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Absence of $J^{\pi},T=0^{+},1$ level excitations in residual nuclei from $(\pi^{\pm},2N)$ reactions

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Gamma-ray spectra taken in prompt coincidence with incident 180-MeV π^{+}, 220-MeV π^{-}, and 0-MeV π^{-} on the self-conjugate targets ^{12}C and ^{32}S show that the cross sections/yields are equal to or near zero for production of the $J^{\pi},T=0^{+},1$ levels of the odd Z, odd N nuclei resulting from np removal. The 0-MeV π^{-} results can be explained by selection rules governing one-step quasifree interactions, but the $\Delta(1232)$ region results cannot. This suggests that there may be additional restrictions upon the pion absorption mechanism.

NUCLEAR REACTIONS ^{12}C$(\pi^{\pm}, X\gamma)^{10}$B, ^{32}S$(\pi^{\pm}, X\gamma)^{30}$P; $E_{\pi^{-}}=0$ MeV, 220 MeV; $E_{\pi^{+}}=180$ MeV; detected γ rays, Ge(Li); measured E_{γ}, 90° σ and Y (%) for np removal; deduced reaction mechanism.

I. INTRODUCTION

Rather extensive studies have been made of the deexcitation γ-ray spectra from excited states of residual nuclei produced in pion-nucleus reactions (see, e.g., Refs. 1–12). The spectra are generally characterized by the residual nuclei from a wide variety of processes, from inelastic[2] and charge exchange scattering[3] to the removal of up to twenty nucleons.[1] The sets of cross sections/yields for production of residual nuclei obtained from these spectra have been somewhat difficult to interpret because they contain contributions both from direct reactions and from intranuclear cascade/statistical evaporation processes. Single γ-ray spectra from fast pion reactions contain, in addition, contributions from both in-flight absorption and scattering processes. Cross sections/yields for removal of large numbers of nucleons ($\Delta A \geq 5$) are reproduced reasonably well by intranuclear cascade/statistical evaporation calculations,[4] but in the $\Delta A \leq 4$ region the cross sections/yields appear to contain sizable contributions from other processes.

This paper focuses on a common characteristic observed in the prompt γ-ray spectra due to one type of two-nucleon removal from self-conjugate (i.e., even $Z=$ even N) target nuclei. There is essentially no production of the J^{π}, $T=0^{+}$, 1 states of the odd Z, odd N residual nuclei which result from removal of a neutron-proton pair. (The reactions considered here result in the removal of an np pair from the target. The incident pion either re-emerges or is absorbed by the np pair and changes it into a pp or nn pair.) This null result appears to hold for stopped π^{-} and for $\Delta(1232)$-energy pions of both charge states on ^{12}C and ^{32}S. Similar null results were obtained in earlier experiments[7,8] with stopped and $\Delta(1232)$-energy π^{-} on ^{16}O. (Because of experimental problems two-nucleon removal from other self-conjugate nuclei which would lead to J^{π}, $T=0^{+}$, 1 states of the residual nuclei cannot be readily observed with prompt γ-ray decay techniques.)

Interaction with a nucleon pair is considered to be the dominant mode of the initial interaction of 0-MeV π^{-} and an important mode in fast pion reactions. Indeed, the cross sections/yields for $T=0$ low-lying states of residual nuclei produced in two-nucleon removal are typically of the order of ~10 mb/2.2%. The absence of cross sections for the low-lying J^{π}, $T=0^{+}$, 1 states of such nuclei was therefore initially surprising. It will be shown (in Sec. IV) that the absence of yields leading to these states can be understood as a consequence of the selection rules governing quasifree π^{-} absorption upon a pair for the stopped pion case, but that additional restrictions upon the mechanism may be necessary to explain their suppression in the Δ(1232) energy region.

II. EXPERIMENTS AND DATA ANALYSIS

The Space Radiation Effects Laboratory synchrocyclotron provided a π^+ beam with an average energy in the targets of 180 MeV, a π^- beam with an average energy of 220 MeV, and a π^- beam of 116 MeV which was energy degraded to maximize π^- stopping events in the target. The thicknesses of the natural carbon targets were 1.55 g/cm^2 for fast $\pi^\pm$ and 5.6 g/cm^2 for stopped π^-. The thicknesses of the natural sulfur targets were 7.6 g/cm^2 for fast π^+, 9.1 g/cm^2 for fast π^-, and 8.4 g/cm^2 for stopped π^-.

