# Core-Excited States of $^{12}_{\Lambda}$C Hypernuclei Formed in the $(\pi^+, K^+)$ reaction

T. Hasegawa,[1] O. Hashimoto,[1] S. Homma,[1] T. Miyachi,[1] T. Nagae,[1] M. Sekimoto,[1] T. Shibata,[1] H. Sakaguchi,[2] T. Takahashi,[2] K. Aoki,[3] H. Noumi,[3] H. Bhang,[4] M. Youn,[4] Y. Gavrilov,[5] S. Ajimura,[6] T. Kishimoto,[6] A. Ohkusu,[6] K. Maeda,[7] R. Sawafta,[8] and R. P. Redwine[9]

[1]*Institute for Nuclear Study (INS), University of Tokyo, Tanashi, Tokyo 188, Japan*
[2]*Department of Physics, Kyoto University, Kitashirakawa, Sakyo-ku, Kyoto 606, Japan*
[3]*National Laboratory for High Energy Physics (KEK), Oho, Tsukuba, Ibaraki 305 Japan*
[4]*Department of Physics, Seoul National University, Seoul 151-742, Korea*
[5]*Institute for Nuclear Research, Academy of Science, 117312 Moscow, Russia*
[6]*Department of Physics, Osaka University, Toyonaka, Osaka 660 Japan*
[7]*Department of Physics, Tohoku University, Kawauchi, Sendai, Miyagi 980-77 Japan*
[8]*Physics Department, Brookhaven National Laboratory, Upton, New York 11973*
[9]*Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*

(Received 5 July 1994; revised manuscript received 7 September 1994)

A spectroscopic study of the $^{12}_{\Lambda}$C hypernucleus by the $(\pi^+, K^+)$ reaction has been performed using a new superconducting kaon spectrometer (INS-SKS) at the KEK 12 GeV Proton Synchrotron with an energy resolution of 2 MeV (FWHM). In addition to two prominent peaks which correspond to the $s$ and $p$ orbitals of a $\Lambda$ hyperon, for the first time two smaller peaks were clearly observed at excitation energies of 2.6 and 6.9 MeV. These two peaks are interpreted as states where the $^{11}$C excited core and a $\Lambda$ hyperon in the $s$ orbit are weakly coupled. The excitation energies and the cross sections of these peaks provide information on the $\Lambda N$ interaction.

PACS numbers: 21.80.+a, 25.80.Hp

Spectroscopy of hypernuclei provides invaluable information on hadronic many-body systems and on the nature of hadronic interactions in the nucleus. One of the most important aims of spectroscopic studies is the investigation of the hyperon-nucleon interaction through the structure of hypernuclei. Since it is not easy to obtain hyperon beams, investigation of the hyperon-nucleon interaction by means of hypernuclear spectroscopy has great importance. In particular, $\Lambda$ hypernuclei afford promising opportunities for investigation because narrow intrinsic widths of their bound states are expected.

Recently, a new generation of hypernuclear experiments has started using the $(\pi^+, K^+)$ reaction, in which high-spin bound states of $\Lambda$ hypernuclei are preferentially populated due to the large momentum transfer. The BNL group [1,2] first demonstrated $\Lambda$ hyperon shell structure in $\Lambda$ hypernuclei from $^{9}_{\Lambda}$Be to $^{89}_{\Lambda}$Y in the $(\pi^+, K^+)$ reaction; later $^{12}_{\Lambda}$C and $^{56}_{\Lambda}$Fe were also studied at the KEK 12 GeV Proton Synchrotron (PS) [3]. Those experiments, together with recent theoretical investigations [4–6], have established the value of the $(\pi^+, K^+)$ reaction for studying bound states of $\Lambda$ hypernuclei.

An intensive shell model analysis of $\Lambda$ binding energies for $p$-shell hypernuclei was carried out using 12 binding energy data available at that time by Gal, Soper, and Dalitz [7]. A comprehensive shell-model approach was developed for $p$-shell $\Lambda$ hypernuclei produced by the $(K^-, \pi^-)$ reaction [8]. Spin dependence of the $\Lambda N$ effective interaction was further examined with more data in the same framework [9]. Recently, the hyperon-nucleon interaction has been theoretically investigated based on meson-exchange models and quark models. Among them, phenomenological interaction models by the Nijmegen group [10] and by the Jülich group [11] provide the basis for calculating hypernuclear structures starting from the two-body interaction in free space. Using these interactions, $\Lambda$ hypernuclear properties were calculated with a $G$-matrix method and various interaction models were compared to each other [12,13]. The $^{16}_{\Lambda}$O $\Lambda$ hypernuclear structure was also studied using the Jülich potentials [14]. The spectroscopic data of hypernuclei now can be used to impose strong constraints on the framework of the $\Lambda N$ interaction. In this regard, high-quality spectroscopy with good energy resolution is greatly needed for investigation of bound hypernuclear states.

