Volume 4, Number 2, 2011. pp. 71-78

Jordan Journal of Physics

ARTICLE

Low Energy Pion Double Charge Exchange Reactions and Dibaryon

Mutazz Nuseirat

Basic Sciences Department, Mail code: 3124, King Saud Bin Abdulaziz University for Health Sciences, P.O.Box 22490, Riyadh 11426, KSA.

Received on: 30/1/2011; Accepted on: 6/9/2011

Abstract: A common characteristic of low energy pion-nucleus double charge exchange reactions is a resonance like peak around 50 MeV. It has been claimed [1] that this peak provides evidence for the existence of hypothetical Dibaryon resonance d' (2.06 GeV) at this energy. This article will show how this peak could be predicted using conventional sequential mechanism without invoking dibaryon degrees of freedom.

PACS numbers: 25.80.Gn, 24.30.Gd.

Keywords: Pion; Dibaryon; Resonance; Nucleon-Nucleon.

Introduction

Due to its isospin-one (I = 1) nature, the pion exists in three charge states π^+, π^0, and π^-. Pions induce a number of reactions in nuclei like elastic and inelastic scattering, single charge exchange, absorption, and double charge exchange. Although, all of these reactions are linked, this article will concentrate on pion double charge exchange (DCX) reactions due to its second order nature for which a pion projectile of one charge entering the nucleus is to emerge as a pion of the opposite charge by exchanging charge with a nucleon (N). Therefore the pion double charge exchange reaction has to proceed via successive charge exchange on two like nucleons in the target nucleus mediated by the exchange of a pion or another meson between the two participating nucleons. This means that DCX is one of the prime reactions for studying nucleon-nucleon (NN) correlations in the nuclear target, because it depends on the separations between the two nucleons involved [2, 3].

This article is organized as follows: In the next section, we will introduce the theory of Dibaryons followed by a short review of the experimental and theoretical history of low energy DCX reactions. Then a discussion will be introduced, and finally the article will be concluded with a summary.

Dibaryon

Dibaryons are a large family of hypothetical particles that would consist of six quarks of any flavors. Based on the theory that quarks (q) are the basic building blocks of hadrons, the idea that this substructure of hadrons should cause nontrivial resonances in the dibaryon system emerged. With the establishment of quantum chromodynamics (QCD) as the appropriate theory of strong interaction first QCD-based model calculations for 6q-systems appeared in the late seventies and early eighties [4, 5], triggered by the paper of Jaffe [6] on possible H-dibaryon or dihyperon with strangeness $S=-2$. The theory of H-dibaryon has been reviewed by Tsutomu *et al*. [7]. Quark models of dibaryon resonances have been studied by Ping [8].

Dibaryons are predicted to be fairly stable once formed. These predictions of a large number of 6q-states, part of which is shown in Fig.1, caused a rush for experimental dibaryon searches in the years to follow. Unfortunately,

Corresponding Author: Mutazz Nuseirat. **Email**: nuseiratm@ksau-hs.edu.sa

despite a vast number of dedicated experiments no unambiguous evidence for their existence could be found. The bulk of these experiments were dedicated to searches for dibaryons *coupled* to NN or NΔ, where their decay will cause widths that would be large compared to those of baryon resonances. Hence, such states should be very difficult to detect in experiments.

The situation is very different for NN- and NΔ-*decoupled* dibaryon states, i.e. for resonances with quantum numbers I = 0 and $J^P = 0^+, 0^-, 2^-, 4^-, \ldots$. In this case the only decay channels are γNN and πNN. If the resonance energy is not far above the πNN threshold, then we expect a very narrow width of the order of MeV only. As seen in Fig. 1 such low-lying states with I = 0 and $J^P = 0^-, 2^-$ have been predicted [9-11] to be the lowest-lying dibaryon states. The suitable reactions for detecting these low-lying states are those reactions with very small cross sections due to conventional processes. Therefore, the formation of a dibaryon resonance has a chance to be detected. It is also desirable that the reaction only involves the minimal number of particles necessary to form or produce such resonance. If the resonance energy is below the πNN-threshold, then γNN is the only decay channel. On the other hand, when it is above πNN-threshold then by far the most dominant decay channel will be πNN. Under the conditions discussed above, one suitable candidate reaction to study dibaryons will be the pionic double charge-exchange reaction.