The γ rays were detected with a Ge(Li) detector of 8% efficiency in coincidence with the incident pions and in anticoincidence with events from a cup-shaped scintillator that surrounded the Ge (Li) detector to veto charged particles. The stopped π^- experiments also included a scintillator immediately downstream from the target which was set in anticoincidence with the beam telescope. A schematic of the fast pion apparatus is shown in Fig. 1. Details concerning the apparati and procedures were similar to those described in Ref. 1.

Portions of typical spectra taken in these experiments are shown in Figs. 2–4. Background and random contributions to the spectra were obtained by taking additional spectra over an interval of about 150 ns which was delayed relative to true coincidence events. Properly normalized delayed-coincidence spectra were subtracted from the prompt spectra to eliminate background peaks. Prompt background arising from secondary target interactions was not eliminated by this procedure.

The spectral peaks were least-squares fitted to a Gaussian line shape and an exponential background. Fits were accepted only when the normalized χ^2 was less than 1.2. Peaks were identified with transitions using published excitation energy, lifetime, and branching ratio values.[13,14] Assignments were made when the measured energy value differed by less than 1 keV from the published value and when observed branching ratios were in agreement.

Yields and cross sections for excitation of each state were computed from the area of the peak, the absolute detector efficiency corrected for γ-ray absorption in the target, the target parameters, and the number of incident (or stopped) pions. Isotropic emission of the γ rays was assumed.

The errors given in the tables represent statistics plus a small additional amount added in quadrature which accounts for uncertainties in the efficiency calibration as a function of energy. One should also allow for a systematic error of up to 20% to conservatively account for uncertainties in absolute normalizations. It should be stressed, however, that this uncertainty scales in direct proportion to the cross section/yield, and consequently does not affect the results regarding the J^π, $T = 0^+$, 1 states.

III. EXPERIMENTAL RESULTS

The γ-ray spectrum produced by stopped π^- on ^{12}C displayed only four target-related lines, all of them from states of ^{10}B. The fast $\pi^\pm$ spectra from ^{12}C showed the same lines, plus lines from ^{11}B and ^{11}C, i.e., lines resulting from single-

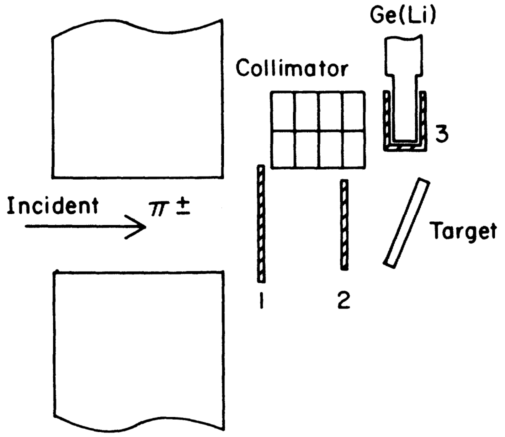

FIG. 1. Apparatus used in the 180-MeV π^+ and 220-MeV π^- experiments. The 0-MeV π^- experiments utilized an additional scintillator placed directly behind the target. This counter was set in anticoincidence with scintillators 1 and 2.

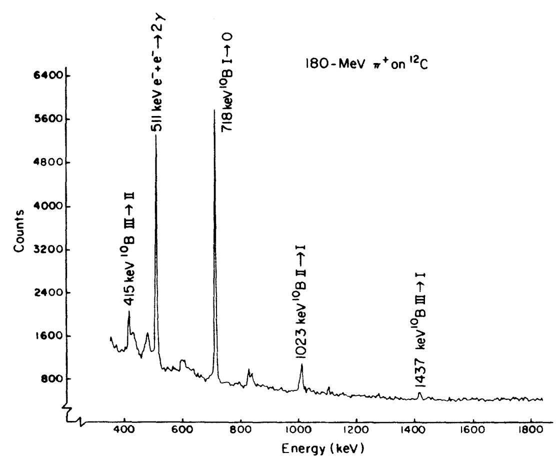

FIG. 2. The spectrum of γ rays taken in prompt coincidence with 180-MeV π^+ incident on carbon.