Intending to take full advantage of the $(\pi^+, K^+)$ reaction, a superconducting kaon spectrometer system (INS-SKS) [15] has been constructed at the KEK 12 GeV PS, and a spectroscopic study of $\Lambda$ hypernuclei has been conducted. The present Letter reports on a high-quality $^{12}_{\Lambda}$C hypernuclear spectrum with a better than 2 MeV (FWHM) resolution and discusses its relevance to the $\Lambda N$ interaction.

A 1.06 GeV/$c$ pion beam was delivered to a 0.89 g/cm$^2$ natural carbon target at the K6 beam channel located in the north experimental area of the KEK 12 GeV PS. The pion beam intensity was typically $3 \times 10^6$/spill, where a spill interval was 4 s and its duration 1.2 s. The present spectrometer system consists of two independent spectrometers as shown in Fig. 1: one a beam spectrometer that measures incident pion momentum particle by particle and the other a scattering particle spectrometer (SKS) which deter-

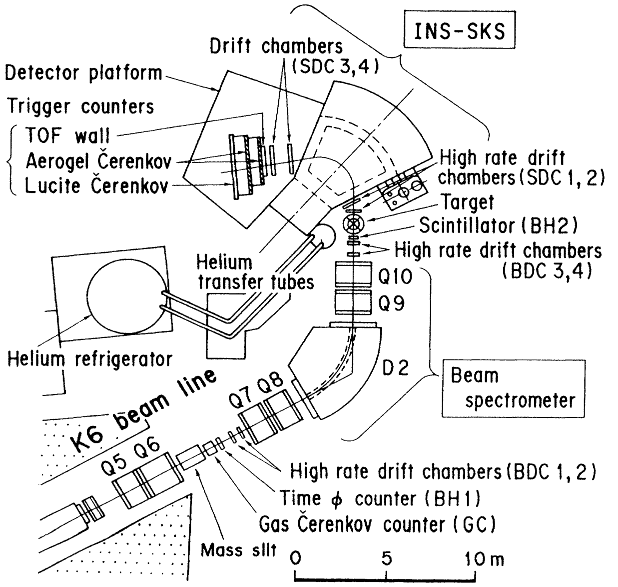

FIG. 1. Experimental setup of the SKS spectrometer system.

mines the momenta of kaons from the target. The beam spectrometer is comprised of a QQDQQ optical system, timing counters, and drift chambers. The drift chambers, with 2.5 mm cell size, measure beam particle trajectories with $\sigma \approx 250$ $\mu$m position resolution for a beam rate up to several times $10^6$ Hz. The SKS spectrometer consists of a large superconducting dipole magnet, drift chambers, and trigger counters. The superconducting magnet [16], which has large bending power (100 deg for 0.72 GeV/$c$) and a wide aperture, is indispensable for simultaneously achieving large acceptance and good momentum resolution for study of hypernuclear levels. The spectrometer was positioned at 0 deg and covered $\pm 15$ deg horizontally and $\pm 5$ deg vertically, corresponding to a solid angle of 100 msr. Two layers of aerogel Cerenkov counters ($n = 1.06$) [17], which were sensitive to pions but not to kaons in the relevant momentum region around 0.7 GeV/$c$, played an essential role in the identification of kaons at the trigger stage.

