PIONIC PROBES FOR EXOTIC NUCLEI*

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Abstract

With the advent of meson factories such as LAMPF, powerful new tools have been added to the list of those used in the study of exotic nuclei far from the valley of stability. These new tools are reactions involving pions in the incident and/or outgoing channels. The most useful, and so far the most used of these reactions are the pion double charge exchange reactions, both ($\pi^+$, $\pi^-$) and ($\pi^-$, $\pi^+$). The ($\pi^+$, $\pi^-$) reaction has been successfully used to study $T_z=3$ nucl. $\alpha_1$ such as $^{16}\text{C}$ and $^{26}\text{Ne}$, and the ($\pi^-$, $\pi^+$) reaction has been used to study $T_z=2$ nuclei such as $^{12}\text{O}$, $^{16}\text{Ne}$, $^{24}\text{Si}$ and $^{32}\text{Ar}$, and $T_z=1$ nuclei such as $^{18}\text{Zn}$. Perhaps the most exciting aspect of these reactions lies in the fact that they can be used to study excited states of exotic nuclei and nuclei which are slightly unbound. An example of the latter is provided by the recent identification and mass measurement of $^{86}\text{He}$. Even more exotic systems such as $^{84}\text{H}$ and $^{86}\text{H}$, which are of great astrophysical interest, are the subjects of current investigations. Recently the ($\pi^+$, $p$) reaction has been used to identify and study $^{84}\text{He}$ and $^{86}\text{H}$.

I. Introduction

Almost immediately after the discovery of nuclear analog states\(^1\), in $(p, n)$ single charge exchange reactions, Drell, Lipkin and de Shalit\(^2\) speculated on the possibility of double charge exchange (DCX) via $(\pi^0, \pi^0)$ reactions. Ericson\(^3\) immediately recognized the potential of pion DCX reactions, particularly $(\pi^+, \pi^-)$ in reaching exotic nuclei and studying their properties. Gilly\(^4\) at CERN actually tried to look for the exotic nuclei, $^{\text{n}}, ^{\text{H}}, ^{\text{Be}}$ and $^{\text{C}}$ by means of $(\pi^+, \pi^-)$ DCX reactions as early as 1965. His efforts were unsuccessful, primarily due to the very poor intensity (and resolution) pion beams available to him. Only with the ushering of the era of "industrial revolution" in pion physics and the construction of "pion factories" did Ericson's dream become practical. If we define a figure of merit for DCX experiments as $M=\text{Flux}/(\text{energy resolution})$ one can see how large an improvement had to take place. For the EPICS channel at LAMPF today, $M=\left(2 \times 10^7 \text{ sec}^{-1}/0.2 \text{ MeV}=10^{10} \text{ sec}^{-1}/\text{MeV}\right)$, whereas at CERN in 1965, Gilly had to fly with $M=\left(2 \times 10^5 \text{ sec}^{-1}/15 \text{ MeV}=10^{12} \text{ sec}^{-1}/\text{MeV}\right)$. It is amazing what a factor $10^5$ advantage can do!

In my talk today I will mainly describe the studies of exotic nuclei by pion double charge exchange. True to my announced topic I will also describe some of the very recent attempts we have made to use the $(\pi^+, p)$ reactions for studying exotic nuclei. All the $(\pi^+, p)$ experiments I will talk about were done at the EPICS channel at LAMPF. The main bulk of the data is from the Northwestern University group\(^5\).

Historically the first mass measurement by a DCX reaction was done at the LEP channel at LAMPF by Burman et al.\(^6\). The measurement was by-product of a reaction study on $^{16}$O and yielded a rather

* Crude measurement of the mass excess for $^{16}\text{Ne}(\approx 24.4$ + 0.5 Mev). All subsequent measurements have been done at the EPICS channel, which we describe below.

II. THE EPICS FACILITY AT LAMPF

The Energetic Pion Channel and Spectrometer facility (Fig. 1) at LAMPF consists of a four dipole channel which provides a vertically momentum dispersed (-4cm horizontal x 20 cm vertical) beam at an extended target at the center of a vacuum scattering chamber. The outgoing particles are analyzed by a QQD0 magnetic spectrometer. The three quadrupoles (QQD0) produce a 1:1 image of the target on a set of four pairs of position sensitive drift chambers (FI-4) at the entrance of the spectrometer dipoles (DS-6). Four position sensitive multiwire proportional counters (R1-4) at the "focal plane" of the spectrometer detect the analyzed particles. The $x, y, \phi$ information at the entrance and the exit of the spectrometer allows soft ware trajectory reconstruction and thus enables one to obtain energy loss spectra on line. Particle identification is done by time of flight between a thin scintillation detector (S1) at the entrance of the spectrometer dipoles and the trigger scintillation counters (S2 and S3) at the "focal plane". Additional electron rejection is done by a Freon-gas threshold Cerenkov counter (C). ($ C^+ $-Magnet)

(Fig. 1. Schematic of the experimental setup.)