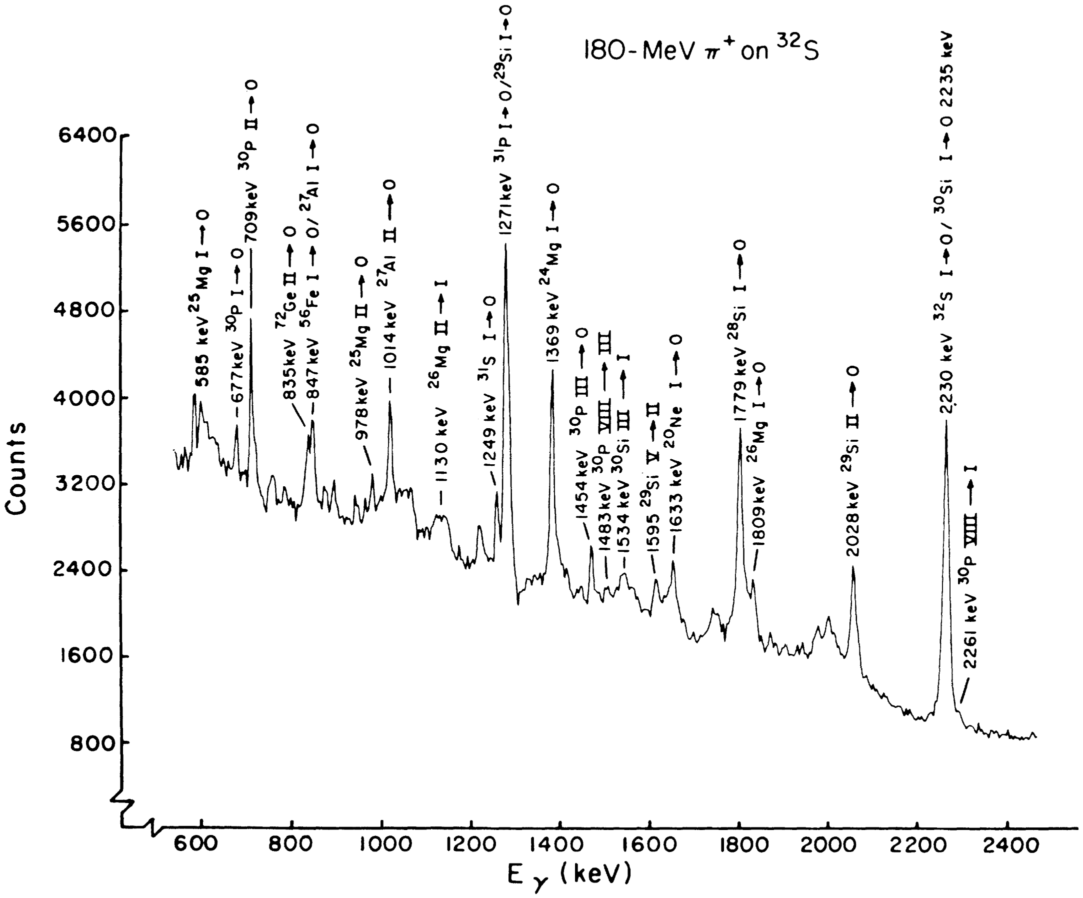

FIG. 3. The spectrum of γ rays taken in prompt coincidence with 180-MeV π^+ incident on sulfur.

nucleon removal reactions that are discussed in a separate paper,[5] as well as lines from ^{9}Be and ^{7}Li. The yields/cross sections for two-nucleon removal resulting in states of ^{10}B are listed in Table I for all three experiments on ^{12}C. The yields/cross sections for two-nucleon removal producing states of ^{30}P in the corresponding reactions on ^{32}S are listed in Table II. The production of other residual nuclei from ^{32}S will be described elsewhere.[6]