In Fig. 2, the measured ${}^{12}_{\Lambda}$C hypernuclear spectrum is plotted as a function of $M_{\mathrm{HY}} - M_A$, where $M_{\mathrm{HY}}$ and $M_A$ stand for ${}^{12}_{\Lambda}$C and ${}^{12}$C masses. The scale for $\Lambda$ binding energy, referencing ${}^{11}$C ground state, and that for ${}^{12}_{\Lambda}$C excitation energy are also indicated in the figure. The absolute scale was adjusted so that the $\Lambda$ binding energy of the ${}^{12}_{\Lambda}$C ground state was 10.76 MeV. In the spectrum, two prominent peaks and two smaller ones were observed together with the quasifree contribution in the unbound region. The prominent peaks were already reported in previous $(\pi^+, K^+)$ experiments [1–3]. These peaks correspond to states in which a $\Lambda$ hyperon in an $s$ or $p$ orbital couples with the ${}^{11}$C ground state. The ground state $s_\Lambda$ peak is assumed to be much narrower than the present experimental resolution, and the energy resolution of the spectrum is thus evaluated to be $1.9 \pm 0.1$ MeV (FWHM). The spectrum was fitted assuming four Gaussian peaks and a quasifree contribution in the unbound region. The quasifree contribution was fitted with a quadratic function rising from $\mathrm{B}_\Lambda = 0$ MeV by convoluting the experimental resolution. Cross sections integrated from 2 to 14 deg corrected for the angular dependence of the spectrometer acceptance were deduced after estimating the total number of pions, thickness of the target, detector efficiencies, analysis efficiencies, decay-in-flight correction of kaons, and dead time of data taking. The excitation energies and the integrated cross sections of these four peaks are summarized in Table I, where only statistical errors are quoted. The differential cross sections of the ground state at 10 and 3 deg, where the BNL [2] and KEK [3] experiments were carried out, can be estimated to be 5.8 $\mu$b/sr and 10.2 $\mu$b/sr from the present one, assuming the angular distribution of the kaons calculated by Itonaga *et al.* [18]. It is to be remembered, however, that the cross sections of the ground state in the previous experiments were obtained from the spectra which could not resolve the smaller peak No. 2. Those values may be better compared with the summed cross section of the No. 1 and No. 2 peaks of the present spectrum.

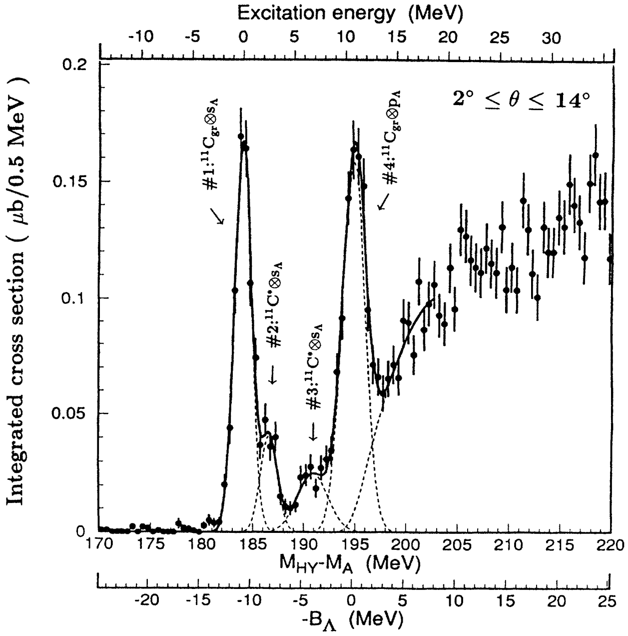

FIG. 2. Excitation spectrum of ${}^{12}_{\Lambda}$C observed in the $(\pi^+, K^+)$ reaction at $p_\pi = 1.06$ GeV/$c$ using the SKS spectrometer. The vertical scale gives a cross section integrated from 2 to 14 deg after correcting the angular dependence of the spectrometer acceptance. The energy resolution is better than 2.0 MeV.

Since a $\Lambda$ hyperon couples weakly to the nuclear core due to weakness of the $\Lambda N$ interaction, the ${}^{12}_{\Lambda}$C hypernuclear states are expected at excitation energies

TABLE I. Excitation energies and cross sections for ${}^{12}_{\Lambda}$C hypernuclear states measured in the $(\pi^+, K^+)$ reaction at $p_\pi = 1.06$ GeV/$c$. The cross sections are those integrated from 2 to 14 deg by correcting the spectrometer angular acceptance.

| Peak | State assignment | $M_{\text{HY}} - M_A$ (MeV) | Excitation energy (MeV) | Peak width (MeV) | Integrated cross section ($\mu$b) ($2^\circ \le \theta \le 14^\circ$) |
|---|---|---|---|---|---|
| No. 1 | $1_1^-$ | 184.02 | 0 | 1.9 ± 0.1 | 0.69 ± 0.04 |
| No. 2 | $(1_2^-)$ | 186.60 | 2.58 ± 0.17 | 1.9 ± 0.1 | 0.17 ± 0.02 |
| No. 3 | $(1_3^-)$ | 190.91 | 6.89 ± 0.42 | 3.5 ± 0.9 | 0.19 ± 0.02 |
| No. 4 | $2^+$ | 194.70 | 10.68 ± 0.12 | 2.6 ± 0.2 | 0.88 ± 0.06 |

