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 (π^+, π^-) and (π^-, π^+). The (π^-, π^+) reaction has been successfully used to study T_z=3 nuclei such as ^{18}C and ^{26}Ne, and the (π^+, π^-) reaction has been used to study T_z=-2 nuclei such as ^{12}O, ^{16}Ne, ^{24}Si and ^{32}Ar, and T_z=-1 nuclei such as ^{58}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 ^{9}He. Even more exotic systems such as ^{7}H and ^{5}H, which are of great astrophysical interest, are the subjects of current investigations. Recently the (π^-, p) reaction has been used to identify and study ^{8}He and ^{5}H.

I. Introduction

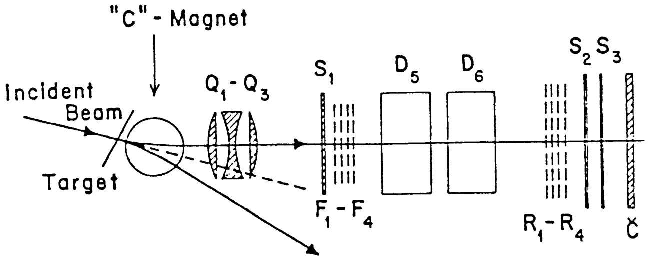
Almost immediately after the discovery of nuclear analog states$^{1)}$, in (p, n) single charge exchange reactions, Drell, Lipkin and de Shalit$^{2)}$ speculated on the possibility of double charge exchange (DCX) via (π^+, π^-) reactions. Ericson$^{3)}$ immediately recognized the potential of pion DCX reactions, particularly (π^-, π^+) in reaching exotic nuclei and studying their properties. Gilly$^{4)}$ at CERN actually tried to look for the exotic nuclei, ^{4}n, ^{7}H, ^{12}Be, and ^{9}C by means of (π^-, π^+) 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=Flux/(energy resolution) one can see how large an improvement had to take place. For the EPICS channel at LAMPF today, $M \simeq [2 \times 10^7\ \pi^-/\mathrm{sec}]/0.2$ MeV $\simeq 10^8 \pi^-/(\mathrm{sec.\ MeV})$, whereas at CERN in 1965, Gilly had to flight with $M \simeq [2 \times 10^5\ \pi^-/\mathrm{sec}]/15$ MeV $\simeq 10^4 \pi^-/(\mathrm{sec.\ MeV})$. It is amazing what a factor 10^4 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 (π^-, p) reactions for studying exotic nuclei. All the pion 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}Ne(=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 (∿6cm 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 QQQDD magnetic spectrometer. The three quadrupoles (Q1-Q3) produce a 1:1 image of the target on a set of four pairs of position sensitive drift chambers (F1-4) at the entrance of the spectrometer dipoles (D5-6). Four position sensitive multiwire proportional counters (R1-4) at the "focal plane" of the spectrometer detect the analyzed particles. The x, y, θ, ϕ information at the entrance and the exit of the spectrometer allows soft-ware trajectory reconstruction and thus enables one to obtain energy loss spectra online. 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 (S_2 and S_3) at the "focal plane". Additional electron rejection is done by a Freon-gas threshold Cerenkov counter (C).



(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 (F1-4) 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 (π^-, for example) away from the front chambers while the oppositely charged particles (π^+, 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°.

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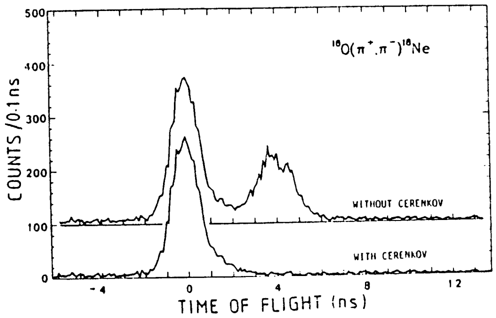

Fig. 2. Particle Identification for DCX

A few characteristics of pion induced reactions in the energy range 100-300 MeV need to be mentioned. This is the region of the well-known (3,3) resonance of the π-nucleon system. Pions are strongly absorbed by nuclei in this entire energy region, the maximum being at ∿180 MeV. The characteristics of neither the DCX reactions, (π^+, π^-), (π^-, π^+) nor the absorption reaction, (π^-, p) are well known7). During the last couple of years, however, it has been shown that non-analog (T-changing) (π^+, π^-) DCX transitions have cross sections which monotonically decrease from ∿100 to 300 MeV. One expects that this is also true of (π^-, π^+) reactions. Since the pion flux at EPICS increases with increasing energy for both π^- and π^+, it turns out that the middle of the range, $T(\pi)$ = 160-200 MeV is the ideal pion energy to use for non-analog DCX reactions.