In the results from all six experiments the J^π, $T = 0^+$, 1 states in the odd Z, odd N residual nuclei formed by two-nucleon removal are seen to be essentially absent. In cases where the peaks are present in the raw data, corrections for branching and for feeding from observed higher levels account for essentially all of their strength: The corrected cross section of 0.07 ± 0.16 mb observed for the 0^+, 1 state of ^{10}B from 220-MeV π^- on carbon, and the corrected yield of 0.14 ± 0.12% for the same state from stopped π^- reactions are both consistent with zero and are certainly negligible compared with the 7.5 mb/14% cross section/yield for the sums of the other two observed states.

In an experiment similar to ours by Zaider *et al.*[9] with 70-MeV $\pi^\pm$ on ^{32}S, the 0^+, 1 state of ^{30}P was not observed either. In an experiment by Kossler *et al.*[7] with 0-MeV π^- on ^{16}O, the 0^+, 1 state of ^{14}N at 2311 keV was only very weakly excited. Likewise, Lieb and Funsten[8] found that the production of this state by 220-MeV π^- incident on ^{16}O could be largely, if not completely accounted for by feeding. On the other hand, there is no suppression of the J^π, $T = 0^+$, 1 states arising from the analogous proton-induced two-nucleon removal reactions $^{16}O(p, {}^3He){}^{14}N$ and $^{12}C(p, {}^3He){}^{10}B$ at $E_p = 39.8$ MeV.[15]

The J^π, $T = 2^+$, 1 state at 2938 keV in ^{30}P is not observed in the reactions of fast $\pi^\pm$ with ^{32}S (apart from feeding from higher levels), but is seen in the spectrum from the stopped π^- interaction. The latter may arise from a different reaction mechanism, or it may simply be an artifact of the