close to corresponding states of the core nucleus ${}^{11}$C. The observed excitation energies of the two peaks are close to those of $1/2^-$ and $3/2_1^-$ states of the ${}^{11}$C core, as illustrated in Fig. 3. In addition, the cross sections of $\Lambda$ hypernuclear states are to first order proportional to the $p_{3/2}$ or $p_{1/2}$ neutron hole strengths of the core ${}^{11}$C nucleus, since the $(\pi^+, K^+)$ reaction populates $\Lambda$ hypernuclear states having a neutron-hole $\Lambda$-particle configuration. These ${}^{11}$C excited states are experimentally known to have $p_{3/2}$ neutron hole strengths of (10–25)% by neutron pickup reactions such as $(p,d)$ and $({}^3\text{He},\alpha)$ [19]. As seen in the table, the newly identified peaks at 2.6 and 6.9 MeV both carry intensities about 25% of those of the ground state peak, similar to the spectroscopic factors of the $1/2^-$ and $3/2_2^-$ states in ${}^{11}$C. Considering the excitation energies and cross sections of the two small peaks, the peaks can be interpreted as corresponding to states in which a $\Lambda$ hyperon in the $s$ orbital and the ${}^{11}$C excited states at 2.0 MeV ($1/2^-$) and 4.8 MeV ($3/2_2^-$), are weakly coupled. Furthermore, the observed spectrum was found in agreement with a recent distorted wave impulse approximation calculation [18], both for the prominent and for the smaller peaks. Spin-parities of the states corresponding to the two small peaks were tentatively assigned, based on the comparison of the present spectrum with the calculated one and the above considerations.

Core-excited hypernuclear states in ${}^{12}_{\Lambda}$C were not seen in a previous experiment using the $(K^-, \pi^-)$ reaction [20], but were later reported in the stopped $(K^-, \pi^-)$ reaction on ${}^{12}$C [21]. The $1_2^-$ and $1_3^-$ core excited states were also assumed in order to account for excess yield between the two prominent peaks in the $(\pi^+, K^+)$ reaction [22]. The present spectrum establishes the two peaks at 2.6 and 6.9 MeV excitation energies. However, the excitation energies of the $1_2^-$ and $1_3^-$ states are considerably higher than those expected in the limit of weak coupling. The deviation is thought to be due to the $\Lambda N$ interaction or to a new mechanism that excites other hypernuclear states around those energies. It was pointed out that the excitation energies of the $1^-$ states depended on the $\Lambda NN$ parameters [7]. We note, however, that it is not easy to explain these high excitation energies by the "standard parameters" for the $\Lambda N$ interaction, with which $p$-shell hypernuclei were intensively investigated based on realistic shell-model wave functions [9,23].

Recently, production and structure of $p$-shell $\Lambda$ hypernuclei by the $(\pi^+, K^+)$ and $(K^-, \pi^-)$ reactions was investigated by Itonaga *et al.* [18] with configuration-mixed shell model wave functions. They calculated the hypernuclear properties by diagonalizing the Hamiltonian $H = H_N^{(\text{Cohen-Kurath})} + t_\Lambda + \xi l_\Lambda \cdot s_\Lambda + \sum v_{\Lambda N}$, which consists of the Cohen-Kurath interaction, the $\Lambda$ kinetic energy, the $\Lambda$ spin-orbit potential, and the $\Lambda$-nucleon potential and obtained good agreement with recent experimental data. The calculation adopted the $\Lambda$-nucleon potential constructed from a phenomenological hyperon-nucleon interaction (Nijmegen D). Properties of light $\Lambda$ hypernuclei were further studied using different hyperon-nucleon interactions such as Jülich A (JA), Jülich B (JB), Nijmegen F (NF), and Nijmegen soft core (NSC) interactions [13]. These investigations revealed that spectroscopic properties of $\Lambda$ hypernuclei strongly depend on the choice of interaction model. Such an investigation was recently performed for the ${}^{12}_{\Lambda}$C hypernucleus, and cross sections and excitation energies of the $1_2^-$ and $1_3^-$ states were calculated with the four model interactions [24]. The cross sections with the JA, NF, and NSC interactions were comparable with the present values, but those with JB resulted in unreasonably large values. On the other hand, the result with the JA, JB, and NF interactions gave almost unity for ratios between excitation energies of the ${}^{12}_{\Lambda}$C core excited states and those of corresponding ${}^{11}$C excited states, while the NSC potential resulted in relatively large ex-