Fig. 2 illustrates a typical particle indentification spectrum. We note that it is this extremely clean particle identification which is responsible for almost background-less spectra observed in our experiments.

One of the major shortcomings of the usual experimental arrangement at EPICS is the fact that the incident particle and elastic scattering flux incident on the front chambers (FI-4) make it impossible to go to very forward angles. Since most DCX reactions tend to be forward peaked, this limitation was found to be very costly of beam time. After the first few DCX experiments at EPICS, the modification shown in Fig. 1 was installed. It essentially consists of a vertical C-magnet across the scattering chamber. This deflects the primary particles ($\pi^+$, for example) away from the front chambers while the oppositely charged particles ($\pi^-$, or protons) of interest head towards the chambers and the spectrometer dipoles. With this magnet it has been possible to take excellent data at angles as small as $^5\text{O}$.  

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Before discussing some examples of our measurements let me give you a statement of my own feelings about the role of pion induced reactions in the pursuit of nuclei far from stability. Because of the limitations which I have described above, pion induced reactions can never be used for "mass-production" of such nuclei, as is possible with several other techniques discussed at this conference. These reactions must be used only in particularly difficult cases. Our own approach has been just this. We have used these reactions only when more standard techniques have failed. For future measurements, for example, we cannot readily think of other techniques for measuring masses of $^{14}$Be and $^{40}$Ti. Even then it is becoming increasingly difficult to convince reluctant PAC's to approve the long beam times needed for these measurements. Patiently, we try and try again!

### III. Some Experimental Results

T=3 Nuclei

a) $^{18}$C: Our interest in masses of exotic nuclei started with T=3 nucleus, $^{18}$C. Since earlier attempts to measure the mass of this particle-stable nucleus by means of heavy-ion DCX reactions had been unsuccessful, we attempted to populate it in the reaction $^{18}$O($^\pi$,p)$^{18}$C. The attempt was quite successful (see Fig. 3). Using the reaction $^{18}$O($^\pi$,p)$^{18}$C

![Graph](image)

Fig. 3. Spectrum for the reaction $^{18}$O($^\pi$,p)$^{18}$C

$^{12}$C($^\pi$,p)$^{12}$B, whose Q-value is known accurately we obtain the mass excess for $^{18}$C as 24.91 ± 0.15 MeV. The errors could be easily improved to the ± 50 keV level if the experiment were repeated today. What would be even more interesting is to determine if the 2e excited state of $^{18}$C exists at ± 2 MeV (as the data suggest) and as Khadikar and Kamle predict in their Hartree-Fock calculations of this nucleus. An experiment designed to study the excited state spectrum of $^{18}$C is currently on the approved list at LAMPF!

b) $^{26}$Ne: This stable nucleus was studied for the same experimental reasons as $^{18}$C. However, our own experimental technique had considerably improved since the $^{18}$C experiment. The beam sweep magnet, shown in Fig. 1 had been installed and it had become possible to make the measurement at $\theta$ = 5°. We measured the mass of $^{26}$Ne via the reaction $^{26}$Mg($^\pi$,p)$^{26}$Ne and used the $^{12}$C($^\pi$,p)$^{12}$Be reaction once again as calibration. The $^{26}$Ne mass spectrum is shown in Fig. 4. The energy resolution realized in this measurement was about 250 keV and the mass excess for $^{26}$Ne was determined as ±0.44 ± 0.07 MeV.

An interesting feature of the spectrum in Fig. 4 is the presence of a relatively strong excited state at ±3.75 MeV. Since at $\theta$ = 5° one does not expect appreciable excitation of any states.
other than those with $L = 0$ angular distributions, this state is assigned $J^p = 0^+$.