The (π^-, p) reactions are highly monentum mismatched reactions and their yield for a given q-transfer is almost independent of energy. It is therefore advantageous to run them at as high a pion energy as possible, limited of course by the ability to handle the proton rigidities in the spectrograph designed for pions.

Let me also point out a few other practical limitations of pion-induced reactions as far as the pursuit of exotic nuclei is concerned. First, the total "π^- beam" available at the world's hottest meson factory (LAMPF) is only ∿2 x 10^7 π^-/sec. To translate it into more familiar terms, we have ∿3 picoamps of "π^- beam". In order to utilize such a beam at all we must resort to quite thick targets, typically several hundreds of mgm/cm^2. This is only possible because at these energies pions are minimum ionizing. Even then, energy resolutions better than ∿200 keV are not possible. The second problem arises because this great "beam" is spread over a 6 cm x 20 cm area. Thus target materials of the order of 20-100 grams are required. Thanks to the rich inventory of the Separated Isotopes Pool, maintained by the U.S. Department of Energy, samples of many separated isotopes (even ^{14}C, for example) are possible. Nevertheless, many scarce isotopes are completely ruled out. As far as cross sections are concerned, the situation is not too bad. As shown later in Table 1, typical DCX cross sections for nuclei with $A \lesssim 58$ are $\sigma(5°) \gtrsim 70$ nb/sr. This compares very favourably with, for example, cross sections for the much-used, competitive reaction (^4He, ^8He). Tribble8) has reported σ(3° to 8°) = 5 to 1 nb/sr for targets ranging from ^{12}C to ^{40}Ca.

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 can not 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_z=3 Nuclei

a) ^{18}C: Our interest in masses of exotic nuclei started with T_z=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 $^{18}O(\pi^-, \pi^+)^{18}C$. The attempt was quite successful (see Fig. 3). Using the reaction $^{12}C(\pi^-,\pi^+)^{12}B$, whose Q-value is known accurately we obtain the mass excess for ^{18}C as 24.91 ± .15 MeV.9) 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 2+ excited state really exists at ∿2 MeV as the data suggest and as Khadkikar and Kamle10) 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 LAMPF11).

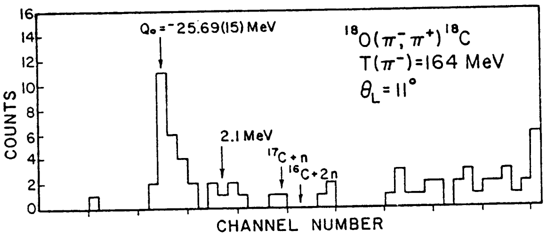

Fig. 3. Spectrum for the reaction $^{18}O(\pi^-,\pi^+)^{18}C$

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 θ = 5°. We measured the mass of ^{26}Ne via the reaction $^{26}Mg(\pi^-,\pi^+)^{26}Ne$ and used the $^{12}C(\pi^-,\pi^+)^{12}Be$ reaction once again as calibration. The ^{26}Ne 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.12)

An interesting feature of the spectrum in Fig. 4 is the presence of a relatively strong excited state at ∿3.75 MeV. Since at θ = 5° one does not expect appreciable excitation of any states

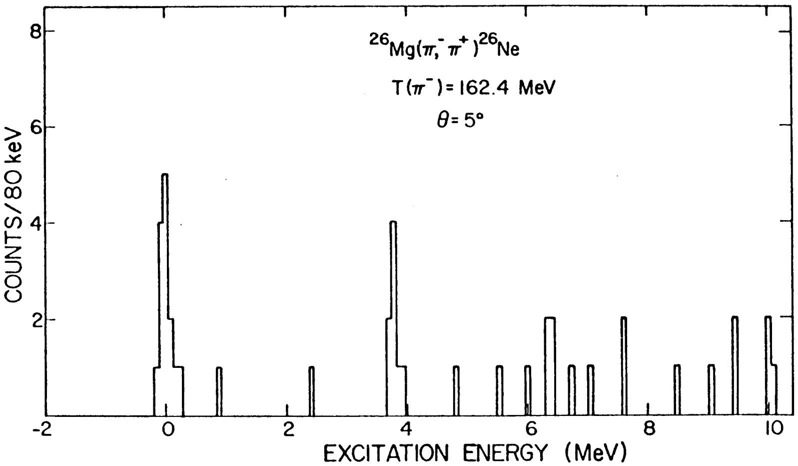

Fig. 4. Spectrum for the reaction $^{26}Mg(\pi^-,\pi^+)^{26}Ne$

other than those with L = 0 angular distributions, this state is assigned $J^\pi = 0^+$

^{26}Ne has Z = 10, N = 16. Both these nucleon numbers are expected to become magic for 2:1 strong deformations[13]) (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]).

