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SINGLE CHARGE EXCHANGE FOLLOWING π^- CAPTURE*

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To complement planned experiments in which deeply bound pionic atom states are to be produced, the reaction (π^-, π^0) was examined close to threshold. Branching ratios for that reaction on CH_2, ^{27}Al, ^{31}P, ^{32}S, ^{45}Sc, and ^{115}In were determined experimentally. The results were compared with previous experimental work and with a calculation based on the Panofsky ratio. The results can be understood in terms of the shell structure of the target nuclei.

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1. Introduction

Negative pion capture into deeply bound atomic states associated with nuclei of mass number $A = 32$ is of considerable current interest, both from a theoretical and experimental point of view. Following the formation of a pionic atom in such a low-lying state, the pion is likely to be captured by the nucleus and to interact with it at close to zero incident energy. Of particular interest is the single charge exchange (SCX) reaction

$$Z^{A(\pi^-\pi^0)}Z - 1^A .$$

That reaction is governed by the effective pion-nucleon (πN) isovector interaction, whereas the effective πN isoscalar interaction governs pionic atom formation. The information obtained from one of these processes is, therefore, complementary to that obtained from the other. Both are needed to understand the πN interaction in nuclei at low energies, in particular to provide constraints on the πN amplitudes in pion-nucleus optical models. While the isoscalar part of the πN interaction is quite well known and the potential parameters have been established for some time, the isovector part is much less known.

One reason why the isovector part of the πN potential at low energies is so little known are the severe experimental problems one encounters in the study of the (π^-, π^0) reaction is general and at incident energies close to zero in particular, among them the following:

- The π^- beam, typically available at energies of not less than 30 MeV, must be degraded to a much lower energy; and the π^- intensity must be determined in the presence of considerable μ^- and e^- contamination.
- The π^0 can only be detected and counted through its decay products:

$$\pi^0 \rightarrow 2\gamma \quad E_\gamma = 67.5 \text{ MeV}; \; \tau = 8.4 \times 10^{-17}\text{s}, \; c\tau = 2.5 \times 10^{-6}\text{cm}.$$

- One must cope with large background due to π^0 decay from (π^-, π^0) reactions in flight, *i.e.* before the π^- comes to rest; from (π^-, π^0) reactions on H, which has a high branching ratio for this reaction and which is present in many materials as a contaminant; and from γ's and neutrons due to other reactions with considerably higher cross sections.

Because of these and other difficulties, only a few experiments involving the (π^-, π^0) reaction close to threshold have been done in the forty years since Panofsky *et al.* determined for the first time the ratio of the transition rate of the (π^-, π^0) reaction relative to that of the (π^-, γ) reaction for π^- capture on H and D [1]. That ratio has been redetermined recently for H [2] and for D [3], and it has also been determined for ^{3}He [4] and ^{6}Li [3].

The branching ratio for (π^-, π^0) relative to all other possible reactions, BR (π^-, π^0), has been determined at TRIUMF (BR values for nine targets ranging from D to Pb) [3, 5]. An earlier attempt at Dubna resulted in upper limits for the BR (π^-, π^0) for seven targets from ^{6}Li to Pb [6]. These results will be shown in Section 3. Our own experiment was motivated by the need for additional and, if possible, more precise determinations of BR (π^-, π^0).

2. Experimental setup

Our experimental setup (Fig. 1) was basically similar to the one used in all previous experiments of this nature: A low-energy π^- beam was collimated and degraded to the lowest possible energy so that it came to rest in the target; the two γ's from the π^0 decay were detected in coincidence in two large detectors that were shielded as well as possible from background photons and particles.

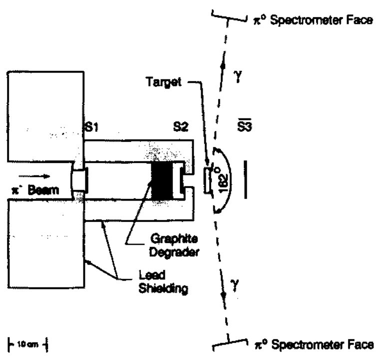

Fig. 1. Schematic top view of experimental setup. Scintillators S1 and S2 define the beam. To avoid background counts from the H content of the scintillators, S2 was housed inside a 5 cm thick and 6.8 cm long Pb collimator, and the veto counter S3 was removed during data collection. (see text.)