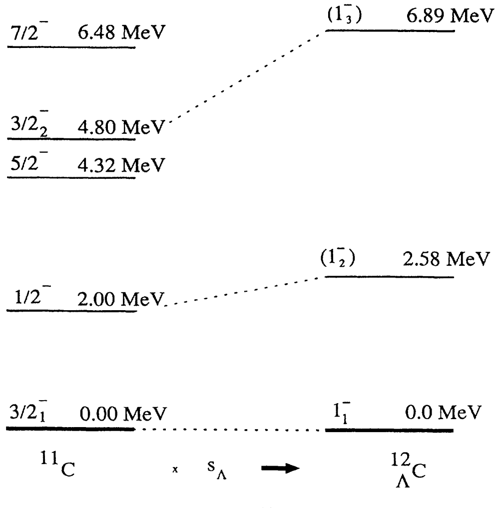

FIG. 3. Correspondence of the ${}^{11}$C energy levels and observed ${}^{12}_{\Lambda}$C hypernuclear states based on weak coupling of a $\Lambda$ hyperon to the nuclear core.

citation energies consistent with the present experimental values. This may be due to a large ratio of spin-singlet to spin-triplet strength, which characterizes the NSC potential compared with the other models. The large excitation energies seem to favor stronger spin-singlet strength of the $\Lambda N$ interaction. This is in accord with the fact that the ground states of ${}^{4}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{He}$ have spin-parity $0^+$.

The 6.9 MeV peak could be composite in view of its width, which is broader than the instrumental resolution. A possible ${}^{12}_{\Lambda}\mathrm{C}$ hypernuclear state that corresponds to the 6.48 MeV $7/2^-$ state in ${}^{11}\mathrm{C}$ can be a candidate for strength in addition to that of the $1_3^-$ state. For example, the $7/2^-$ state could be connected to the $3^-$ state of ${}^{12}_{\Lambda}\mathrm{C}$ at around 6 MeV excitation if $f_{7/2}^{-1}$ neutron hole strength in that state is large enough or if a two-step reaction that involves collective excitation plays a considerable role in the $(\pi^+, K^+)$ reaction. It would be a future issue, however, whether such a process contributes to the extra intensity comparable to that of the $1_3^-$ state. If we consider this large width as due to compositness of two equal-strength peaks, the $1_3^-$ excitation energy could be either lowered or raised by 0.7 MeV from the value quoted in the table.

The width of the No. 4 peak is found to be broader than the spectrometer resolution. This observation is consistent with a theoretical calculation that predicts excitation of $2_1^+$ (10.0 MeV), $3_1^+$ (10.1 MeV), $2_2^+$ (10.6 MeV), $0_1^+$ (10.9 MeV), and $2_3^+$ (11.8 MeV) states by the $(\pi^+, K^+)$ reaction [18]. Since the $2_1^+$ and $2_2^+$ states are predicted to be predominant among them with almost equal strengths [18], the No. 4 peak was fitted assuming two Gaussians with equal intensity and the 2 MeV resolution. The level spacing between the two $2^+$ states in the peak was then derived to be $1.2 \pm 0.5$ MeV under the above assumption. The two $2^+$ states have configurations of either ${}^{11}\mathrm{C}(3/2_1^-) \otimes p_{3/2}^{\Lambda}$ or ${}^{11}\mathrm{C}(3/2_1^-) \otimes p_{1/2}^{\Lambda}$, respectively, and the splitting of these two states can be regarded as partly due to the spin-orbit interaction. The value is consistent with the difference between excitation energies of the two $2^+$ states that was obtained for ${}^{12}_{\Lambda}\mathrm{C}$ [25].

In summary, a high quality ${}^{12}_{\Lambda}\mathrm{C}$ hypernuclear spectrum with an energy resolution better than 2 MeV has been obtained for the first time. It clearly reveals core excited $\Lambda$ hypernuclear states, which can be interpreted as core excited ones of ${}^{12}_{\Lambda}\mathrm{C}$. The present data possibly impose constraints on the effective hyperon-nucleon potential. Further systematic spectroscopy of light $\Lambda$ hypernuclei with good resolution should further enhance and improve our knowledge of the $\Lambda N$ interaction and structure of $\Lambda$ hypernuclei.