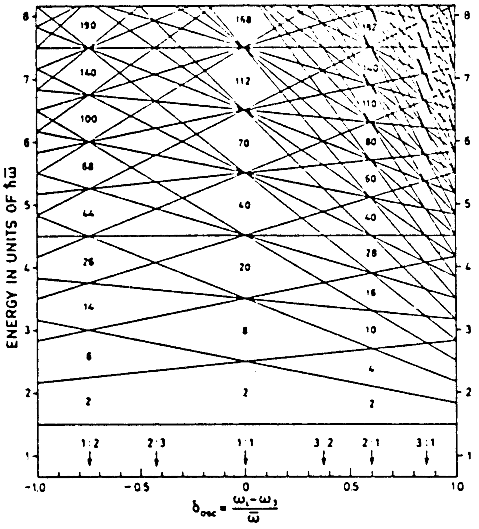

Fig. 5. Single-particle spectrum for axially symmetric oscillator potential (from ref. 13). Note the magic numbers at 2:1 deformation.

c) ^{14}Be: This, lightest of the known, stable $T_z=3$ nuclei, can be studied by DCX reactions. Detraz[15]) has attempted to study the $^{48}Ca(^{14}C, ^{14}Be)^{48}Ti$ reaction, but had no success in identifying ^{14}Be. This appears to be at least partly due to the very negative Q(=-33MeV) for this reaction. We have proposed[16]) to measure the mass of ^{14}Be by means of the reaction $^{14}C(\pi^-,\pi^+)^{14}Be$. Unfortunately we have not yet succeeded in convincing the LAMPF PAC that this is an important measurement. We propose to try again.

T_z = 5/2 Nuclei

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

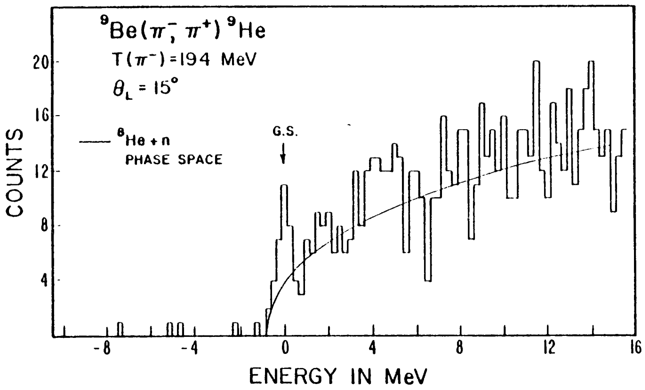

Fig. 6. Missing mass spectrum for the reaction $^{9}Be(\pi^-,\pi^+)^{9}He$

^7H: From time to time there has been speculation about the possible existence of ^7H. Since it has the same neutron structure as particle-stable ^8He (1s 1/2, 1p 3/2 completely full), and has one less proton, one wonders whether it comes close enough to stability to be identifiable. For this purpose we have studied the reaction ^7Li $(\pi^-,\pi^+)^7H$. The resulting spectrum is shown in Fig. 7. It is clear 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 ^7H is not unbound by more than 5 MeV with respect to the break-up channel $^3H + n + n + n + n$. This upper limit for the production cross section is a factor 30 lower than the one established recently by Evseev et al.,[17] in a recent experiment done at SIN.

