction is dominant in the elementary kaon photo-production amplitudes, and also the momentum transfer is large enough, the selective excitation of unnatural parity highest-spin states (natural parity ones for the LS-closed targets) is clearly demonstrated. These aspects provide unique opportunities to investigate series of Λ single-particle energies in the medium-heavy mass region that has not yet been explored with sub-MeV energy resolution.

Keywords: Hypernuclei; Photo-production; Kaon-wave distortion; Hyperon single-particle energy

1. Introduction

Some of the most exciting progress in recent hypernuclear reaction spectroscopy has been driven by the high-energy and high-intensity electron beams that have become available at the Thomas Jefferson National Accelerator Facility (JLab). In fact, the first experiment on a p-shell target, $^{12}\text{C}(e, e'K^+)^{12}_{\Lambda}\text{B}$, was successfully carried out [1,2]. Following the Hall C experiments with ^{12}C [1], new experimental data with higher-energy electron beam at Hall A were recently reported for many p-shell nuclear targets up to ^{16}O [3–5]. It is remarkable that the energy resolution achieved in these experiments is close to 0.5 MeV which manifests great progress when compared with the best energy resolution ($\simeq$1.2 MeV) achieved so far in the (π^+, K^+) reaction [6,7].

E-mail address: motoba@isc.osakac.ac.jp.

0375-9474/$ – see front matter
http://dx.doi.org/10.1016/j.nuclphysa.2013.01.084

The $(e,e'K^+)$ process is also unique in that a proton in the nucleus is converted to Λ hyperon involving a sizable momentum transfer.

On the theory side, (γ,K^+) spectra were predicted many years ago for ^{10}B, ^{12}C, and ^{16}O targets [8], and also $(e,e'K^+)$ spectra for ^{7}Li, ^{9}Be, ^{12}C, and ^{16}O targets [9]. Among others, the predictions for the case of ^{12}C and ^{16}O targets were remarkably confirmed by the pioneering JLab experiments. The good theory versus experiment agreement encourages us to extend applications of the theoretical framework to the production of heavier hypernuclei beyond the p-shell. In fact, the pioneering experimental proposals were made a long time ago [10–12], and actually the hot data for one of those experiments, the $^{28}\mathrm{Si}(e,e'K^+)^{28}_{\Lambda}\mathrm{Al}$ case, have appeared quite recently [13]. We note that the JLab facility will provide new opportunities with upgraded electron beams and that the new Mainz facility has already taken data [14].

Given this progress, our major purpose is to provide theoretical excitation spectra for typical medium-mass targets, following Refs. [17,18], in order to show feasibility of spectroscopic studies for heavier hypernuclei. Because of the new experimental report [13], the present paper also deals with an important update of Λ single-particle energies which are closely related to the nature of realistic effective ΛN interactions, such as the Nijmegen models.

2. Brief description of the calculational framework

The hypernuclear photo-production cross section is expressed in DWIA as

$$\frac{d\sigma}{d\Omega}\left(\theta_K^{\mathrm{L}}\right)=\frac{s p_K^2 E_K E_H}{p_K(E_H+E_K)-E_\gamma E_K\cos\theta_K^{\mathrm{L}}}\sum_{M_f}R(fi;M_f), \tag{1}$$

where p_K and E's are the momentum and energies in the A-body laboratory frame, and s is square of the sum of the γ and proton energies in the C.M. system. $R(fi;M_f)$ is the transition matrix element defined as

$$R(fi;M_f)=\frac{1}{2J_i+1}\sum_{M_i}\left|\langle J_f M_f T_f \tau_f|\mathcal{O}|J_i M_i T_i \tau_i\rangle\right|^2. \tag{2}$$

Here, the magnetic subspace quantum number M_f in final hypernuclear state is kept explicitly so as to be convenient for estimates of hypernuclear polarization [19].

The transition operator $\mathcal{O}$ for the $p(\gamma,K^+)\Lambda$ reaction is written in terms of the elementary amplitudes (t-matrix) as

$$\mathcal{O}=\int d^3\mathbf{r}\,\chi_K^{(-)*}(\mathbf{p},\xi\mathbf{r})\chi_\gamma^{(+)}(\mathbf{k},\mathbf{r})\sum_{\nu=1}^{A}V_-^{(\nu)}\delta(\mathbf{r}-\eta\mathbf{r}_\nu)\langle\mathbf{k}-\mathbf{p},\mathbf{p}|t|\mathbf{k},0\rangle_{2\mathrm{Lab}}, \tag{3}$$

where $\xi=M_{\mathrm{A}}/M_{\mathrm{H}}$ and $\eta=(M_{\mathrm{H}}-M_{\mathrm{A}})/M_{\mathrm{A}}$ are introduced to take recoil into account. For the K^+ distorted waves, the partial-wave solutions of the Klein–Gordon equation are adopted. In the present calculation, we use the elementary amplitudes from the Saclay–Lyon A model (SLA) [20].

The transferred momentum in the photo-production runs from $q_\Lambda^{(\gamma,K)}=350$ MeV/c at $\theta_K^{\mathrm{Lab}}=0°$ to 430 MeV/c at 10° which is comparable to $q_\Lambda^{(\pi,K)}$. This fact leads to the remarkable selectivity in exciting hypernuclear high-spin states. Secondly, it should be emphasized that the elementary $\gamma p\to\Lambda K^+$ transition amplitudes are characterized by spin-flip dominance.