PHYSICAL REVIEW C VOLUME 51, NUMBER 4 APRIL 1995

Λ-nucleon interaction in nuclei probed by the quasifree $^{12}C(\pi^+, K^+)$ reaction

T. Kishimoto, S. Ajimura, H. Ejiri, F. Nakamura, H. Noumi,*
A. Higashi,† and G. Inoue
Department of Physics, Osaka University, Toyonaka, Osaka 560, Japan

D. R. Gill, L. Lee, A. Olin, and S. Yen
TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia, Canada V6T 2A3
(Received 4 October 1994)

It is shown that hypernuclei are produced in the quasifree region of the $^{12}C(\pi^+, K^+)^{12}_{\Lambda}C$ reaction where a free Λ is expected to be knocked out from a nucleus. The production ratio, which gives the Λ-nucleon cross section in a nucleus, was derived as a function of excitation energy of $^{12}_{\Lambda}C$. It is shown that the Λ-nucleon cross section in the nucleus has to be modified by both Pauli blocking and Fermi averaging to reproduce the observed ratio.

PACS number(s): 25.80.Hp, 21.80.+a, 27.20.+n

Hadron-nucleon (N) scattering in a nucleus may be different from that in free space. The Pauli principle gives strong reduction to the low-energy hadron-nucleon scattering cross section since a scattering where a final nucleon state is occupied is forbidden. This is less important for energetic incident particles where a scattered nucleon receives momentum much larger than the Fermi momentum (p_F). Actually, it is well known that the hadron-nucleus optical potential at high energy is given almost solely by the imaginary part which in turn is related to the total hadron-nucleon cross section in free space. Although a vast amount of data has been accumulated for reactions with nonstrange projectiles, little has been studied for strange particles. The exception is the kaon-nucleus interaction, since relatively intense kaon beams are available, and there have been intensive studies to probe the interior region of a nucleus by utilizing the relatively weak kaon-nucleon interaction [1].

The Λ hyperon presents an interesting and simple case for gaining understanding of such an effect since one does not have to consider the Pauli blocking for the projectile nor its annihilation, as is the case for nucleons or mesons. Recently, production of hypernuclei by GeV protons is being pursued. A Λ produced by the primary $N(p, K^+N)\Lambda$ reaction carries large momentum; thus it is trapped in a nucleus with very tiny probability by the single-step reaction. Abundant production of hypernuclei might be realized by a multistep process for which the ΛN scattering cross section in a nucleus is of primary importance [2]. Here we present a study of the ΛN total cross section in a nucleus through the formation of Λ hypernuclei with a Λ produced by the quasifree (QF) process in the $^{12}C(\pi^+, K^+)$ reaction. Preliminary results were presented partially elsewhere [3].

*Present address: Institute for Nuclear Study, Univ. of Tokyo, Tanashi, Tokyo 188, Japan.

†Present address: National Laboratory for High Energy Physics, Oho, Tsukuba, Ibaragi, Japan.

The (π^+, K^+) reaction has become popular for the study of hypernuclei since the reaction demonstrated the shell structure of the Λ single-particle orbitals [4–6] and the ability to produce the polarized hypernuclei [7, 8]. The large momentum transfer of the reaction ($\sim$ 0.4 GeV/c) gives a dominant share of the cross section to the high-excitation region where a Λ is knocked out from a nucleus by the so-called QF process. The experimentally measured excitation energy spectrum [6] and corresponding Λ polarization showed that the production of a free Λ characterizes the reaction mechanism of the QF region [8, 9]. However, a certain fraction of the Λ is trapped in a nucleus through the ΛN scattering in the QF region. Once hypernuclei are produced, they decay either by mesonic (M) decay or nonmesonic (NM) decay;

$$\text{M decay,} \qquad \Lambda \to p + \pi^-,\ n + \pi^0, \qquad (1)$$

$$\text{NM decay,} \qquad \Lambda + n \to n + n,\ \Lambda + p \to p + n. \qquad (2)$$

The M decay, which is simular to the free Λ decay, is suppressed in heavy hypernuclei by the Pauli blocking because of its small momentum transfer (~ 0.1 GeV/c $< p_F$). The large momentum transfer of the NM decay (~ 0.4 GeV/c $> p_F$) makes the Pauli blocking negligible; thus it is the major decay mode of hypernuclei heavier than mass number $\sim$7. The energy of a nucleon from the free Λ decay is generally much lower than that from the NM decay. Consequently, detection of the energetic nucleon, which is solely from the NM decay, is a genuine signal of the production of Λ hypernuclei.