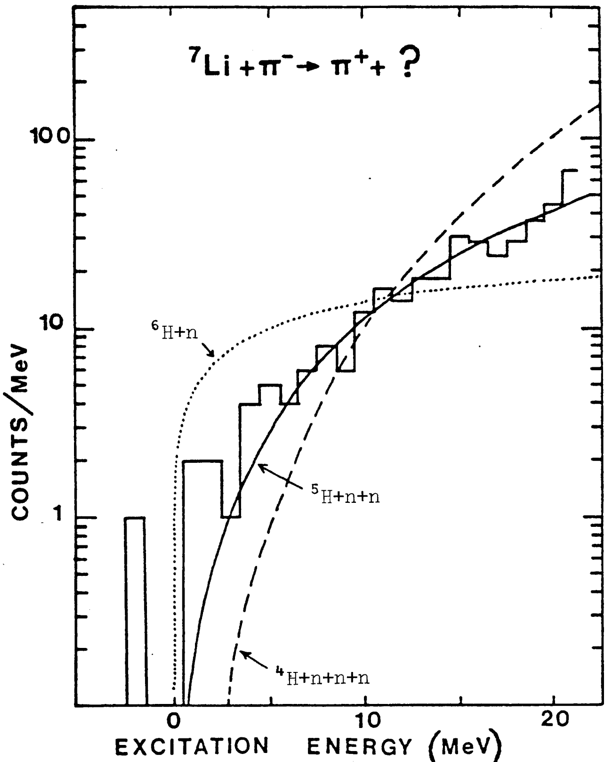

Fig. 7. Spectrum for the reaction $^7Li(\pi^+,\pi^-)X$

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, $^3H + n + n + n + n$ (not shown, much steeper rising than any shown), $^4H + n + n + n$, or $^6H + n$. On the other hand, it is in remarkable agreement with the phase space results for $^5H + n + n$ breakup. While this doesn't permit one to claim that ^5H exists, it does suggest that the possible stability of ^5H should be seriously examined. Indeed, it was precisely this motivation which prompted us to look for reactions in which ^5H could occur as part of two-body final state. Such a reaction is $^6Li(\pi^-,p)^5H$. With a little help from Prof. Bethe, we were given the opportunity to study it. In the following we present the results from this experiment.

(π^-,p) Reactions

It is not clear at this point as to what extent the (π^-,p) 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 π^- would be absorbed on a nucleon pair, for example, a n-p pair, and change it into a p-p 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 (π^-,p) reactions (or their time-reversed (p,π^-) reactions), and it is not at all obvious if (π^-,p) reactions leading to discrete states in exotic nuclei would have any measureable cross sections. To examine this serious experimental question we first studied the reaction $^9Be(\pi^-,p)^8He$.

The experimental spectrum for $^9Be(\pi^-,p)^8He$ reaction is shown in Fig. 8. The ^8He(g.s.) is clearly seen at the expected energy ($\pm$ 100 keV). The cross section, $\sigma(20°) = 43 \pm 7$ nb/sr is not too small either. It appears that the (π^-,p) reaction has no great difficulty in reaching exotic nuclei. This gives us the hope that if ^5H exists we should have a good chance of seeing it in ^6Li $(\pi^-,p)^5H$ reaction.

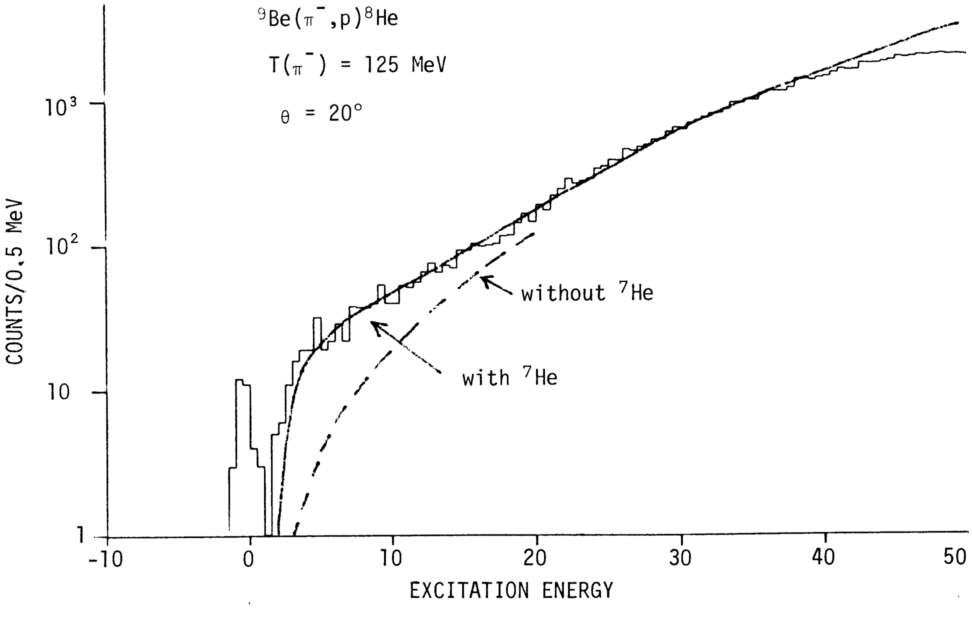

Fig. 8.

Spectrum for the reaction $^9Be(\pi^-,p)$ ^8He at $T(\pi^-)$ = 125 MeV, θ = 20°.

Before passing on to ^{5}H we wish to make an observation concerning the phase space observed in the ^{9}Be(π^-,p)^{8}He reaction. We find that the observed continuum cannot be fitted with any combination of multi-body phase spaces which involve only particle-stable helium nuclei like ^{6}He, ^{4}He or ^{3}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 break-up 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, Goldonskij and Zeldovich[19] and the other by Argan et al.[20]. These reviews concluded that in all likelihood particle-stable ^{5}H does not exist. All attempts to search for the β-activity of ^{5}H were uniformly unsuccessful.[21] 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 ^{3}He(^{3}He,n)^{5}Be reaction[23] 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 ^{9}Be(α,^{8}B) led[24] 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 ∿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 ∿1 MeV or so.