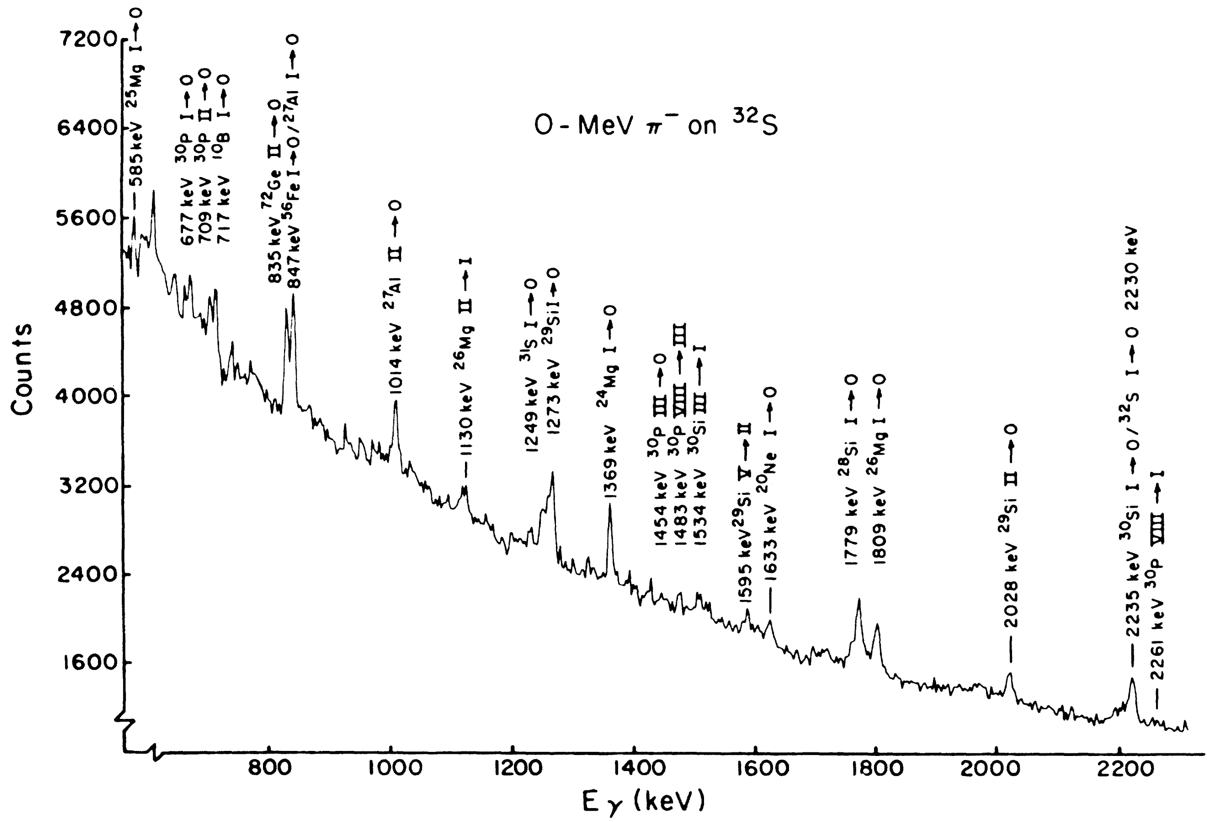

FIG. 4. The spectrum of γ rays taken in prompt coincidence with 0-MeV π^- stopped in sulfur.

stopped π^- experiment. The counting statistics in this spectrum were not as good as they were in those arising from fast pion reactions. Thus some high-energy lines which feed the level at 2938 keV may have been below the statistical threshold. Also, it is impossible to extract any feeding contribution from the ^{30}P state at 4734 keV because its primary branch has an energy of 1796 keV and it would thus lie on the shoulders of the Doppler-broadened peaks at 1779 keV (^{28}Si $2^+ \to 0^+$) and 1809 keV (^{26}Mg $2^+ \to 0^+$).

IV. DISCUSSION

Pion capture on a nucleus of mass A involving a first-order direct one-step absorption on a nucleon pair implies selection rules forbidding certain J^π, T states in the residual $A-2$ nucleus. In an earlier paper[7] on $\pi^- + {}^{16}O$ these were obtained from the usual nonrelativistic pseudovector πN absorption interaction on the ith nucleon:

$$H_{\text{int}} \propto \tau_i \vec{\sigma}_i \vec{\nabla}_\pi \Phi . \tag{1}$$

TABLE I. Levels of ^{10}B observed in $\pi^\pm + {}^{12}C \to {}^{10}B^* + \binom{2N}{2N+\pi}$ reactions.

State		180-MeV π^+		220-MeV π^-		0-MeV π^-	
J^π, T	E (keV)	Uncorrected σ (mb)	Corrected σ (mb)	Uncorrected σ (mb)	Corrected σ (mb)	Uncorrected Y (%)	Corrected Y (%)
$1^+, 0$	718	13.3 ± 2.5	11.1 ± 2.3	7.2 ± 1.3	5.7 ± 1.1	12.7 ± 0.2	9.46 ± 0.31
$0^+, 1$	1740	1.2 ± 0.7	0	1.0 ± 0.2	0.07 ± 0.16	1.71 ± 0.12	0.14 ± 0.12
$1^+, 0$	2154	3.84 ± 0.63	3.84 ± 0.63	1.8 ± 0.4	1.8 ± 0.4	3.09 ± 0.24	4.23 ± 0.23
$2^+, 0$	3587	<7.8	<7.8	<3.7	<3.7		

TABLE II. Levels of ^{30}P observed in $\pi^{\pm}+{}^{32}\text{S}\rightarrow{}^{30}\text{P}^{*}+\binom{2N}{2N+\pi}$ reactions.