A 50 MeV π^0 beam from the Low-Energy Pion (LEP) Channel at the Clinton P. Anderson Meson Physics Facility (LAMPF) was slowed to 4 ± 1 MeV in a graphite degrader (Fig. 1a). The pions were further slowed in the material between degrader and target (air and scintillator S2) and come to rest in the target. The LEP beam was composed of 40% π^-, 50% or more e^-, and about 10% μ^- [7].

Each of the two γ's from the π^0 decay was detected in one arm of the LAMPF π^0 spectrometer [8]. Each arm consisted of a thin scintillator to veto charged particle events, three converter planes, and an array of total-absorption Pb-glass blocks (Fig. 1b). The converter planes each consisted of an active Pb-glass converter, three multi-wire proportional chamber

(MWPC) planes, and a trigger scintillator. For photons converting in one of the three planes, the conversion coordinates were determined from the MWPC information; the energy deposited in the converters and the blocks, which contained the full shower, was measured. The total energy of the π^0 was found from the opening angle between the decay photons and the asymmetry between the energy deposited in each arm. The spectrometer was set with the γ-γ opening angle in the horizontal plane. The opening angle was 162°, as required by the energies of the decaying π^0 in the lab system. These energies varied between 1.33 and 3.66 MeV, depending on the (π^-, π^0) Q values (see Table I).

TABLE I

The targets used in this work.
All targets were thick enough (1.1 to 3.4 g/cm^2) to stop π^- beam.

Target	$Q(\pi^-, \pi^0)$ (MeV)	Purpose
CH_2	3.3	Expect large BR; compare with previous work.
^{12}C	−9.31	Expect zero BR; compare with previous work.
^{27}Al	1.33	Expect small BR[1]; compare with previous work.
^{31}P	2.39	
^{32}S	2.15	Expect relatively large BR[2]
^{45}Sc	3.43	
^{115}In	1.66	Expect small BR[1].

[1]because of mismatch between target and product nuclear wave functions.
[2]because of overlap between target and product nuclear wave functions.

The targets used in this work were selected according to the criteria listed in Table I. In addition, they had to have a relatively simple shell structure, only one isotope with positive Q value for the reaction, and a minimum of hydrogen contamination.

We determined the number of π^-'s that come to rest in the target, N_{π^-} before and after each data run with the scintillator combination $S1.S2.\overline{S3}$ (Fig. 1). Typical rates were of the order of 10^5 π^-/s. During the data runs the anticoincidence counter S3 was removed to avoid π^0 background from the hydrogen content of the scintillator. The relative beam intensity during each data run was monitored with a toroidal current monitor through which the primary proton beam passed. The absolute normalization of the pion intensity was established before and after each data run by measuring the ^{11}C activity induced in scintillator disks and making use of the known cross section for ^{12}C (π^-, π^0N) ^{11}C [9]. Since that cross section is known down to the energy with which the pions enter the degrader but not to the energy with which they leave it, the activation was made in front of the degrader. The uncertainty in the beam flux determination was about 6%. Knowledge of the π^- flux was sufficient to normalize the experiment, because the μ^-/e^- contamination could not produce π^0's.

The number of π^0's produced, N_{R^0}, and the π^0 energy spectrum were determined in one or more data runs on each target. The CH_2 target was run for periods of an hour, the others for periods of three to thirty hours, depending on the yield. Target-out runs showed that there was no background due to reacting in the air in front of the target. Appropriate shielding prevented background events from in-flight π^-'s that reacted in the components of the setup or the intervening air. Neutrons from (π^-, 2e) reactions could not produce background, because such neutrons produce below-threshold signals in the spectrometer arm calorimeters. Contributions to the yield from the π^-'s that enter the target with finite velocity, v, and interact before they are completely stopped are considered to be quite small, because one can expect that the cross section $\sim 1/v$. Such contributions cannot be determined directly because severe experimental difficulties prevent (π^-, π^0) cross section measurements below 30 MeV [9].