The SKS spectrometer was constructed in collaboration with T. Kitami, Y. Matsuyama, T. Morimoto, and K. Omata (of INS) and with Prof. T. Shintomi, Prof. Y. Doi, Dr. M. Nomachi, Dr. O. Sasaki, Y. Makida, and Y. Kondo of KEK. We thank Prof. Y. Shida, Prof. F. Soga, Prof. T. Fukuda, and Y. Yamanoi for their contribution at the earlier stage of the construction. Intensive discussion with the late Prof. H. Bando, Prof. T. Motoba, Prof. K. Itonaga and Prof. Y. Yamamoto was indispensable for the present research. We are also thankful for critical reading of the manuscript by Dr. D. J. Millener. Continuous encouragement by Prof. T. Yamazaki, Prof. K. Nakai, Prof. J. Imazato, and Prof. T. Ohshima throughout the experiment is also greatly appreciated. The present research is partly supported by the US-JAPAN collaborative research program of the National Science Foundation and of the Japan Society for Promotion of Science.

[1] C. Milner *et al.*, Phys. Rev. Lett. **54**, 1237 (1985).
[2] P. H. Pile *et al.*, Phys. Rev. Lett. **66**, 2585 (1991).
[3] M. Akei *et al.*, Nucl. Phys. **A534**, 478 (1991).
[4] C. B. Dover, L. Ludeking, and G. E. Walker, Phys. Rev. C **22**, 2073 (1980).
[5] H. Bando and T. Motoba, Prog. Theor. Phys. **76**, 1321 (1986).
[6] T. Motoba, H. Bando, R. Wünsch, and J. Zofka, Phys. Rev. C **38**, 1322 (1988).
[7] A. Gal, J. M. Soper, and R. H. Dalitz, Ann. Phys. (N.Y.) **63**, 53 (1971); **72**, 445 (1972); **113**, 79 (1978).
[8] E. H. Auerbach, A. J. Baltz, C. B. Dover, A. Gal, S. H. Kahana, L. Ludeking, and D. J. Millener, Ann. Phys. (N.Y.) **148**, 381 (1983).
[9] D. J. Millener, A. Gal, C. B. Dover, and R. H. Dalitz, Phys. Rev. **31**, 499 (1985).
[10] Th. A. Rijken *et al.*, Nucl. Phys. **A547**, 245c (1992).
[11] K. Holinde, Nucl. Phys. **A547**, 255c (1992).
[12] Y. Yamamoto and H. Bando, Prog. Theor. Phys. Suppl. **81**, 9 (1985).
[13] Y. Yamamoto, A. Reuber, H. Himeno, S. Nagata, and T. Motoba, Czech. J. Phys. **42**, 1249 (1992).
[14] J. Hao, T. T. S. Kuo, A. Reuber, K. Holinde, J. Speth, and D. J. Millener, Phys. Rev. Lett. **71**, 1498 (1993).
[15] O. Hashimoto, T. Nagae, T. Fukuda, S. Homma, T. Shibata, Y. Yamanoi, T. Shintomi, J. Imazato, Y. Makida, T. Mito, and S. Kato, Nuovo Cimento Soc. Ital. Fis. **102A**, 679 (1989).
[16] T. Shintomi, K. Aoki, Y. Doi, Y. Kondo, Y. Makida, O. Hashimoto, T. Hasegawa, T. Kitami, T. Miyachi, T. Nagae, and M. Sekimoto, IEEE Trans. Magnetics, **MAG-28**, 585 (1992).
[17] T. Hasegawa, O. Hashimoto, T. Nagae, and M. Sekimoto, Nucl. Instrum. Methods. Phys. Res., Sect. A **342**, 383 (1994).
[18] K. Itonaga, T. Motoba, and H. Bando, Prog. Theor. Phys. **84**, 291 (1990); K. Itonaga, T. Motoba, O. Richter, and M. Sotona, Phys. Rev. C **49**, 1045 (1994).
[19] F. AjzenbergSelove, Nucl. Phys. **A506**, 1 (1990).
[20] R. Chrien *et al.*, Phys. Lett. **89B**, 31 (1979).
[21] H. Tamura, Doctorial thesis, University of Tokyo, UTPN-220 (1988).
[22] R. Chrien, in *Particle and Field Series 43—1990,* AIP Conf. Proc. No. 224 (AIP, New York, 1990), p. 28.
[23] V. N. Fetisov, L. Majling, J. Zofka, and R. A. Eramzhyan, Z. Phys. A **339**, 399 (1991).
[24] T. Motoba (private communication).
[25] R. H. Dalitz, D. H. Davis, and D. N. Tovee, Nucl. Phys. **A450c**, 311 (1986).