State		180-MeV π^+		220-MeV π^-		0-MeV π^-	
J^{π},T	E (keV)	Uncorrected σ (mb)	Corrected σ (mb)	Uncorrected σ (mb)	Corrected σ (mb)	Uncorrected Y (%)	Corrected Y (%)
$0^+,1$	667	2.6 ± 0.4	0	4.1 ± 1.0	0	0.48 ± 0.10	0
$1^+,0$	709	8.4 ± 0.4	7.7 ± 0.4	7.5 ± 1.2	6.1 ± 1.2	0.83 ± 0.19	0.70 ± 0.19
$2^+,0$	1454	5.9 ± 0.5	3.8 ± 0.7	6.7 ± 1.0	4.9 ± 1.5	1.07 ± 0.22	0.65 ± 0.29
$3^+,0$	2538	1.6 ± 1.1	1.7 ± 1.2				
$2^+,0$	2723	1.2 ± 0.4	1.2 ± 0.4	3.9 ± 0.7	3.9 ± 0.7	0.95 ± 0.30	0.95 ± 0.30
$2^+,1$	2938	3.4 ± 0.8	0	4.2 ± 1.2	$0.3\,^{+2.5}_{-0.3}$	0.85 ± 0.40	1.15 ± 0.29
$1^+,0$	3019	0.9 ± 0.4	0.9 ± 0.4	1.4 ± 0.5	1.4 ± 0.5	0.24 ± 0.12	0.24 ± 0.12
$2^+,0$	3834	2.4 ± 0.3	4.0 ± 0.5	2.5 ± 0.3	4.2 ± 0.5		
$1^+,0$	5712	2.7 ± 1.1	2.7 ± 1.1	4.2 ± 2.0	4.2 ± 2.0		

Koltun[16] has derived selection rules applicable to pion absorption at rest with more general operators which include not only πN, but also πNN absorption, the latter involving pion rescattering. He obtained selection rules for absorption from pionic orbitals $l_\pi=0$:

$\Delta I_p=0$, parity change

$$\begin{array}{lll} \Delta L=0, & \Delta l=1 & T_p,S_p=1,0\leftarrow 1,1 \\ & & \qquad\;\; 0,1\leftarrow 1,1 \\ \Delta L=1, & \Delta l=0,2 & T_p,S_p=1,1\leftarrow 1,1 \\ & & \qquad\;\; 1,1\leftarrow 0,0 \\ & & \qquad\;\; 1,0\leftarrow 0,1 \\ & \Delta L_p=1 \text{ both cases,} & \end{array} \tag{2}$$

and $l_\pi=1$:

$\Delta I_p=0$, no parity change

$$\begin{array}{lll} \Delta L=0, & \Delta l=0,2 & T_p,S_p=1,1\leftarrow 1,1 \\ & & \qquad\;\; 1,1\leftarrow 0,1 \\ & & \qquad\;\; 1,0\leftarrow 0,1 \\ \Delta L=1, & \Delta l=1,3 & T_p,S_p=1,1\leftarrow 1,0 \\ & & \qquad\;\; 1,1\leftarrow 0,1 \\ & \Delta L_p=0,2 \text{ both cases.} & \end{array} \tag{3}$$

These rules are stated in terms of the center-of-mass orbital angular momentum (L), the relative orbital angular momentum (l), the total orbital angular momentum of the absorbing pair (L_p), its spin (S_p), total angular momentum (I_p), and isospin (T_p), using the fact that the absorption transition operator transforms as a tensor of rank l_π and parity $l_\pi+1$ in the complete pair space.

For both ^{12}C and ^{32}S, pion capture at rest occurs mainly from the $l_\pi=1$ atomic orbital. The fraction of pions in the l_π orbital which capture is

$$[\Gamma/(\Gamma+\Gamma_{em})]_{l_\pi}=1-Y/P_{l_\pi}, \tag{4}$$

where Γ and Γ_{em} are the (nuclear) capture and x-ray dipole widths, ignoring Auger transitions. Y is the x-ray yield from this state with population P_{l_π}. From results of pionic x-ray work,[17,18] $(1-Y/P)\simeq0.9$ for the $2p$ orbital in the ^{12}C case, and $\simeq0.8$ for ^{32}S, i.e., $l_\pi=1$ a major fraction of the time, and hence selection rules (3) apply. These are also valid for a p-wave pion relative to the nucleon pair.