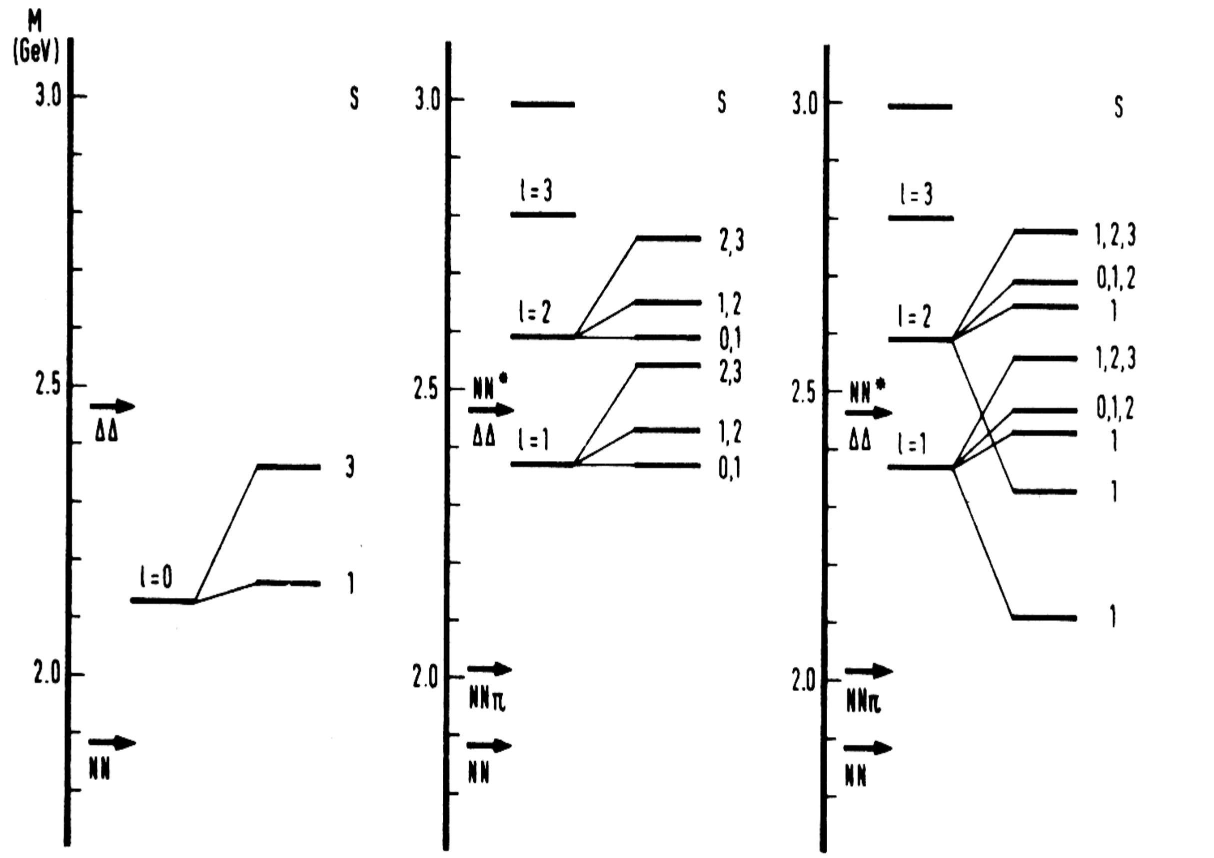

FIG. 1. Example of a predicted mass spectrum for nonstrange and isoscalar (**I** = 0) dibaryon resonances (Ref. 9).

Low Energy Pion Double Charge Exchange Reactions

Pion double charge exchange reactions on nuclear targets have been studied extensively, both experimentally and theoretically, for a survey see DCX reviews [12, 13]. Measurements of pionic double charge exchange to individual final nuclear states have become feasible soon after meson factories had been commissioned. DCX cross sections are in the range of nb/sr to μb/sr, while elastic scattering cross sections are larger by many orders of magnitudes in the range of mb/sr to b/sr. Thus the DCX experiment has the task of finding a single negative pion from the (π^+, π^-) reaction among billions of elastically scattered positive pions. This can only be achieved by using magnetic spectrometers, where particles can easily be separated according to their charge and momentum.