$^{26}$Ne has $Z = 10$, $N = 16$. Both these nucleon numbers are expected to become magic for $2:1$ strong deformations\(^{14}\) (see Fig. 5), and one may conjecture\(^{14}\) about the extent to which strong competition between spherical and deformed $0^+$ states may exist in such a nucleus\(^{14}\).

\( ^{14}\text{Be} \): This, lightest of the known, stable $T = 3/2$ nuclei, can be studied by DCX reactions. Detraz\(^{15}\) has attempted to study the $^{40}\text{Ca}(^{14}\text{C}, ^{14}\text{Be})^{40}\text{Ti}$ reaction, but had no success in identifying $^{14}\text{Be}$. This appears to be at least partly due to the very negative $Q(-33\text{MeV})$ for this reaction. We have proposed\(^{16}\) to measure the mass of $^{14}\text{Be}$ by means of the reaction $^{12}\text{C}(\pi^-, \pi^-)^{14}\text{Be}$. Unfortunately we have not yet succeeded in convincing the LAMPF PAC that this is an important measurement. We propose to try again.

\[ T = \frac{5}{2} \text{Nuclei} \]

\[ ^{9}\text{Be} \]: The odd-isotopes $^{5}\text{He}$ and $^{7}\text{He}$, though particle unstable, turn out to be far less unbound than was suggested on the basis of the masses of adjoining even isotopes of helium. Their widths are also small. For $^{5}\text{He}$ (g.s.) $r = 0.6\text{MeV}$, for $^{7}\text{He}$ (g.s.) $r = 0.16\text{MeV}$. Therefore, although the systematics of adjoining masses suggested that $^{9}\text{He}$ might be unbound by $2.5$ to $3.8\text{MeV}$, we conjectured that it might also turn out to be more bound and therefore have an identifiable width. Accordingly, we studied the reaction $^{9}\text{Be}(\pi^-, \pi^-)^{9}\text{He}$. The resulting spectrum is shown in Fig. 6 along with the 3-body phase space for the break-up into $^{8}\text{He} + n$. The peak corresponding to $^{9}\text{He}$ (g.s.) is clearly identifiable at the end of the phase space. The width of this peak is $\sim 1\text{MeV}$, which is equal to our experimental energy resolution. The mass excess we obtain is $40.81 \pm 0.12\text{MeV}$ which corresponds to being unbound for single neutron emission by $1.14 \pm 0.12\text{MeV}$. This is $2.4\text{MeV}$ more bound than obtained from a local application of the transverse Garvey-Kelson relation, using the experimental mass of $^{8}\text{He}$. We note that the experimental mass of $^{9}\text{He}$ is also smaller by $1.85\text{MeV}$ than its Garvey-Kelson prediction, using the same $^{8}\text{He}$ mass. In other words, $^{8}\text{He}$ appears to be about $2\text{MeV}$ less bound than it would have to be in order to be consistent with $^{7}\text{He}$ and $^{8}\text{He}$. 

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\[ ^7\text{Li} + \pi^- \rightarrow \pi^+ \ ? \]

![Graph](image)

**Fig. 7.** Spectrum for the reaction \(^7\text{Li}(\pi^-,\pi^+)X\)

that all we see is phase space. There is no identifiable bump anywhere, and we put the upper limit of \(<3\) nb/sr for the production cross section if \(^7\text{H}\) is not unbound by more than 5 MeV with respect to the break-up channel \(^3\text{He} + n + n + n\). This upper limit for the production cross section is a factor 30 lower than the one established recently by Eseev et al.\(^{17}\) in a recent experiment done at SIN.

The interesting feature of the continuum spectrum in Fig. 7 is that it does not at all fit with phase space predictions\(^{18}\) for the break-up channels, \(^3\text{He} + n + n + n\) (not shown, much steeper rising than any shown), \(^4\text{He} + n + n\), or \(^4\text{He} + n\). On the other hand, it is in remarkable agreement with the phase space results for \(^4\text{He} + n + n\) breakup. While this doesn't permit one to claim that \(^5\text{He}\) exists, it does suggest that the possible stability of \(^5\text{He}\) should be seriously examined. Indeed, it was precisely this motivation which prompted us to look for reactions in which \(^5\text{He}\) could occur as part of two-body final state. Such a reaction is \(^6\text{Li}(\pi^-,\pi^+)\).