We studied the ratio of Λ hypernuclei produced in the QF region of the $^{12}C(\pi^+, K^+)$ reaction by detecting protons from the NM decay. The experiment was carried out at the K2 beamline of the 12 GeV proton synchrotron at KEK (KEK-PS). The beam momentum was 1.05 GeV/c where the cross section of the elementary $n(\pi^+, K^+)\Lambda$ reaction is near its maximum. Kaons scattered at $\pm 14°$ were detected by the PIK spectrometer [10] to produce the polarized hypernuclei and to study their asymmetric weak decay [7, 8]. Since details of the experiment have been described elsewhere [7, 8], we present here only what is relevant for the present discussion.

Decay particles from the target (pions and protons) were detected in coincidence with the (π^+, K^+) reaction. They were detected by the counter system ROYAL [7, 8] which was sensitive to 10–50 MeV pions and 30–200 MeV protons emitted from the target. ROYAL consisted of two interchangeable symmetric counter systems above and below the target. It covers roughly half of the total solid angle. Each counter system consisted of 16 NaI detectors each of which was $81 \times 81 \times 76$ mm^3 and four slabs of plastic scintillator 5 mm thick placed in front of the NaI detector to give dE/dx information for particle identification. The plastic scintillator target covered an area of 60 (wide) $\times$ 20 (high) mm^2 with a thickness of 64 mm and was divided into two halves (an "upper" and "lower" half), each consisting of 32 segments of plastic scintillator to obtain better spatial resolution of the interaction vertex [11].

Figure 1(a) shows an excitation energy spectrum of the ^{12}C(π^+, K^+) at $P_\pi = 1.05$ GeV/c, where no correction for the spectrometer acceptance has been made, since the spectrum shape has already been discussed [6] and is irrelevant to the present argument. The broad bump in the spectrum corresponds to the quasifree production of Λ from ^{12}C.

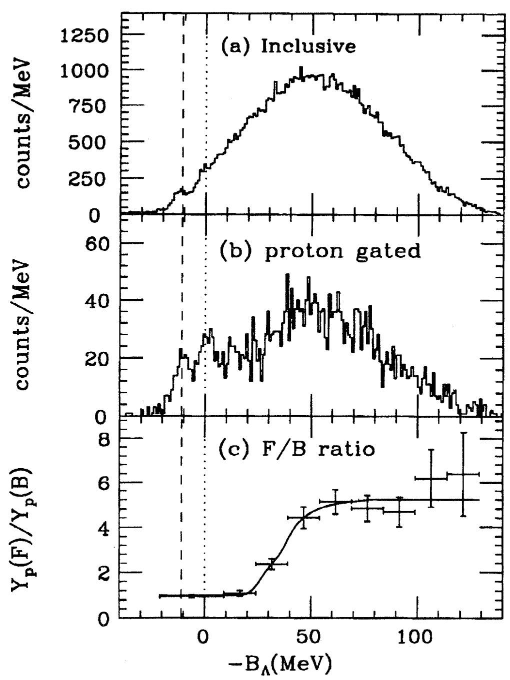

FIG. 1. (a) Excitation energy spectrum of the ^{12}C(π^+, K^+) reaction at $\theta_K = 14°$ obtained from bombardment of the scintillator target by 1.05 GeV/c pions. Horizontal axis represents binding energy of Λ. (b) The spectrum gated by decay protons whose energy is higher than 45 MeV. (c) Shown is the ratio of proton yields emitted forward and backwards where proton energy is higher than 45 MeV. Solid line represents the F/B ratio used to obtain NM decay protons from Fig. 1(b). Dashed and dotted lines represent the position of the ground state ($^{12}_{\Lambda}$C) and the substitutional state (^{11}B), respectively.

Figure 1(b) shows the excitation energy spectra gated by decay protons whose energy is higher than 45 MeV, an energy above which protons are expected to be primarily from the NM decay [7]. Peaks of the $^{12}_{\Lambda}$C ground state and the substitutional state are enhanced in the proton gated spectrum. Since the bound region consists exclusively of hypernuclei, the enhancement shows a large branching ratio of the NM decay which is consistent with previous works [12, 13] and that we derived from the data [14]. One sees an appreciable number of protons in the QF region, which indicates the production of hypernuclei through ΛN scattering in a nucleus.