The largest part of presently available DCX data have been collected at pion energies between 100 MeV and 300 MeV. In 1984 the first low energy pion DCX measurements were conducted on ^{14}C at incident pion energy of $T_\pi = 50$ MeV [14, 15]. Surprisingly, the forward angle cross section for this reaction was found to be as large as at $T_\pi \approx 300$ MeV. At this energy the pion-nucleon forward single charge-exchange reaction exhibits a deep minimum due to the well-known destructive isovector sp-wave interference in the πN system [16] as shown in Fig. 2. However, initial DCX calculations [17, 18] predicted a dip rather than a bump at these energies, until one realized that inclusion of distortions, double spin-flip, and coupled channel effects could wash out this dip and even produce some kind of bump in such calculations [19]. Many measured DCX transitions with different nuclei showed a resonance-like structure in their forward angle cross section peaking in the energy range 40-60 MeV as shown in Fig. 3.

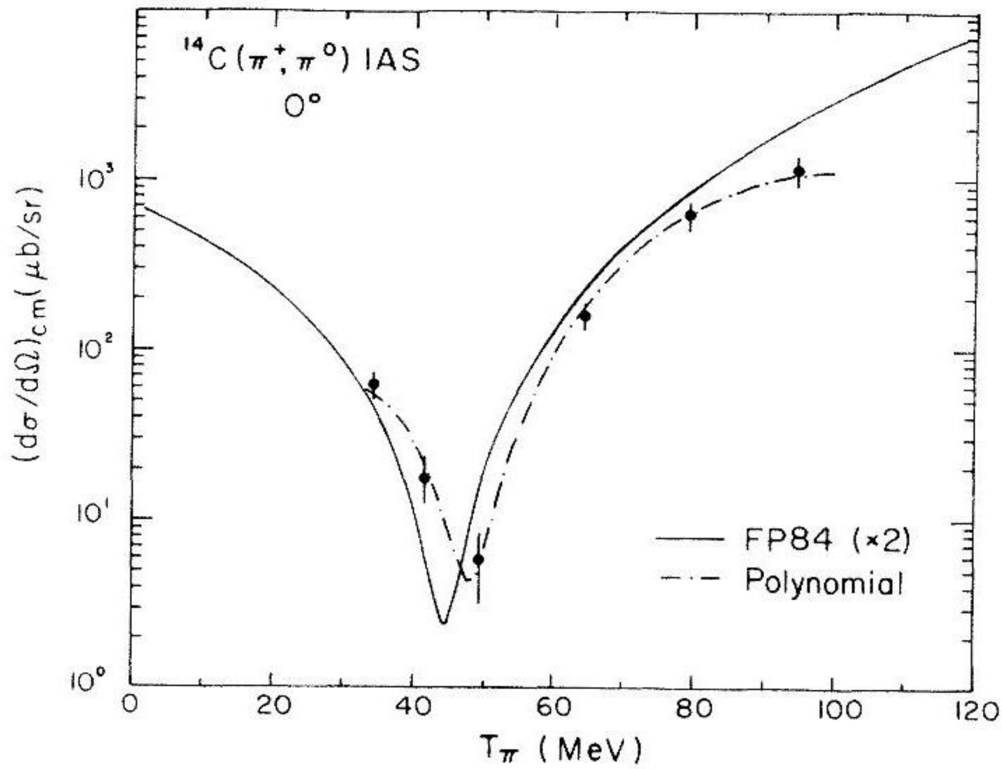

FIG. 2. The 0° c.m. cross section plotted vs laboratory energy for the $^{14}C(\pi^+,\pi^0)^{14}N$ reaction (Ref. 16). FP84 is the free $\pi^+ n \rightarrow \pi^0 p$ cross section, multiplied by 2.The dash-dot curve is the result of a fourth-order polynomial fit to the data.