**\((\pi^-\cdot\pi^-)\) Reactions**

It is not clear at this point as to what extent the \((\pi^-\cdot\pi^-)\) reaction can be considered as a one-step direct reaction. Since the nuclear charge in this reaction changes by two units, at least two nucleons in the nucleus need to be involved. In a simple picture the incident \(\pi^-\) would be absorbed on a nucleon pair, for example, a \(n\)-pair, and change into it into a \(\pi^-\cdot\pi^-\) pair. The large amount of energy-momentum transfer would be accomodated by ejecting one of the protons while the other sits on the high momentum tail of the wave function of a nuclear state. This kind of a reaction mechanism would automatically lead to very small cross sections. Small cross sections are therefore the rule for transitions to discrete nuclear states in nuclei near stability in \((\pi^-\cdot\pi^-)\) reactions (or their time-reversed \((\pi^-\pi^-)\) reactions), and it is not at all obvious if \((\pi^-\cdot\pi^-)\) reactions leading to discrete states in exotic nuclei would have any measurable cross sections. To examine this serious experimental question we first studied the reaction \(^9\text{Be}(\pi^-\cdot\pi^-)\).

The experimental spectrum for \(^9\text{Be}(\pi^-\cdot\pi^-)\) reaction is shown in Fig. 8. The \(^9\text{Be}(g.s.)\) is clearly seen at the expected energy \(\approx 100\) keV. The cross section, \(\sigma(20^\circ) = 43 \pm 7\) nb/sr is not too small either. It appears that the \((\pi^-\cdot\pi^-)\) reaction has no great difficulty in reaching exotic nuclei. This gives us the hope that if \(^5\text{He}\) exists we should have a good chance of seeing it in \(^6\text{Li}(\pi^-\cdot\pi^-)\) reaction.
Before passing on to $^5$H we wish to make an observation concerning the phase space observed in the $^3$Be($\pi^-$,$p$)$^9$He reaction. We find that the observed continuum cannot be fitted with any combination of multi-body phase space which involve only particle-stable helium nuclei like $^6$He, $^7$He or $^8$He. What is absolutely needed in order to explain the bump in the 5-10 MeV excitation energy region is a contribution which can only be provided by the breakup channel, $^7$He + n. This means that even though $^7$He is particle unstable, its nearly bound nature enables it to make an explicit contribution to the phase space.

$^5$H: The experimental data and its theoretical interpretation bearing on the possible existence of $^5$H up to 1965 is well reviewed in two articles, the first by Baz, Goldenskii and Zeldovich[25] and the other by Argan et al.[26]. These reviews concluded that in all likelihood particle-stable $^5$H does not exist. All attempts to search for the $\beta$-activity of $^5$H were uniformly unsuccessful[25]. Several low energy experiments in which particle-unstable $^5$H could be detected, were subsequently attempted. However these suffered from severe limitations. For example, a study of the $^3$H($t$,p) reaction, for which the threshold triton energy is 17 MeV could only be done with a 22.25 MeV triton beam.[22] It showed an enhancement indicating a $^5$H(g.s.) unbound against decay into $^3$H + n + n by only 1.8 MeV. A search for the mirror nucleus $^5$Be using the $^7$Be($^3$He,n)$^7$Be reaction[27] led to the conclusion that $^5$H is unbound by at least 2.1 MeV. A direct, but much more difficult search by means of the reaction $^7$Be($\alpha$,p)$^8$B led[28] to no clear evidence for a narrow state corresponding to $^5$H.

Two studies of the very promising reactions

$$\pi^- + ^7\text{Li} \rightarrow ^5\text{H} + d$$

and,

$$\pi^- + ^6\text{Li} \rightarrow ^5\text{H} + p$$

were attempted with stopping pions.[25,26] These experiments were done under rather primitive conditions with $\sim 10^3$ pions/sec beams and range spectrometers of extremely limited capabilities and led to very non-conclusive results. After a very critical study of all the experimental literature, we reached the conclusion that no definitive experiment exists in the published literature to date which can rule out a $^5$H ground state which is unbound by one or two MeV only and which therefore may have an identifiable width of $\sim$1 MeV or so.

In view of the above history of experiments on $^5$H and our very provocative result from the $^7$Li($\pi^-$,
$$\pi^+$$) reaction indicating the existence of at least a very strong final state interaction in the (1p + 4n) system, we did our present study of the

$$\pi^- + ^6\text{Li} \rightarrow ^5\text{H} + p$$

reaction.