Energetic protons may not be solely from the NM decay of hypernuclei. Protons from the M decay of the Λ produced by the QF process can be detected by ROYAL due to transverse momentum given by the nucleon Fermi motion and momentum released by the decay. Also, the Λ knocks out protons in a nucleus which may hit ROYAL. In these cases energetic protons are detected even though no hypernuclei are produced. These processes depend on the high-momentum tail of the nucleon Fermi motion and on the ΛN scattering cross section; thus a quantitative estimate is not straightforward. It is, however, found that no energetic protons are emitted backwards because of the large momentum transfer of the (π^+, K^+) reaction (~ 0.4 GeV/c) in the forward direction. On the contrary, protons from the NM decay are emitted isotropically. Figure 1(c) shows the forward to backward (F/B) ratio of the protons observed by ROYAL. The ratio is found to be unity in the bound region, which is consistent with exclusive production of hypernuclei.

A yield of protons from the NM decay of hypernuclei was obtained by correcting the F/B ratio to Fig. 1(b). In order to convert the yield to the production ratio of hypernuclei we need to know the branching ratio of the NM decay for a hypernucleus produced in a particular excitation energy region. In the high excitation energy region, NM decay protons are from hypernuclei lighter than $^{12}_{\Lambda}$C since a couple of nucleons are emitted in its formation process. We assume that the branching ratio of the NM decay is proportional to the mass number, which is consistent with the experiments [12, 13] and is reasonable since the ratio is proportional to the overlap integral of Λ and nucleon density distribution. We thus made up to 20% correction, assuming proportionality.

Figure 2 shows the production ratio ($R_{\rm HY}$) of hypernuclei obtained by taking the ratio of Fig. 1(b) to Fig. 1(a) with corrections of the F/B ratio and the NM decay branching ratio as explained above. Since hypernuclei are produced at 100% in the bound region, the ratio is normalized to unity.

The intranuclear cascade calculation was employed to obtain $R_{\rm HY}$ for the given ΛN cross section. Relevant formulas for the calculation can be found elsewhere [16]. The ΛN scattering is assumed to be isotropic in the ΛN center of mass system. In order to obtain the probability of the ΛN scattering in a nucleus, we calculated integrated nucleon densities along the path of the recoil Λ produced by the (π^+, K^+) reaction. For the density

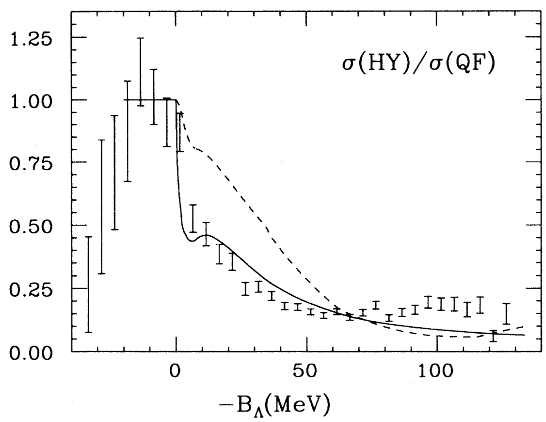

FIG. 2. Ratio of hypernuclear production [$R_{\rm HY} = \sigma({\rm HY})/\sigma({\rm QF})$] derived from the ratio of Fig. 1(a) to Fig. 1(b) with correction of the F/B ratio and the NM decay branching ratio is shown. Here the bound region is normalized to unity where hypernuclei are exclusively produced. Dashed line shows calculation with cross section modified by the Pauli blocking. Fermi averaged cross section $\tilde{\sigma}_A$ with Pauli blocking is used to obtain solid line.

distribution of the nucleus we used the charge distribution of ^{12}C given by electron scattering [17]. We assumed that the total cross sections of π^+N and K^+N are 41 and 14 mb, respectively, in order to determine the position of the Λ production. Production of a hypernucleus means that the Λ is bound, which is represented by $\frac{p_\Lambda^2({\rm nucleus})}{2M_\Lambda} + V_\Lambda(r) < 0$ where $p_\Lambda({\rm nucleus}) = \sqrt{2m_\Lambda(E_\Lambda + V_\Lambda)}$. We assume that the shape of this potential is the same as the density distribution with a depth of 28 MeV. The centrifugal barrier, which reduces the escape probability, was included in the calculation. It is important only for low-energy Λ's (below 5 MeV). The energetic Λ after a ΛN scattering may interact with another nucleon and stick to the nucleus, increasing the probability of hypernuclear production. We included this multistep process in the calculation.