Due to the large final-state momentum of the capturing nucleons with respect to each other, pion absorption is enhanced by a short-range interaction or an NN pair correlation. Pion absorption without either is smaller by several orders of magnitude, as can be seen by taking the overlap integral I_l between an initial state consisting of the two nucleons in a central harmonic oscillator well of parameter $k_i=0.6f^{-1}$ with relative angular momentum l and a plane wave pair final state with relative momentum $k_{pf}=1.8f^{-1}$. Using a Moshinsky transformation[19] with the initial-state pair center of mass R_p and relative coordinates r_p, I_l becomes just the pair relative momentum wave function $\Psi(\sqrt{2}k_{pf})$, evaluated far out on the tail of the initial-state pair relative-momentum wave function, which falls off approximately as $\exp[-(k/0.6f^{-1})^2]$ for $k\gtrsim0.6f^{-1}$. Even if the tensor absorption transition operator induces an angular momentum change between the initial and final l values of the pair l_i and l_f, the resulting overlap

$$I_{n_il_i,l_f}=\int\Psi_{n_il_i}(k_ir_p/\sqrt{2})\,j_{l_f}(k_{pf}r_p)\,r^2\,dr \tag{5}$$

will still be small. For example, $I_{01,2}\sim\frac{1}{20}\,|\Psi_1(k)|_{\max}$

A short-range interaction such as, e.g., a Jastrow pair Gaussian correlation

$$f(\mu r_p)=1-\exp[-(\mu r_p)^2], \tag{6}$$

where $\mu\simeq2f^{-1}$, effectively substitutes μ for k_i, thereby strongly increasing I_l. Furthermore, for $n=0$ shells, using the Jastrow function $f(\mu r_p)$,

$$(I_l/I_0)^2 = \frac{2^l}{(2l+1)!!}\{[\tfrac{1}{2} + 2(\mu/k_i)^2][\tfrac{1}{2}(k_i/k_{pf})^2 + 2(\mu/k_{pf})^2]\}^{-l} \simeq 0.01 \qquad (7)$$

for $l = 1$, and substantially less for higher l values. Hence short-range interactions retain only the (symmetric) $l = 0$ initial relative spatial wave function.

For $^{12}C(\pi^-, 2n)^{10}B$, with low-lying ^{10}B levels arising mainly from a $(1p)^{-2}$ configuration, requiring the initial and final relative states of the pair to be antisymmetric, Δl equals 0 or 2 [Eq. (2)], and (T_p, S_p) changes from (1,0) to (1,0) for the 0^+, 1 ^{10}B state. This is forbidden by the selection rules. Transitions to $J^\pi = 1^+$, 2^+, 3^+, $T = 0$ states, being of the type $(0,1) \rightarrow (1,0)$, are permitted.

Wildenthal wave functions for ^{32}S and ^{30}P, using the full $(1d\frac{5}{2})(2s\frac{1}{2})(1d\frac{3}{2})$ space,[20] yield mainly a $(2s\frac{1}{2})^{-2}$ and $(1d\frac{3}{2})^{-2}$ configuration for the 0^+, 1 level in ^{30}P at 677 keV. Hence it too should be similarly suppressed. The 2^+, 1 level at 2938 keV in ^{30}P is predominantly a $(2s\frac{1}{2})^{-1}(1d\frac{3}{2})^{-1}$ configuration, i.e., it consists of inequivalent nucleon orbitals. Hence the wave function of the initial pair should have $(T_p, S_p) = (1, 1)$, which yields a forbidden $(1,1) \rightarrow (1,0)$ transition.

If the in-flight pion absorption reaction proceeds primarily by pion rescattering through a $\Delta(1232)$ resonance,[21] the relative wave function of the pion-nucleon pair will be a p wave which, as noted previously, involves the selection rules cited above [Eq. (3)], except that the relevant Koltun selection rules assume that the pion contributes almost no angular momentum to the absorbing pair $(\Delta L_p = 0)$. One does not expect this to be the case for 200-MeV pions, however. If the in-flight reaction involved a $(\pi, \pi 2N)$ knockout reaction instead, the $0^+, 1$ and $2^+, 1$ states would not be forbidden by the selection rules of Eq. (3) either. In both cases, processes having intermediate or final stages containing only an identical nucleon pair in relative S states would still be inhibited. This condition, however, is more restrictive than Koltun's interaction mechanism requires.