In view of the above history of experiments on ^{5}H and our very provocative result from the ^{7}Li (π^-, π^+) experiment 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 $\lesssim$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 + ^{3}H + n + n. Over a 30 MeV missing mass region, from ∿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 ∿10 MeV. This is better seen perhaps in Fig. 10, in which the vertical scale is linear. If

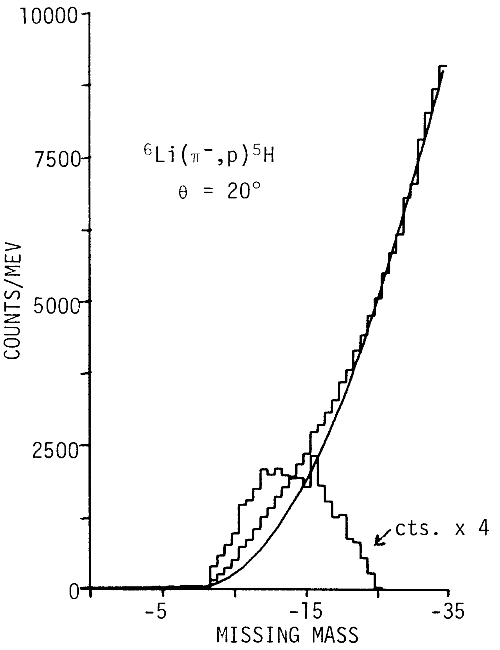

Fig. 10. Missing mass spectrum for the ^{6}Li(π^-,p)^{5}H reaction at θ = 20°

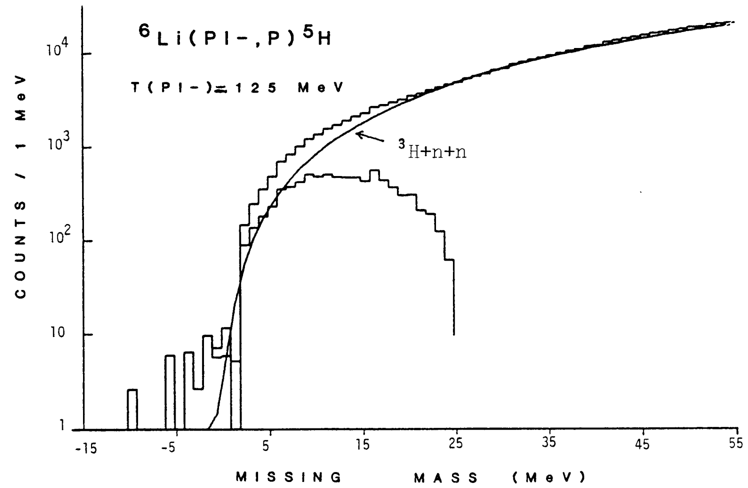

Fig. 9. Missing mass spectrum for the ^{6}Li(π^-,p)^{5}H reaction at θ = 20°.

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 ∿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 Nuclei

The main interest in these nuclei lies in completing isopsin quintets and in determining how well the IMME formula with no cubic terms works. The nuclei ^8C, ^{12}O, ^{16}Ne, ^{20}Mg, ^{24}Si and ^{36}Ca have been previously studied by means of (^4He, ^8He) reactions by Tribble et al.[27,28,29,31]) and Kekelis et al.[30]) All T_z = -2 nuclei up through ^{40}Ti can also be reached very conveniently by (π^+,π^-)DCX reactions on self conjugate targets. Burleson et al. at LAMPF[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[32,33]).

TABLE 1. SUMMARY OF RESULTS FOR PION INDUCED REACTIONS.

REACTION	T_z	MASS EXCESS (MEV)	T(π) (MEV)	PRODUCTION (θ°) nb/sr	REF.
$^7Li(\pi^-,\pi^+)^7H$	5/2	no evidence	192	(15°) ≤ 3	39
$^9Be(\pi^-,\pi^+)^9He$	5/2	40.81(12)	192	(15°) 40 ± 10	39
$^{14}C(\pi^-,\pi^+)^{14}Be$	3				
$^{18}O(\pi^-,\pi^+)^{18}C$	3	24.91(15)	162	(11°) 420 ± 90	9
$^{26}Mg(\pi^-,\pi^+)^{26}Ne$	3	0.44(7)	162	(5°) 260 ± 70	12
$^7Li(\pi^+,\pi^-)^7B$	-3/2	27.80(10)	180	(5°) 350 ± 50	39
$^{12}C(\pi^+,\pi^-)^{12}O$	-2	32.06(5)	180	(5°) 400 ± 50	32
$^{16}O(\pi^+,\pi^-)^{16}Ne$	-2	24.05(5)	180	(5°) 340 ± 40	32
$^{24}Mg(\pi^+,\pi^-)^{24}Si$	-2	10.68(5)	180	(5°) 110 ± 30	32
$^{28}Si(\pi^+,\pi^-)^{28}S$	-2				
$^{32}S(\pi^+,\pi^-)^{32}Ar$	-2	-2.18(5)	180	(5°) 84 ± 25	32
$^{40}Ca(\pi^+,\pi^-)^{40}Ti$	-2				
$^{58}Ni(\pi^+,\pi^-)^{58}Zn$	-1	-42.32(10)	291	(5°) 70 ± 30	39
$^9Be(\pi^-,p)^8He$	2	31.60(10)	125	(20°) 43 ± 7	39
$^6Li(\pi^-,p)^5H$	3/2	44.5 (15)?	125	(20°) 1400?	39