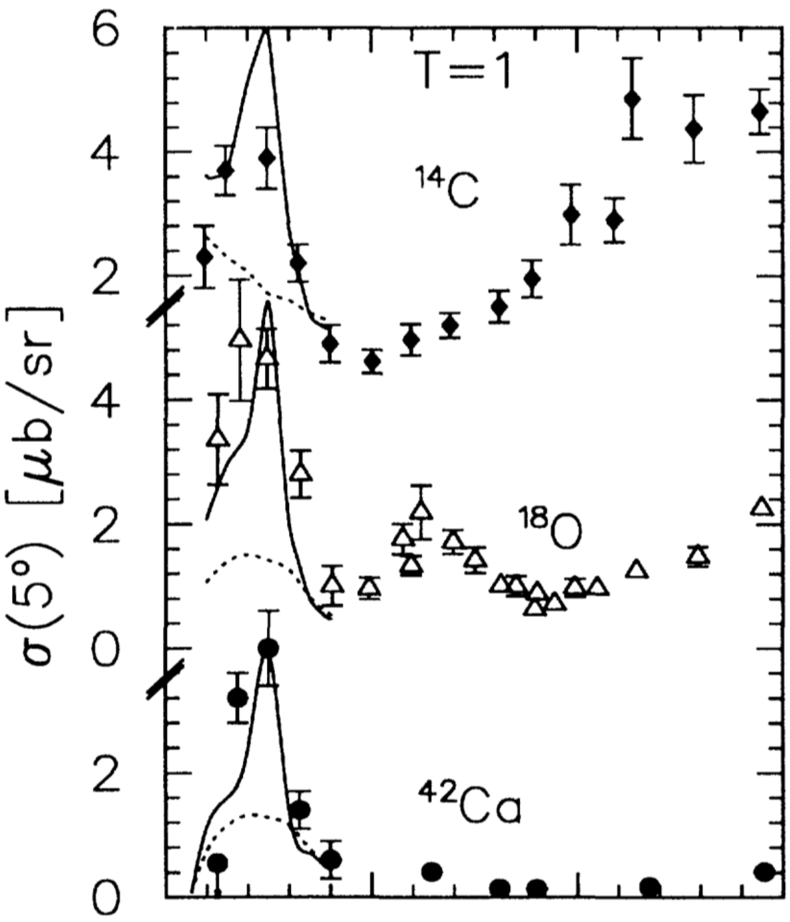

FIG. 3. Calculations of energy dependence of Pion DCX reactions for several nuclei by including degrees of freedom. The solid curves give the result, when the d ' amplitude is added and the dotted curve without (Ref. 1).

Discussion

Several reaction mechanisms have been used to study pion DCX nuclear reactions [20, 21]. In this section, we will address the peak issue using a two-step sequential mechanism, first by involving solely the conventional degrees of freedom of pions and nucleons and secondly by invoking dibaryon degrees of freedom.

Conventional Sequential Mechanism

In order to explain the DCX low energy peak, some authors [22-23] suggested that such a peak arises naturally because of the pion propagation in the conventional sequential process.

At low energy the mean free path of a pion in the nucleus is typically larger than the nuclear size. It is then natural to base the description of the DCX process on a multiple-scattering approach. To leading order, the basic mechanism for the (π^+,π^-) reaction is the sequential process illustrated in Fig. 4, in which DCX occurs through two successive πN single charge exchange reactions on two neutrons. Each single charge-exchange in this process is dominated by the spin-averaged s- and p-wave amplitudes.

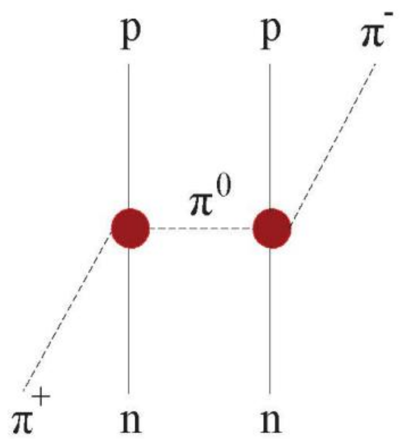

FIG. 4. Sequential DCX mechanism.