We have also taken a prompt γ-ray spectrum produced by the interaction of 180-MeV π^+ with ^{31}P, a complete analysis of which will be given elsewhere.[6] Of interest here are the states in ^{30}P produced, in this case, by single-neutron removal. The cross sections for production of these states are given in Table III. The pattern of excitation of the ^{30}P states is seen to be quite different from that produced by two-nucleon removal from ^{32}S (Table II). In two-nucleon removal, the $1^+, 0$ states at 709 and 5712 keV and the $2^+, 0$ states at 1454, 2723, and 3834 keV are most prominent, while in single-neutron removal, the $3^+, 0$ state at 1973 keV is dominant. Also, single-neutron removal from ^{31}P produces a nonzero cross section for the $0^+, 1$ state at 677 keV. However, because of the size of the error bars, as well as the possibility of feeding from higher levels, it is possible that the cross section for direct production of the $0^+, 1$ state is nearly zero here too.

Calculations of the momentum distributions of the recoiling nuclei which assume absorption of π^- on an np pair with relative pair $n = l = 0$, $S = 1$, $T = 0$ coupling are in reasonable agreement with the observed Doppler broadening of γ-ray lines from ^{12}C and ^{14}N arising from π^- reactions on ^{14}N and ^{16}O, respectively.[10,7] In those cases other couplings are either highly unlikely because their two-particle coefficients of fractional parentage are very small,[22] or the absorption process is forbidden by selection rules. Because these other couplings do not appear with measurable amplitudes, there are no contrasting examples for comparison. Note, however, that the recoil momentum distribution has no explicit dependence on the spin-isospin coupling of the absorbing pair. The shifts toward momenta slightly higher than those predicted by the shell model may arise from final-state interactions of the outgoing nucleons, or from selection processes in the full pion absorption interaction which would form higher pair momenta, e.g., some form of correlation preference.[7]

A kinematically complete 0-MeV π^- measurement by Bassalleck *et al.*[23,24] of the excitation energy spectrum of neutron pairs emitted in the $^{14}N(\pi^-, 2n)^{12}C$ reaction indicates that the contribution of absorption on an np pair in the spin triplet state is large compared with that on an np pair in the singlet state, in agreement with the selec-

TABLE III. Levels of ^{30}P observed in the $\pi^+ + {}^{31}P \rightarrow {}^{30}P^* + \binom{n\,(+\pi^+)}{p\,(+\pi^0)}$ reaction.

State		180-MeV π^+	
		Uncorrected	Corrected
J^π, T	E (keV)	σ (mb)	σ (mb)
$0^+, 1$	677	2.6 ± 0.6	1.1 ± 0.8
$1^+, 0$	709	4.9 ± 1.5	0
$2^+, 0$	1454	1.7 ± 0.8	0
$3^+, 0$	1973	18.5 ± 3.2	18.5 ± 3.2
$1^+, 0$	2839	2.2 ± 0.9	0
$2^+, 1$	2938	1.9 ± 0.8	4.5 ± 1.9

tion rules. They also found a similar result in a kinematically complete study of the ^{40}Ca(π^-, $2n$) ^{38}K reaction at rest.[25] Thus the quasideuteron mechanism appears to be valid for medium-mass nuclei in spite of the apparent increased likelihood of final-state interactions. On the other hand, recoil velocities decrease as the target mass increases.

Occasionally $0^+, 1$ states are excited in multinucleon-removal processes. The $0^+, 1$ level of ^{14}N, e.g., is observed in fast pion reactions on ^{19}F (Ref. 11) and ^{23}Na.[6] Although in both cases the excitation of this level may simply arise from unobserved feeding by higher levels, it may well come from nondirect processes such as intranuclear cascading and statistical evaporations of nucleons.

In summary, production of J^π, $T = 0^+, 1$ levels by pion-induced np removal from self-conjugate nuclei is strongly suppressed for both π^- absorption at rest and $\pi^\pm$ interactions in the $\Delta(1232)$ energy region. The 0-MeV π^- results can be explained by standard selection rules, but the $\Delta(1232)$ region results may imply a reaction mechanism which is more restricted than the general form given by Koltun.[16]

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