The calculated ratio of hypernuclear production is shown in Fig. 2. Here the ΛN cross section includes the Pauli blocking, which is expressed as

$$\sigma_A(E_\Lambda) = \sigma(E_\Lambda)\left(\frac{4\pi p_F^3}{3}\right)^{-1}\int^{p_F}\theta(p_F - p_f)d^3p_i, \tag{3}$$

where $\vec{p}_i$ and $\vec{p}_f$ are the initial and final nucleon momenta, respectively. Here the Fermi momentum (p_F) is taken to be 221 MeV/c from electron scattering information [15]. The Pauli blocking suppresses the ΛN cross section in free space [18] by 0.1–0.6. However, the calculated ratio is still too large at the low-excitation region. Obviously, a large cross section gives a large production rate; thus further reduction of the cross section is needed to reproduce the observed rate.

Nucleons in a nucleus are moving with Fermi momentum; thus the relative ΛN momentum is not fixed even though the Λ nucleus energy (excitation energy) is given. Consequently one should use the cross section with Fermi averaging. In order to carry out the averaging we gave the cross section as a function of relative ΛN momentum. The averaging is expressed as

$$\tilde{\sigma}_A(E_\Lambda) = \left(\frac{4\pi p_F^3}{3}\right)^{-1}\int^{p_F}\sigma(p_{\Lambda N})d^3p_i, \tag{4}$$

where $\vec{p}_{\Lambda N}$ represents the Λ momentum in the nucleon rest frame, which is represented as $\vec{p}_{\Lambda N} = \vec{p}_\Lambda({\rm nucleus}) + \frac{m_\Lambda}{m_N}\vec{p}_N$ where $p_\Lambda({\rm nucleus})$ is given by $\sqrt{2m_\Lambda(E_\Lambda + V_\Lambda)}$. Figure 3 shows the cross section obtained by this Fermi averaging. Since the Fermi momentum of a nucleon and the Λ potential make $p_{\Lambda N}$ higher than p_Λ, the Fermi averaged cross section becomes small at low energy as shown in Fig. 3. The calculated ratio of the Fermi averaged cross section shown in Fig. 2 agrees well with the experiment. There may be discrepancy above 80 MeV. The averaging needs to include the total cross section above the ΣN threshold. Here we just used the $\Lambda N \to \Lambda N$ scattering cross section. Inclusion of the ΣN channel will increase the ratio around 80 MeV and would improve the agreement. However, this region is of minor importance for the present argument and the quality of the data and the calculation have yet to be improved; we thus leave the discussion to future study.

The production of hypernuclei has an effect on the polarization of a Λ produced by the QF process [8]. It was shown that the polarization can be explained by the QF process although there is some discrepancy between the calculation and the measurement [8, 9]. In the measurement the Λ polarization was derived from the asymmetry of the pions, which was assumed solely from the free Λ. It was suggested that the depolarization observed in the experiment was due to pions from the M decay of hypernuclei, which had no asymmetry [8]. We can now estimate the polarization given by the pion asymmetry ($P_{\rm tot}$) from the polarization of the QF process ($P_{\rm QF}$) which is

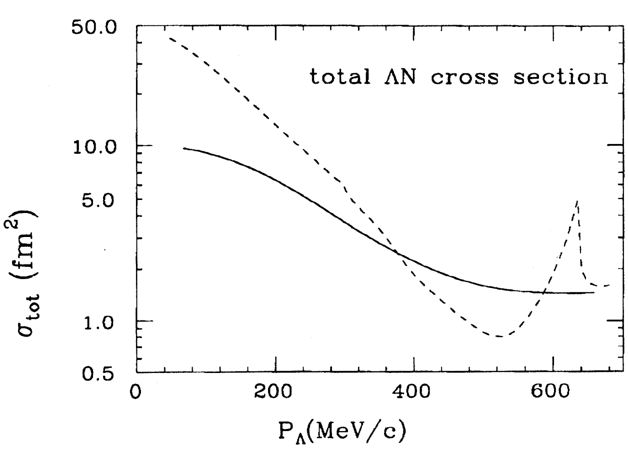

FIG. 3. Total elastic ΛN cross section is shown. Dashed line shows free $\Lambda N \to NN$ cross section given in Ref. [18]. Fermi averaging gives the solid line. Here P_Λ is given in the laboratory system.