The method used in calculating the DCX reaction involves the evaluation of the matrix element [22]

$$M(\vec{k},\vec{k}';\vec{r}_1,\vec{r}_2)=\int d\vec{r}_1 d\vec{r}_2 \varphi_f^*(\vec{r}_1,\vec{r}_2)\,[\psi_{\pi^-}^{*(-)}(\vec{k}',\vec{r}_2) f_2(\vec{q}_2,\vec{q}_2')G(\vec{r}_1,\vec{r}_1) \times f_1(\vec{q}_1',\vec{q}_1)\psi_{\pi^+}^{*(+)}(\vec{k},\vec{r}_1)]\,\varphi_i(\vec{r}_1,\vec{r}_2) \tag{1}$$

The quantity in square brackets is the sequential (double-scattering) operator for the pion double-charge-exchange amplitude. The method for evaluating the effect of the operator on DCX amplitude is fully described by authors of reference [24]. The DCX operator is a function of the coordinates $\vec{r}_1$, $\vec{r}_2$ and spin variables $\vec{\sigma}_1$, $\vec{\sigma}_2$ (implicit in the two single charge operators f) of the two nucleons. The momenta $\vec{q}_1=\left(\frac{\hbar}{i}\right)\vec{\nabla}_1$ and $\vec{q}_2=\left(\frac{\hbar}{i}\right)\vec{\nabla}_2$ are operators on the conjugate coordinates in the pion wave functions $\psi_{\pi^+}^{*(+)}(\vec{k},\vec{r}_1)$ and $\psi_{\pi^-}^{*(-)}(\vec{k}',\vec{r}_2)$ and the primed values operate on the corresponding coordinates in the green function, $G(\vec{r}_2,\vec{r}_1)$ which is the pion propagator in the nuclear target between the relevant two nucleons. The functions $\varphi(\vec{r}_1,\vec{r}_2)$ are the wave functions of the two active nucleons.

The quantities f_1 and f_2, the pion-nucleon charge-exchange (off-shell) amplitudes, are operators in the nucleon spin space. They are expressed in momentum space as

$$\left.\begin{aligned} f(\vec{q},\vec{q}') &= \lambda_0(E)v_0(\vec{q})v_0(\vec{q}') \\ &+\lambda_1(E)\vec{q}.\vec{q}'v_1(\vec{q})v_1(\vec{q}') \\ &+\vec{\sigma}.\vec{q}\times\vec{q}'\lambda_f(E)v_f(\vec{q})v_f(\vec{q}') \end{aligned}\right\} \tag{2}$$

The parameters λ_0, λ_1, λ_f are calculated from the charge exchange amplitude obtained from the phase shifts [25]. The quantities $\vec{q}$ and $\vec{q}'$ are treated as gradient operators on the initial and final pion wave functions and $v(\vec{q})$ is the off-shell form factor for the pion-nucleon interaction.

We applied the above technique on $^{42\text{-}48}$Ca DCX reactions [24] and showed that this peak can be understood based on a two-step sequential process in the conventional pion-nucleon system with proper handling of nuclear structure and distortion of pion scattered wave as shown in Fig. 5. Both pion wave distortion and the effect of configuration mixing ratios in the nuclear structure have been applied to DCX reactions on ^{40}Ca and ^{16}O nuclei and were able to reproduce the peak without the need to include extra dibaryon degrees of freedom [26].

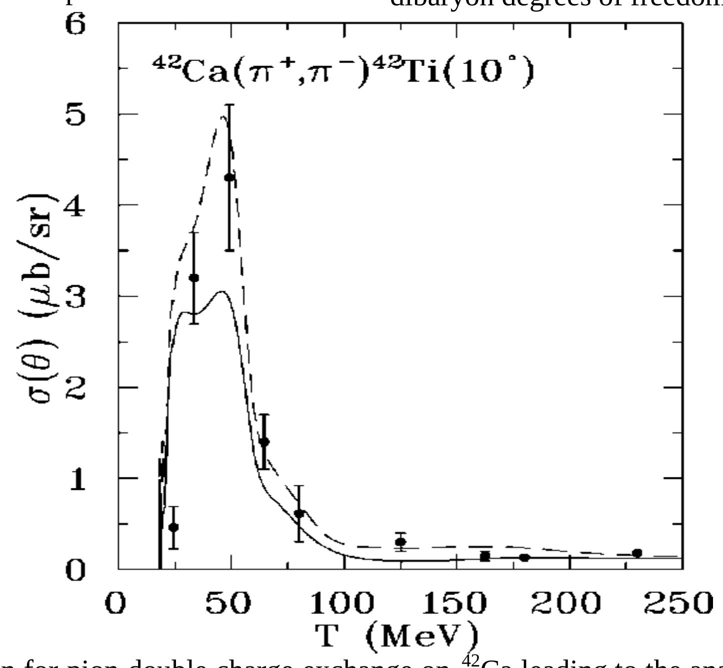

FIG. 5. Cross section for pion double charge exchange on ^{42}Ca leading to the analog state. The dotted curve displays the results of the calculation without the double spin flip included and the solid curve with.