The results of our experiment are shown in Fig. 9. This very high statistics experiment (1 count = 0.2 nb/sr) gives us a smooth, featureless spectrum in which no enhancements of widths $\sim$5 MeV can be discerned anywhere. One can only hope to deduce what one can from a very careful analysis of the phase space. In Fig. 9 we show a plot of the phase space corresponding to the 4-body final state, $p + ^5$H + n + n. Over a 30 MeV missing mass region, from $\sim$25 MeV to 55 MeV this phase space fits the data excellently (within $\pm$ 3%). However, it shows large deviations from the data in the 0-20 MeV region. The deviations are as large as a factor two at $\sim$10 MeV. This is better seen perhaps in Fig. 10, in which the vertical scale is linear. If

![Fig. 9. Missing mass spectrum for the $^6$Li($\pi^-$,p)$^5$H reaction at $\theta = 20^\circ$.](image)

![Fig. 10. Missing mass spectrum for the $^6$Li($\pi^-$,p)$^5$H reaction at $\theta = 20^\circ$.](image)
the 4-body phase space is subtracted from the data we get a residual peaked structure centered around 11 MeV as shown in both figures 9 and 10. This structure has a centroid at 11 ± 1.5 MeV and a half width of ~14 MeV. Without a detailed theory for this reaction all we can say is that if this structure is 5H it is unbound by 0.11 MeV instead of ~2.7 MeV as suggested by systematics.

We can also state with confidence that we find no evidence for a 2 or 3 MeV unbound state. If it exists its cross section must be well under 10 nb/sr.

\[ T_z = -2 \text{ Nuclei} \]

The main interest in these nuclei lies in completing isospin quintets and in determining how well the IMME formula with no cubic terms works. The nuclei 4C, 12O, 16Ne, 20Mg, 24Si and 40Ca have been previously studied by means of (4He, 5He) reactions by Trible et al.\textsuperscript{[27]29,23,31} and Kellog et al.\textsuperscript{[30]} All \( T_z = -2 \) nuclei up through 40Ti can also be reached very conveniently by (\( e^+,\pi^- \))DCX reactions on self conjugate targets. Burleson et al. at LAMPF\textsuperscript{[32]} have indeed measured several of these. The results, which are summarized in Table 1, agree with those of refs. 27-31. No significant deviations from the quadratic IMME have been found\textsuperscript{[32,33]}

<table>
<thead>
<tr>
<th>REACTION</th>
<th>( T_z )</th>
<th>MASS EXCESS (MEV)</th>
<th>( T(\pi^-) ) (MEV)</th>
<th>PRODUCTION (( 6^6 )) nb/sr</th>
<th>REF.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^7Li(e^+,\pi^-))8(^H)</td>
<td>5/2</td>
<td>no evidence</td>
<td>192</td>
<td>(35°) 3</td>
<td>39</td>
</tr>
<tr>
<td>(^9Be(e^+,\pi^-))(^{10He})</td>
<td>5/2</td>
<td>40.81(12)</td>
<td>192</td>
<td>(35°) 40 ± 10</td>
<td>39</td>
</tr>
<tr>
<td>(^{14}C(e^+,\pi^-))(^{16}Be)</td>
<td>3</td>
<td>24.91(15)</td>
<td>162</td>
<td>(11°) 420 ± 20</td>
<td>9</td>
</tr>
<tr>
<td>(^{18}O(e^+,\pi^-))(^{20}Ne)</td>
<td>3</td>
<td>0.44(7)</td>
<td>162</td>
<td>(5°) 260 ± 70</td>
<td>12</td>
</tr>
<tr>
<td>(^{22}Ne(e^+,\pi^-))(^{26}Mg)</td>
<td>-3/2</td>
<td>27.80(10)</td>
<td>180</td>
<td>(5°) 350 ± 50</td>
<td>39</td>
</tr>
<tr>
<td>(^{24}O(e^+,\pi^-))(^{26}Mg)</td>
<td>-3/2</td>
<td>24.05(5)</td>
<td>180</td>
<td>(5°) 400 ± 100</td>
<td>32</td>
</tr>
<tr>
<td>(^{24}Mg(e^+,\pi^-))(^{28}Si)</td>
<td>-2</td>
<td>10.68(5)</td>
<td>180</td>
<td>(5°) 340 ± 50</td>
<td>32</td>
</tr>
<tr>
<td>(^{26}Si(e^+,\pi^-))(^{28}Si)</td>
<td>-2</td>
<td>-2.18(5)</td>
<td>180</td>
<td>(5°) 84 ± 25</td>
<td>32</td>
</tr>
<tr>
<td>(^{32}S(e^+,\pi^-))(^{36}Ar)</td>
<td>-2</td>
<td>-42.32(10)</td>
<td>291</td>
<td>(5°) 70 ± 30</td>
<td>39</td>
</tr>
<tr>
<td>(^{36}Ar(e^+,\pi^-))(^{40}Ca)</td>
<td>-2</td>
<td>31.60(10)</td>
<td>125</td>
<td>(20°) 43 ± 7</td>
<td>39</td>
</tr>
<tr>
<td>(^{40}Ca(e^+,\pi^-))(^{44}Ti)</td>
<td>2</td>
<td>44.5(15)</td>
<td>125</td>
<td>(20°) 14007</td>
<td>39</td>
</tr>
</tbody>
</table>