3. Experimental results

Typical histograms showing N_{π^0} *vs.* π^0 kinetic energy are shown in Fig. 2. Results of Monte Carlo calculations of the energy spectrum are shown for comparison. Such histograms were obtained for each data run. The BR of (π^-, π^0) relative to all other possible interactions was calculated from the relation

$$BR(\pi^-,\pi^0) = \sum_{i=1}^{n} \frac{N_{\pi_i^0}}{N_{\pi^-} \cdot \varepsilon_{tot} \cdot \Delta\Omega_g} \cdot 4\pi ,$$

where i is the number of bins in the histogram, $N_{\pi_i^0}$ the number of counts per bin, N_{π^-} the number of stopped π^- in the target ε_{tot} the total efficiency, and $\Delta\Omega_g$ the geometrical solid angle. That angle was calculated with a Monte Carlo program, with errors ranging from 2 to 8%. The errors contributing to ε_{tot} were about 2%. The BR values obtained from our experimental results are listed in Table I.

Comparison of the experimental histograms with the Monte Carlo results allows an estimate of the contribution to the π^0 yield from incompletely

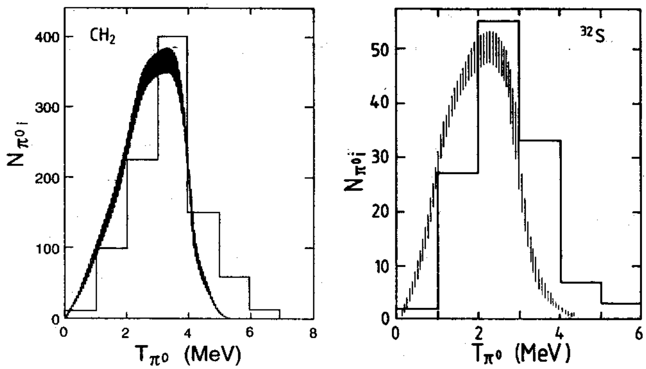

Fig. 2. Histograms showing the number of π^0 spectrometer counts *vs.* π^0 kinetic energy. The results of the Monte Carlo simulation (shaded area) are also shown.

stopped π^-'s in the target. In the Monte Carlo calculation, the π^-'s are assumed to be completely stopped, so that the calculated distribution is centered around a π^0 kinetic energy determined by the reaction Q-value (Table I). The experimental distributions are shifted to higher energies; the highest is about 4 MeV above the Monte Carlo centroid, the average energy with which the π^-'s enter the target. The BR determined in this experiment is, therefore, the BR for SCX between 0 and 4 MeV incident energy. The difficulty of excluding events produced by incompletely stopped pions in the target is systematic and was also present in all previous BR determinations near threshold. The BR values so obtained must, therefore, be considered upper limits of the values at threshold.

4. Discussion and results

For ^{12}C, the BR(π^-, π^0) was found to be zero, as expected from the low negative Q-value for the reaction. The BR(π^-, π^0) for CH_2 has been determined previously in the course of determinations of the pion capture rate, W at CERN [10] and Nevis [11]. From another determination of W at Dubna [12], one can obtain a value for the BR(π^-, π^0), if one calculates the BR(π^-, γ) from the Panofsky ratio BR(π^-, π^0)/BR(π^-, γ)=1.546±0.009 [2] and notes that W=BR(π^-, π^0)+BR(π^-, γ). Our result is seen to be in good agreement with the CERN result, while the Nevis and Dubna values are just above and below, respectively, our error limits. (See Table II.)

For the other targets, our BR values show a strong correlation with the reaction Q-values (Table I), although other factors affect the outcome of the reactions as well. The Q-values were calculated from the equation

$$Q = m_{\pi^-} + m_A + \mathrm{E}_n - (m_{\pi^0} + m_{B_{gs}}),$$

where E_n is the negative energy of the π^- bound in an atomic orbit having principal quantum number n. The most probable pionic orbit in In has $n = 3$ and in the other target materials $n = 2$. The Q value calculated for CH_2 is that for the elementary reaction $p(\pi^-_{stop}, \pi^0)n$, because the reaction on ^{12}C is energetically forbidden. A special feature of the (π^-, π^0) reaction close to threshold is that the momentum transferred to the nucleon on which the reaction takes place is close to zero. Consequently, in order to have nonzero nuclear transition matrix elements, the initial and final nuclear wave functions must have good spatial overlap. Larger Q-values will make more final states energetically accessible and thus enhance the probability of the reaction to take place.