Dibaryon Degrees of Freedom

Miller [27] claimed that high sensitivity to short range phenomena leads to the hypothesis of the formation of a narrow dibaryon resonance in the πNN channel, the so called d' with $I(J^P) = even(0^-)$ and $m_{d'} \approx 2.06\ GeV$ [1,28]. Such a resonance must be decoupled, as otherwise a huge width due to the fall-apart decay into the NN channel would be observed as we mentioned earlier.

According to Bilger [1], the DCX transition process is given by the primary resonance amplitude evaluated from the graph shown in Fig. 6, and folded
with the NN c.m. wave functions for valence nucleons in initial and final nuclear states, this amplitude is given by:

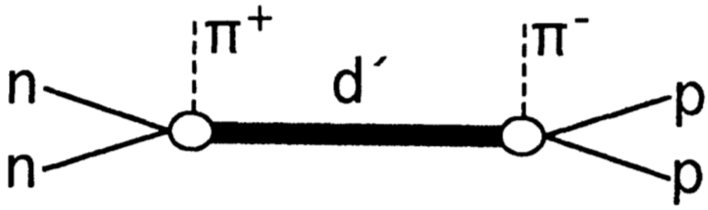

FIG. 6. Graph of the d' resonance process in DCX.

$$\left.\begin{aligned} F_{res} = {} & \left[\frac{2^7}{m_N^3 m_\pi}\right]^{1/2} \frac{\alpha^6}{\pi^2 (E_R - m_\pi)^2} \frac{k_R}{k} \left[\frac{k'}{k}\right]^{1/2} \sqrt{\Gamma_+ \Gamma_-} \\ & \times \sum_{\substack{NN'nn'L \\ j_1 j_2 j_1' j_2'}} \left[\int \psi_{n0}(\vec{r}) e^{-\alpha^2 r^2} d^3\vec{r}\right] \left[\int \psi_{n'0}(\vec{r}') e^{-\alpha^2 r'^2} d^3\vec{r}'\right] \\ & \times c_L(j_1 j_2) d_{L'}(j_1' j_2') b_{LNn}(j_1 j_2) b_{L'N'h'}(j_1' j') \\ & \times \int \frac{R_{NL}(Q) R_{L'N'}(Q') P_L(\cos\beta) P_J(\cos\gamma)}{E - E_R - \frac{k_R^2}{4m} - \frac{\vec{Q}.\vec{k}}{2m} + i\frac{\Gamma}{2}} d^3\vec{Q} \end{aligned}\right\} \tag{3}$$

Here $\Gamma,\ \Gamma_+,\ \Gamma_-,\ E_R = M_R - 2m_N$ denote total and partial widths as well as the resonance energy of d' in the nuclear medium, and k_R is the pion momentum at resonance. R_{NL} and $R_{N'L'}$ (Q and Q') are the radial wave functions (momenta) of the c.m. motion of NN pair in initial and final nuclear states, whereas $\psi_{n0}(\vec{r})$ and $\psi_{n'0}(\vec{r}')$ describe the relative motion of the two nucleons with $l = 0$ and $S = 0$ at distances $\vec{r}$ and $\vec{r}'$, respectively. N, N', n, n', L, and L' are the quantum numbers for nodes and c.m. angular momentum resulting from the Talmi-Moshinsky transformations [coefficients $b_{LNn}(j_1 j_2)$ including $jj \to LS$ coupling] of the single particle wave functions with j_1 and j_2, and $c_L(d_L)$ denote the two-nucleon coefficients of fractional percentage for initial (final) nuclear states. The angles β and γ appearing in the Legendre polynomials $P_L(\cos\beta)$ and $P_J(\cos\gamma)$ are functions of momenta Q, Q', k, and k', where k and k' denote initial and final pion momenta, respectively, and J stand for the spin of d'.