We have studied the reaction \(^7Li(e^+,\pi^-)\)\(^7B\) at \( T(\pi^-) = 180 \) MeV and \( \theta = 5° \). The resulting \( \pi^- \) spectrum is shown in Fig. 12. The \(^{40}Ca(e^+,\pi^-)\)\(^{40}Ti\) reaction, which has a Q-value within 500 keV of that for the \(^7Li(e^+,\pi^-)\)\(^7B\) reaction, was used for calibration. The broad peak corresponding to \(^7B(\text{g.s.})\) transition is clearly visible in Fig. 12 and the continuum can be followed for at least 15 MeV before the spectrometer acceptance begins to cut it down. Unfortunately, inspite of our much better delineation of the phase space, we find ourselves no better off in understanding it. We can clearly rule out a 5-body phase space corresponding to \(^4He + 3p\) break-up since it would rise much too fast, but we are unable to fit the observed continuum with any combination of 3-body and 4-body phase space either. In Fig. 13 we show the results of our efforts to fit the data with allowed, pure phase space contri-

Unbound \(^7B\)

Our interest in \(^7B\) was aroused by Guy Pâlci who has been studying the shift in the apparent position of peaks when they are unbound and have finite widths and when they ride on large phase space continua.\textsuperscript{[35]} The mass of \(^7B\) had been measured earlier by McGrath, Cerny and Norbeck\textsuperscript{[36]} by means of the reaction \(^{10}B(4He, 5He)\)\(^7B\) at \( T(\text{g.s.}) = 50 \) MeV. They had measured a mass excess of 27.94 ± 0.10 MeV and a width \( \Gamma = 1.4 ± 0.2 \) MeV. The measurement had one major weakness. The outgoing \(^6He\) spectrum could only be followed about 4 MeV into the continuum, and this made it quite difficult to understand the phase space continuum and to untangle its effects. A 7% impurity of \(^11B\) in the target also added to the problems. Their\textsuperscript{[37]} analyzed spectrum is shown in Fig. 11. The authors concluded that there was no evidence for a \(^6Be + p\) break-up and used a 4-body phase-space, corresponding to \(^5Li + p + p\) break-up, to analyze their data.
Fig. 12. Missing mass spectrum for the reaction $^7\text{Li}(\pi^+,\pi^-)^7\text{B}$.

\begin{align*}
^7\text{Li}(\pi^+,\pi^-)^7\text{B} \\
T(\pi^-) = 160 \text{ MeV} \\
\theta = 5^\circ
\end{align*}

Fig. 13. Missing mass spectrum and phase space curves for the $^7\text{Li}(\pi^+,\pi^-)$ reaction.

\begin{align*}
^7\text{Li}(\pi^+,\pi^-)^7\text{B} \\
T(\pi^-) = 160 \text{ MeV} \\
\theta = 5^\circ
\end{align*}

\begin{align*}
\text{SUM} \\
^6\text{Be} + p \\
^5\text{Li} + 2p
\end{align*}

Contributions. It is obvious that things do not work, particularly near the threshold for $^6\text{Be}+p$ break-up. Evidently, the particle instability of both $^6\text{Be}$ and $^5\text{Li}$ leads to phase space which is substantially different from that calculated by assuming as though they were stable. Since a proper calculation of this pseudo-phase space seems to be impossible for the present, and since the shape of our continuum is quite well defined, we have made the most plausible shape reconstruction under the peak as shown in Fig. 12 and analyzed the residual structure remaining after the subtraction of this phase space 'background'. The structure has a clear peak corresponding to $^7\text{B}$ (gs.). We obtain the mass excess for it as $27.80 \pm 0.10$ MeV and the width $\Gamma = 1.2 \pm 0.2$ MeV. These results are fully consistent with those of Mcgarth et al. Our data indicates the presence of a narrower structure at an excitation of $\approx 1.5$ MeV. However the statistics are poor and the 'background' construction is somewhat arbitrary. We cannot therefore claim the existence of an excited state with any confidence.