The level of accuracy obtainable presently in the determination of masses by pion DCX experiments is about ± 50 keV. At this level it does not seem too profitable to push the study of the masses of T_z = -2 nuclei by DCX experiments any further. Of the only two missing nuclei in this series, ^{28}S can be reached by (^4He, ^8He), whereas ^{40}Ti can not. We have therefore proposed[34]) the measurement of this mass by the $^{40}Ca(\pi^+,\pi^-)^{40}Ti$ reaction, but have so far not received approval to proceed.

Unbound ^7B

Our interest in ^7B was aroused by Guy Paić 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.[35]) The mass of ^7B had been measured earlier by McGrath, Cerny and Norbeck[36]) by means of the reaction $^{10}B(^3He, ^6He)^7B$ at $T(^3He)$ = 50 MeV. They had measured a mass excess of 27.94 ± 0.10 MeV and a width Γ = 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 ^{11}B in the target also added to the problems. Their 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.

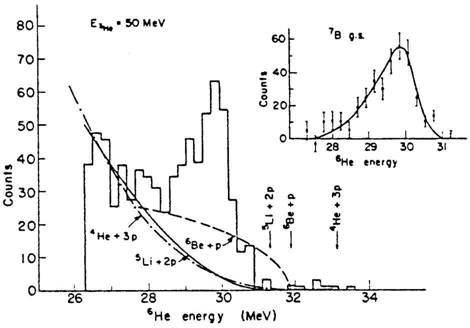

Fig. 11. Composite spectrum of ^7B from ref. 36.

We have studied the reaction $^7Li(\pi^+,\pi^-)^7B$ at $T(\pi^-)$ = 180 MeV and θ = 5°. The resulting π^- spectrum is shown in Fig. 12. The $^{42}Ca(\pi^+,\pi^-)^{42}Ti$ reaction, which has a Q-value within 500 keV of that for the $^7Li(\pi^+,\pi^-)^7B$ reaction, was used for calibration. The broad peak corresponding to ^7B(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-