TABLE II

Branching ratios for $(\pi^-, \pi^0)/(\pi^-, \text{all})$, $E_{\pi^-} \to 0$ MeV

Tgt.	Dubna 1964[a,b] $(\times 10^{-5})$	Nevis 1964[c] $(\times 10^{-5})$	CERN 1963[d] $(\times 10^{-5})$	TRIUMF 1977[e];1981[f] $(\times 10^{-5})$	LAMPF 1993[g] $(\times 10^{-5}$
CH_2	640 + 100[a]	1070 + 110	850 + 70		869 + 53
^2D				14.5 ± 0.19[e]	
^6Li				0.28 ± 0.064	
	< 3				
$^7Li^*$				0.033 ± 0.046	
$^9Be^*$	< 6				
$^{12}C^*$	< 4			0.010 ± 0.023	0
^{27}Al	< 5			0.48 ± 0.15	< 0
^{31}P					4.79 ± 0.91
^{32}S					19.4 ± 4.4
^{45}Sc					4.70 ± 1.67
$^{47,49}Ti$	< 4			2.7 to 6.0	
$^{63,65}Cu$	< 5			0.45 to 1.61	
^{93}Nb				0.10 to 0.21	
^{115}In					< 0.21
^{207}Pb	< 2			0.17 to 0.87	

* (π^-, π^0) reaction energetically forbidden at $E_{\pi^-} \to 0$ MeV.

a See calculation, Section 4 and Ref. [12].

b See Ref. [6].

c See Ref. [11].

d See Ref. [10].

e See Ref. [3].

f See Ref. [5].

g Present work.

The nuclear structure of ^{31}P and ^{32}S contains significant s- and d-shell configuration mixing. The Q values for these targets are about 2.2 MeV, which are sufficient for the neutron produced in the reaction to access nearly all states with s–d shell mixing in the final nucleus, resulting in a good overlap between initial and final nuclear wave functions. For ^{45}Sc, where the nuclear structure is represented by f–p shell mixing, the Q-value is 3.43 MeV, sufficient to allow the produced neutron to access all states with f–p shell mixing in the final nucleus. The good wave function overlap can be considered to be responsible for the relatively high BR's observed for ^{31}P, ^{32}S, and ^{45}Sc.

The much lower BR's for ^{27}Al and ^{115}In can be understood in a similar way. Since ^{27}Al is described by a shell model space much larger than just the levels due to s- and d-shell mixing and since the Q-value in that case is only 1.33 MeV, the produced neutron can only access a few low-lying states in the final nucleus. These few states comprise only a small fraction of the shell model space and overlap, therefore, poorly with the initial proton state. For ^{115}In, the Q-value of 1.66 MeV allows the produced neutron to occupy states mainly in the $3s_{1/2}$ and $1h_{11/2}$ region in the final nucleus, and these states are nearly orthogonal to the initial $1g_{9/2}$ proton state. For the BR of ^{27}Al, a similar value has been found in a previous experiment [3].

In summary, we have determined the branching ratio for single charge exchange induced by negative pions close to threshold in CH_2, ^{31}P, ^{32}S, and ^{45}Sc, and we have established upper limits for ^{27}Al and ^{115}In. We have found our results to be in agreement with considerations based on the shell model structure of the target and product nuclei and with previous work where comparisons are possible. Theoretical calculations with which our results can be compared are called for. They are expected to lead to values of the parameters for the isovector part of the pion-nucleon potential at low energies. Additional experimental work with the new LAMPF zero charge meson spectrometer, in particular on a ^3He target, is planned. The results of the present work may also be of use in pionic atom experiments, because the detection of a π^0 near the threshold can be used as a signal that a pionic atom had been formed [13].

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