It is worth pointing out that the mass excess predicted for $^7\text{B}$ using the $M(T_2) = a + bT_2 + cT_2^2$ form of the isobaric mass multiplet equation and the masses of the $J=3/2^-$, $T=3/2$ states in $^7\text{Be}$, $^7\text{Li}$ and $^7\text{He}$ is $27.99 \pm 0.08$ MeV. This barely overlaps with our result. The conclusion that the coefficient, $d$, of the $T_2^2$ term is zero is therefore only marginally consistent with our data.
$^{58}$Zn: The masses of all zinc isotopes down to $^{48}$Zn are known. $^{52}$Zn is known to be a $\beta$-delayed proton emitter and its mass has been inferred indirectly by measurements of $\beta$-end point energies. However, no convenient means have yet been found to measure the mass of $^{52}$Zn. We have measured this mass now by $^{54}$Ni ($\pi^+,\pi^-)^{58}$Zn reaction. Since DCX analog cross sections have minima at $T(\pi^+) = 160$-200 MeV, and rise again at higher energies, we chose $T(\pi^-) = 291$ MeV for our experiment. Even then a target of $0.97$ gm/cm$^2$ had to be used in order to obtain the spectrum shown in Fig. 14. A mass excess of $-42.32 \pm 0.10$ MeV was obtained. This result is to be compared with the predictions listed in Table II. It is in quite reasonable agreement with predictions based on the transverse Garvey-Kelson relation.

**V. CONCLUSIONS, PROSPECTS FOR FUTURE**

In 1970 when we wrote our first proposal for pion-induced double charge exchange at LAMPF, we made the foolish statement in it that DCX was not possible with conventional nuclear projectiles, but we did go on to state in a wiser footnote that the above statement was true only as long as heavy-ions were not yet considered conventional. In the meantime, as we all know, heavy-ions have become quite conventional and DCX reactions with $^{16}$O, $^{12}$C and even $^{48}$Ti beams have been tried. Unfortunately however, these heavy-ion induced DCX experiments continue to suffer from low cross sections and large backgrounds, and have not been successful in reaching exotic nuclei with large negative Q-values. Thus, at the present, pion-induced DCX reactions appear to be the only viable ones for these studies. Not only can they be used to determine ground-state masses rather accurately ($\pm 5$ keV appears to be possible with some hard work), but excited states and sometimes their J$^\pi$ can be quite directly determined. Similarly, the ($\pi^+,\pi^-$) reaction, whose analog would be a reaction of the type ($n,2p$), appears to be the only possible one of its type presently. ($\pi^+,\pi^+$), and even more exotic reactions are clearly on the horizon.

In my talk I have tried to show that pion-in-

![Graph](image)