To calculate the DCX cross sections, we break the DCX amplitude into two components, one due to conventional DCX process "F_c" and the second is due to d' degrees of freedom.

$$F_{tot} = F_c + e^{i\phi_0} F_{res} \tag{4}$$

with ϕ_0 being a relative phase between conventional and resonance amplitude [1].With the adjustment of ϕ_0, total vacuum width $\Gamma_{\pi NN} \approx 0.5\ MeV$ and spreading width $\Gamma_s \approx 10 - 20\ MeV$ due to collision damping all known data for transitions in the final nucleus could be described reasonably well [28-30], in their energy dependence as shown in Figs. 3 and 7.

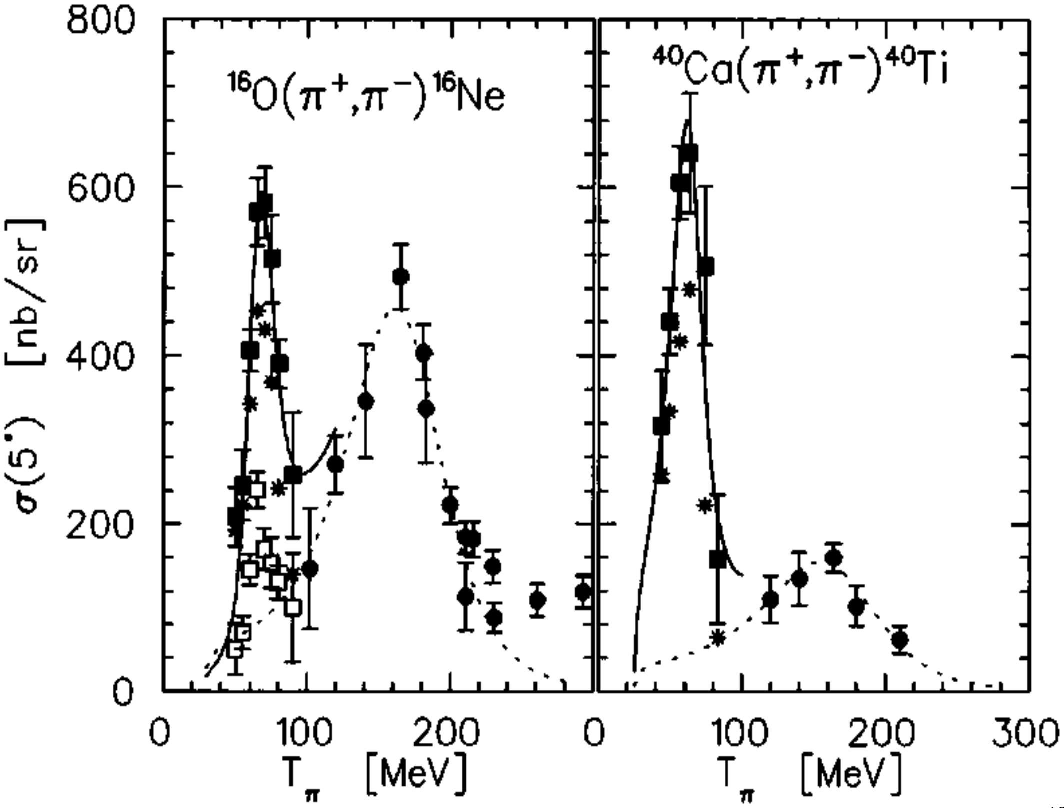

FIG. 7. Energy dependence of the forward angle cross section of the ground state transitions in ^{16}O and ^{40}Ca from Refs. [29]. Dotted lines represents $\Delta\Delta$ process and solid curves give the results with the d' amplitude added.

Summary

The hypothetical d' dibaryon assumption used the technique of adjustment of parameters in equations 2 and 3 to fit the claimed resonance for all DCX data, while the conventional calculations predicted the peaks in $^{40\text{-}48}Ca$ and ^{16}O nuclei. Also, the d' dibaryon theoretical model has been rejected by Garcilazo [31]. According to Garcilazo calculations on πNN system [32] a 0^- resonance with isospin 0 is not possible. Based on this we believe that there is no need to invoke dibaryon degrees of freedom in DCX calculations to predict those peaks at low energy. More DCX calculations on other nuclei both of angular and energy dependence, are under investigation by the author to support the conventional sequential mechanism calculations.