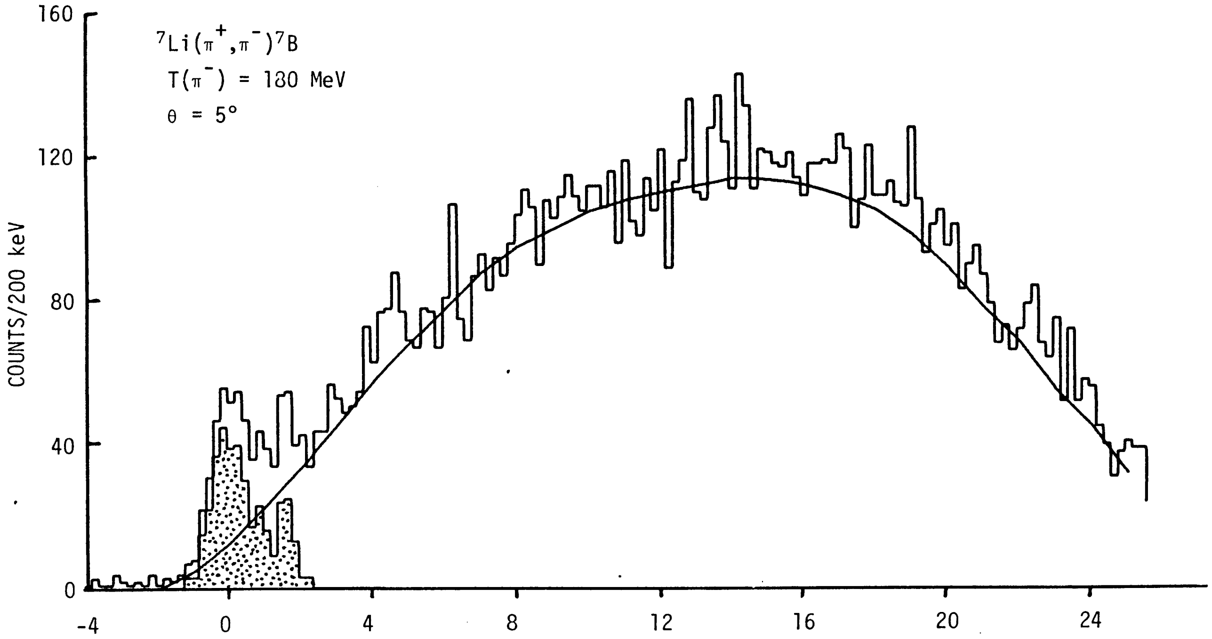

Fig. 12. Missing mass spectrum for the reaction $^7Li(\pi^+,\pi^-)^7B$.

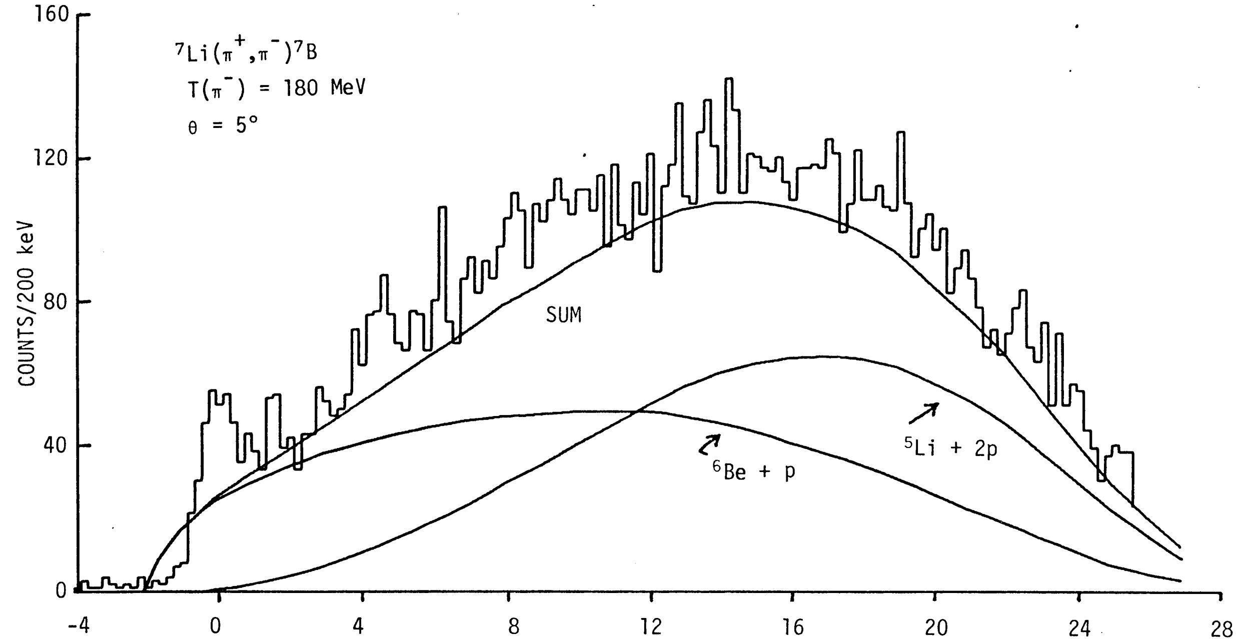

Fig. 13. Missing mass spectrum and phase space curves for the $^7Li(\pi^+,\pi^-)$ reaction.

butions. It is obvious that things do not work, particularly near the threshold for ^6Be+p break-up. Evidently, the particle instability of both ^6Be and ^5Li 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 ^7B (g.s.). We obtain the mass excess for it as 27.80±0.10 MeV and the width $\Gamma = 1.2 \pm 0.2$ MeV. These results are fully consistent with those of McGarth et al.[36]) Our data indicates the presence of a narrower structure at an excitation of ∿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 ^7B using the $M(T_Z) = a + bT_Z + cT_Z^2$ form of the isobaric mass multiplet equation and the masses of the J = 3/2-, T = 3/2 states in ^7Be, ^7Li and ^7He is 27.99 ± 0.08 MeV.[37]) This barely overlaps with our result. The conclusion that the coefficient, d of the T_Z^3 term is zero is therefore only marginally consistent with our data.

^{58}Zn: The masses of all zinc isotopes down to ^{60}Zn are known. ^{57}Zn is known to be a β-delayed proton emitter and its mass has been inferred indirectly by measurements of β-end point energies. However, no convenient means have yet been found to measure the mass of ^{58}Zn. We have measured this mass now by ^{58}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 ± 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.