**Fig. 14.** Missing mass spectrum for $^{54}$Ni($\pi^+,\pi^-)^{58}$Zn reaction.

<table>
<thead>
<tr>
<th>NUCLEUS</th>
<th>MASS EXCESS (MeV)</th>
<th>EXPERIMENT</th>
<th>M</th>
<th>GHZ</th>
<th>LZ</th>
<th>BLM</th>
<th>JGK</th>
<th>MN</th>
<th>WB</th>
</tr>
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<tbody>
<tr>
<td>$^1$H</td>
<td>44.5(15)</td>
<td>29.8</td>
<td>33.79(80)</td>
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<td>$^7$B</td>
<td>40.81(12)</td>
<td>30.0*</td>
<td>42.02*</td>
<td></td>
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<tr>
<td>$^9$Be</td>
<td>24.91(15)</td>
<td>25.09</td>
<td>22.6</td>
<td>25.53</td>
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<tr>
<td>$^{24}$Ne</td>
<td>0.44(7)</td>
<td>0.45</td>
<td>0.13</td>
<td>-0.31</td>
<td></td>
<td></td>
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<tr>
<td>$^7$B</td>
<td>27.80(10)</td>
<td>25.0*</td>
<td>27.94(10)</td>
<td></td>
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<tr>
<td>$^{16}$O</td>
<td>32.06(5)</td>
<td>32.52**</td>
<td>32.20</td>
<td>33.05</td>
<td></td>
<td></td>
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<tr>
<td>$^{16}$Ne</td>
<td>24.05(5)</td>
<td>25.01**</td>
<td>21.90</td>
<td>24.67*</td>
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<td></td>
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<tr>
<td>$^{24}$S</td>
<td>10.68(5)</td>
<td>4.13</td>
<td>9.62</td>
<td>10.81</td>
<td></td>
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<tr>
<td>$^{28}$S</td>
<td>0.09</td>
<td>3.88</td>
<td>4.00</td>
<td>3.10</td>
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<tr>
<td>$^{32}$Ar</td>
<td>-2.18(5)</td>
<td>-5.84</td>
<td>-2.81</td>
<td>-2.19</td>
<td></td>
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<tr>
<td>$^{40}$Ti</td>
<td>-12.65</td>
<td>-11.51</td>
<td>-8.89</td>
<td>-9.60</td>
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<td></td>
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<tr>
<td>$^{50}$Zn</td>
<td>-42.32(8)</td>
<td>-47.73</td>
<td>-43.32</td>
<td>-42.60</td>
<td></td>
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</table>

* Table II. Summary of experimental results with predictions.

M, GHZ, LZ, BLM, JGK and WB, predictions compiled in Atomic and Nuclear Data, 17 (1976) 474.

MN: Ref. 38.
sult is often twenty counts and one final number. It is therefore prudent to use these techniques sparingly, to study only those specially exotic nuclei which can be reached or have not been successfully reached by any other techniques. For such special cases we will just have to try harder, and again and again if necessary, to communicate the excitement of this fascinating field to the larger community of nuclear physicists, of which the PAC's are a part.

REFERENCES

2. S.D. Drell, H. Lipkin, and A. de Shalit, as quoted in ref. 2 below.
5. The Northwestern Group involved in DCX experiments at LAMPF at various times include: D. Barlow, M. Bosko, J. Hirid, S. Iversen, M. Kaletka, H. Nann, A. Obst, A. Saha, K. Seth and D. Smith.
18. We are very thank ful to Prof. M.M. Block for calculating of relativistically invariant phase space for multi-body break-ups.
39. Kamal K. Seth, et. al., to be published.

DISCUSSION

K. Bleuler: Can you see in your experiments the width of the Δ-resonance-state which might change for nucleons within nuclear matter?

K.K. Seth: Pion DCX will be a very expensive way of looking for the modification of the free Δ in nuclear matter. We see it only indirectly in our excitation curves for analog DCX where a broad minimum is seen at the (3.3) position. Much better delineation of the (3.3) resonance in nuclear matter has been done in measurements of pion total cross sections on nuclei.

M. Berms: The (11C, 4He) double-charge exchange reaction has cross section one to two order of magnitude larger than the (π, π-) ones. But their measurements were performed on target nuclei lying in the stability valley. Do you have an idea of the dependence of (π, π-) cross section with the Q when one is going on the side of the valley?

K.K. Seth: I am not an expert on (11C, 4He). I have however talked to the experts both at Los Alamos (Peng et al.) and Orsay (Détraz et al.) and they tell me that these cross sections fall precipitously with increasingly negative Q. For a reaction like that to 11B, the Q is almost -40 MeV. I am told that there is very little hope at the presently available 11C energies to make such excitation off the stability valley. You can not draw any conclusions from the Q=-3 to -5 MeV experiments done so far at Los Alamos.

We of course have enough energy in our (π, π-) experiments so that a -40 MeV Q value is no problem. The cross sections show no noticeable decrease.

C. Détraz: As reported in a communication to this conference (Nautil et al.) we have observed double charge heavy ion reactions at the AP Tandem: the (11B, 11C) reaction confirms the mass you obtained. It has 40 nb per sr, which indeed made it just possible with a thick target. As for the 11B mass, we plan to use the similar (11C, 11Be) reaction, but of course do not know if the cross-section will still remain on the good side of feasibility.

P.L. Reeder: Previous papers on 3H have been titled "Search for 4H", "Another search for 4H" and "Still another search for 5H". Do you have a title for your paper on 3H?

K.K. Seth: Yes, the title will be: The Last Word on 3H.