References

[1] Bilger, R., Clement, H. and Schepkin, M.G., Phys. Rev. Lett. 71 (1993) 42; 72 (1994) 2972.

[2] Proc. LAMPF Workshop on Pion-Nucleus Double Charge Exchange (1985), Los Alamos National Laboratory Report No. LA-10550.

[3] Proc. Second LAMPF Workshop on Pion-Nucleus Double Charge Exchange (1989), Los Alamos, New Mexico, USA Word Scientific (1990).

[4] Mulders, P.J., Aerts, A.T. and de Swart, J.J., Phys. Rev. D, 19 (1979) 2635.

[5] Mulders, P.J., Aerts, A.T. and de Swart, J.J., Phys. Rev. D, 21 (1980) 2653.

[6] Jaffe, R.L., Phys. Rev. Let. 38 (1977) 195.

[7] Tsutomu, S., Kiyotaka, S. and Koichi Y., Prog. Theor. Phys. Supplement, 137 (2000) 121.

[8] Ping, J.L., Phys. Rev. C, 79 (2009) 024001.

[9] Mulders, P.J., Aerts, A.T. and de Swart, J.J., Phys. Rev. Lett. 40 (1978) 1543.

[10] Kontratyuk, L.A., Sov. J. Nucl. Phys. 45 (1987) 776.

[11] Johnson, M.B. and Morris, C.L., Annu. Rev. Nucl. Part. Sci. 43 (1993) 165.

[12] Clement, H., Prog. Part. Nucl. Phys. 29 (1992) 175.
[13] Navon, I., Phys. Rev. Lett. 52 (1984) 105.
[14] Leitch, M.J., Phys. Rev. Lett. 54 (1985) 1482.
[15] Ullmann, J.L., Phys. Rev. C, 33 (1986) 2092.
[16] Auerbach, N., Gibbs, W.R., Ginocchio, N.J. and Kaufmann, W.B., Phys. Rev. C, 38 (1988) 1277.
[17] Siciliano, E.R., Johnson, M.B. and Sarafian, H., Ann. Phys. (N.Y.) 203 (1990) 1.
[18] Liu, Y., Faessler, A., Schwieger, J. and Bobyk, A., J. Phys. G, 24 (1998) 1135.
[19] Jiang, M.F. and Koltun, D.S., Phys. Rev. C, 42 (1990) 2662.
[20] Oset, E., Khankhasayev, M., Nieves, J., Sarafian, H. and Vicente-Vacas, M.J., Phys. Rev. C, 46 (1992) 2406.
[21] Gibbs, W.R., Kaufmann, W.R. and Dedonder, J.P., Phys. Lett. B, 231 (1989) 6.
[22] Kagarlis, M.A. and Johnson, M.B., Phys. Rev. Lett. 73 (1994) 38.
[23] Liu, Y., Faessler, A., Schwieger, J., and Bobyk, A., J. Phys. G 24, (1998) 1135.
[24] Nuseirat, M., Lodhi, M.A.K., El-Ghossain, M.O., Gibbs, W.R. and Kaufmann, W.B., Phys. Rev. C 58, (1998) 2292.
[25] Siegel, P.B., and Gibbs, W.R., Phys. Rev. C 33, (1986) 1407.
[26] Wu, H.C., and Gibbs, W.R., Phys. Rev. C 68, (2003) 054610.
[27] Miller, G. A., Phys. Rev. Lett. 53, 2008 (1984); Phys. Rev. C 35, (1987) 377.
[28] Bilger, R., Z. Phys. A 343, (1992) 491.
[29] Föhl, K., Phys. Rev. Lett.79, (1997) 3849.
[30] Pätzold, J., Phys. Lett. B 428, (1998) 18; 443, (1998) 77.
[31] Garcilazo, H., and Mathelitsch, L., preceding comment, Phys. Rev. Lett. 72, (1994) 2971.
[32] Garcilazo, H., and Mathelitsch, L., Phys. Rev. C 34, (1986) 1425.