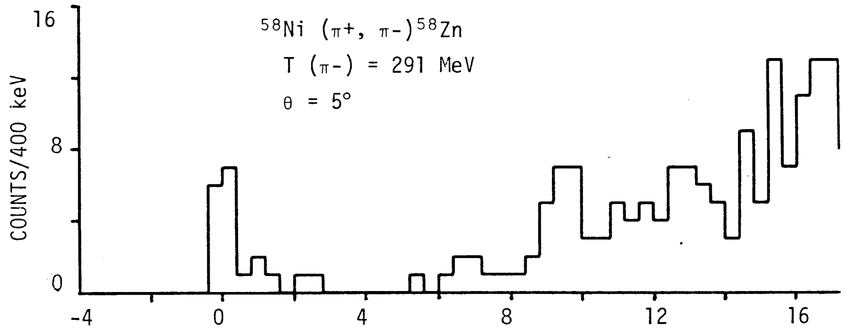

Fig. 14. Missing mass spectrum for ^{58}Ni$(\pi^+,\pi^-)^{58}$Zn reaction.

TABLE II. SUMMARY OF EXPERIMENTAL RESULTS WITH PREDICTIONS§

NUCLEUS	MASS EXCESS (MeV)							
	EXPERIMENT	M	GHT	LZ	BLM	JGK	MN	WB
^{5}H	44.5(15)				29.8			33.79(80)
^{7}H								
^{9}He	40.81(12)				38.0*	42.03*		
^{14}Be			41.72**		37.9	40.72		
^{18}C	24.91(15)		25.09		22.6	25.53		
^{26}Ne	0.44(7)	0.45	0.13	-0.31	-1.2	0.19	0.40	
^{7}B	27.80(10)				25.0*			27.94(10)
^{12}O	32.06(5)		32.52**		28.20	33.05		32.07(26)
^{16}Ne	24.05(5)		25.01**		21.90	24.67**		24.11(14)
^{24}Si	10.68(5)	4.13	9.62	10.81	9.40	10.74	9.90	10.75(12)
^{28}S		0.09	3.88	4.09	3.10	4.41	2.77	4.20(12)
^{32}Ar	-2.18(5)	-5.84	-2.81	-2.19	-2.00	-2.20	-2.35	-2.20(13)
^{40}Ti		-12.65	-11.51	-8.89	-9.60	-9.01	-10.19	-9.03(23)
^{58}Zn	-42.32(8)	-47.73	-43.32	-42.60	-41.60	-42.59	-41.84	

§ M, GHT, LZ, BLM, JGK and WB, predictions compiled in Atomic and Niclear Data, 17 (1976) 474.
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IV. 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 ^{18}O, ^{14}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 (±25 keV appears to be possible with some hard work), but excited states and sometimes their J^π can be quite directly determined. Similarly, the (π^-,p) reaction, whose analog would be a reaction of the type (n,2p), appears to be the only possible one of its type presently. $(\pi^-, {}^3\text{He})$, and even more exotic reactions are clearly on the horizon.

In my talk I have tried to show that pion-induced reactions are powerful new tools in the study of exotic nuclei. In the short span of three years they have made valuable contribution to the field. This achievement is particularly impressive when it is realized that barely three out of the twelve measurements reported in Table 1 were approved by the program advisory committees. The rest, including the first one on ^{18}C, were done on the side, *par la main gauche*, in 'left-over' time from other approved experiments that the groups happened to have been doing. In other words, most of the experiments were not optimised to give the best results they could. This is, of course, an unfortunate situation and must be avoided. On the other hand, it is a fact that intense pion beams are rarer and perhaps costlier than any other beams, and PAC's are indeed most reluctant to approve long experiments whose end result 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 cannot 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.

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DISCUSSION

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

K.K. Seth: Pion DCX would 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. Bernas: The $(^{14}C,^{14}O)$ 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 $(^{14}C,^{14}O)$. I have however talked to the experts both at Los Alamos (Peng et al.) and Orsay (Dêtraz et al.) and they tell me that these cross sections fall precipitously with increasingly negative Q. For a reaction like that to ^{14}Be, the Q is almost - 40 MeV. I am told that there is very little hope at the presently available ^{14}C energies to make such excursion 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. Dêtraz: As reported in a communication to this conference (Naulin et al.) we have observed double charge heavy ion reactions at the AP Tandem: the $(^{18}O,^{18}C)$ reaction confirms the mass you obtained. It has a 40 nb per sr, which indeed made it just possible with a thick target. As for the ^{14}Be mass, we plan to use the similar $(^{14}C, ^{14}Be)$ 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 ^{5}H have been titled "search for ^{5}H", "Another search for ^{5}H" and "Still another search for ^{5}H". Do you have a title for your paper on ^{5}H?

K.K. Seth: Yes, the title will be: The Last Word on ^{5}H.