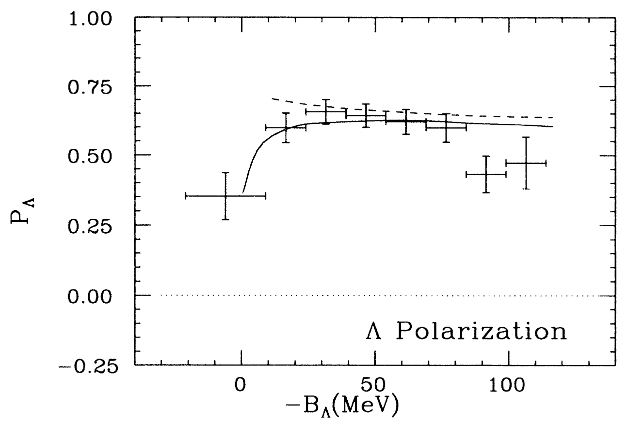

FIG. 4. Polarization of Λ obtained from the asymmetry of pions is shown. Pions from the M decay of hypernuclei are corrected to give solid line.

represented by

$$P_{\rm tot} = \frac{P_{\rm QF}(1 - R_{\rm HY})}{(1 - R_{\rm HY}) + \frac{B_{\pi^-}({\rm HY})}{B_{\pi^-}({\rm QF})} R_{\rm HY}}. \quad (5)$$

Here B_{π^-} stand for the branching ratio of π^- decay. B_{π^-}(QF) is the π^- decay branching ratio of free Λ which is known to be 0.64. B_{π^-}(HY) has been calculated theoretically for p-shell hypernuclei. It turns out to be 0.15 to 0.25 for hypernuclei from mass number 8 to 11 [19]. We thus used 0.2 for B_{π^-}(HY). Figure 4 shows the calculated polarization based on the Lorentz invariants s and t to specify the scattering amplitude for the calculation of the polarization. Here experimental data and the calculation without hypernuclear production were taken from previous works [8, 9]. The Λ polarization with correction of hypernuclear production reproduces the experiment well especially depolarization in the low excitation energy region.

We have shown that Λ hypernuclei are produced in the quasifree region. The ratio of hypernuclear production is consistent with the total ΛN cross section, which is modified from that in free space by Pauli blocking and Fermi averaging. The observed ratio of the hypernuclear production rate consistently explains the polarization of Λ in the QF region.

The authors are grateful to the members of the KEK-PS E160 Collaboration with whom a series of studies was carried out. They thank Professor K. Nakai, Professor K. Takamatsu, Professor J. Chiba, and Professor T. Ohsuka of KEK for support for the experiment. T.K. is grateful to Professor T. Motoba and Professor Y. Yamamoto for discussions on related subjects.

[1] Y. Marador *et al.*, Phys. Rev. Lett. **65**, 2110 (1990).
[2] O. Schult, in Proceedings of the International Conference on Hypernuclear and Strange Particle Physics, Vancouver, Canada, 1994 [Nucl. Phys. A (to be published)].
[3] T. Kishimoto, in *Proceedings of XIII International Conference on Particles and Nuclei (PANIC)*, edited by A. Pascolini (World Scientific, Singapore, 1994), p. 638.
[4] E. C. Milner *et al.*, Phys. Rev. Lett. **54**, 1237 (1985).
[5] P. H. Pile *et al.*, Phys. Rev. Lett. **66**, 2585 (1991).
[6] M. Akei *et al.*, Nucl. Phys. **A534**, 478 (1991).
[7] S. Ajimura *et al.*, Phys. Lett. B **282**, 293 (1992).
[8] S. Ajimura *et al.*, Phys. Rev. Lett. **68**, 2137 (1992).
[9] T. Kishimoto and S. Ajimura, Prog. Theor. Phys. **89**, 1021 (1993).
[10] M. Akei *et al.*, Nucl. Instrum. Methods Phys. Res. Sect. A **283**, 46 (1989).
[11] L. Lee *et al.*, Nucl. Instrum. Methods Phys. Res. Sect. A **327**, 287 (1993).
[12] J. J. Syzmanski *et al.*, Phys. Rev. C **43**, 849 (1991).
[13] R. Grace *et al.*, Phys. Rev. Lett. **55**, 1055 (1985).
[14] H. Noumi *et al.* (in preparation).
[15] S. Frullani and J. Mougey, Adv. Nucl. Phys. **14**, 1 (1984).
[16] Y. Yamamoto, M. Wakai, T. Fukuda, and M. Sano, Prog. Theor. Phys. **88**, 1163 (1992).
[17] H. de Vries, C. W. de Jager, and C. de Vries, At. Data Nucl. Data Tables **36**, 495 (1987).
[18] M. M. Nagels, T. A. Rijken, and J. J. de Swart, Phys. Rev. D **20**, 1633 (1979).
[19] T. Motoba, K. Itonaga, and H. Bandō, Nucl. Phys. **A489**, 683 (1988).