Nuclear gamma rays from ^{51}V levels populated by 200 MeV $\pi^{\pm}$ inelastic scattering*

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(Received 21 March 1977)

Nuclear γ rays from 200-MeV $\pi^{\pm}$ inelastic scattering on ^{51}V were measured. Observed were ^{51}V levels at 0.32, 0.93, 1.61, 1.81, and 2.70 MeV. γ ray cross sections were similar for both $\pi^{\pm}$. If the interaction were direct with no distortion on a $(1f_{7/2})^3$ proton configuration, the π^- cross sections would be 1/9 the π^+ cross sections.

[NUCLEAR REACTIONS ^{51}V$(\pi^{\pm}, \pi^{\pm\prime}\gamma)$; $E_{\pi^{\pm}} = 200$ MeV; detected γ's; Ge(Li); measured 90° σ for 320, 930, 1610, and 2700 keV ^{51}V levels.]

I. INTRODUCTION

Because of the isospin character of the π-N, $\Delta(1232)$, resonance, 200-MeV pions may be a useful probe to study nuclear configurations. In particular, inelastic nuclear scattering of pions at this energy may be sensitive to the relative proton to neutron components of the nuclear level wave functions. In an extreme picture in which the pion inelastic scattering occurs in lowest order, e.g., single direct π-N scattering in the nucleus with no distortion of the pion wave function, $\pi^{\pm}$ inelastic cross sections would reflect the behavior of the free π-N scattering, yielding proton and neutron configuration information. For example, in a nucleus whose excited levels are obtained from the ground state by a recoupling of only a certain group of protons, inelastic π^+/π^- cross section ratios to these levels will simply be equal to the ratio of free $\pi^{\pm}$-proton cross sections $\frac{9}{1}$, since pion charge exchange scattering would not occur. Effects such as the apparently strong surface absorption of 200-MeV pions on medium and heavy nuclei, yielding diffraction-like angular distributions, multiple scattering, etc., appreciably modify the above idealized picture.

A measurement of 200-MeV $\pi^{\pm}$ inelastic scattering on ^{51}V was obtained at the SREL synchrocyclotron by examining nuclear deexcitation γ rays from the target. ^{51}V was chosen because of its apparent simple structure, three valence protons outside a closed core. This nucleus has been studied extensively both theoretically and experimentally.[1-4,14,17] Low lying levels arise mainly from recoupling among the three valence protons. The ground state ($J = \frac{7}{2}^-$) and negative parity states at E_x(MeV), $J = 0.32, \frac{5}{2}$; $0.93, \frac{3}{2}$; $1.61, \frac{11}{2}$; $1.81, \frac{9}{2}$; and $2.70, \frac{15}{2}$ are characterized as 90–95% $(1f_{7/2})^3$ proton configuration outside a closed ^{48}Ca core, the small remaining parts of these wave functions being higher $1f, 2p$ proton configurations. An additional $\frac{3}{2}^-$ state at 2.41 MeV is considered as being a $(1f_{7/2})^2(1p_{3/2})$ or a $(1f_{7/2})^2(1f_{5/2})$ configuration. Measured values of $B(E2)$ obtained from γ transition studies of the first group of levels can be explained in terms of the above configuration [or a 100% $(1f_{7/2})^3$ proton configuration] and an effective proton charge $e_p/e \simeq 1.8$. All these states have the ground state isospin $T = \frac{5}{2}$.

If pion excitation of the $T = 4$ ^{48}Ca core is minimal, direct inelastic π^+ scattering, to lowest order, should therefore be 9 times stronger than the corresponding π^- scattering to these states.

II. EXPERIMENTAL METHOD

Due to the inherently poor energy resolution of pion beams, inelastic pion scattering on ^{51}V was obtained, as mentioned above, by observing γ rays from decay of the ^{51}V excited levels. This method

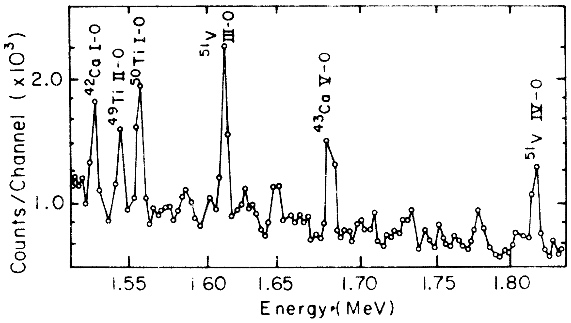

FIG. 1. Portion of a beam-coincident γ ray spectrum for a π^- run. Transition assignments are labeled above peaks.

has been used previously[5] for examining pion reactions on nuclei. In brief, γ rays were detected by a 105-cm^3 Ge(Li) in coincidence with a pion incident upon the target. The incident pion beam was defined by a two counter telescope, consisting of an upstream 20- $\times$25- $\times$0.3-cm scintillator and a downstream 13- $\times$13- $\times$0.2-cm scintillator adjacent to the target. The γ detector was placed at an angle of 90° with respect to the incident pion beam and surrounded by an anticoincidence scintillator to veto charged particles in the Ge(Li). The distance between the target center and the center of the Ge(Li) sensitive volume was 10 cm. The $\pi^{\pm}$ energies were 180 and 215 MeV, respectively. Two ^{51}V targets were used in order to eliminate effects of neutron contamination, as explained in Sec. III. A γ spectrum noncoincident with the π beam was also taken to eliminate contributions from target β decay, room background, etc. A γ ray with random timing with respect to an incident pion, the 2223.3-keV, $n+p\rightarrow d$ capture γ ray, produced a ratio of noncoincident-coincident spectra peak area of ~6/1. Peaks in the beam-coincident γ spectrum were then identified indicating levels in a variety of residual nuclei previously observed with a larger ^{51}V target.[5] Figure 1 shows a π^- spectrum section, 1.5 MeV$\leq E_\gamma \leq$1.9 MeV.

Using published γ decay schemes and branching ratios for the residual nuclei, cross sections for pion excitation directly to these levels were determined, assuming isotropic γ ray distribution. Corrections were made for γ ray absorption in the target. No γ transitions from other residual nuclei were observed to interfere with the inelastically produced deexcitation γ rays in ^{51}V.

III. NEUTRON CONTAMINATION

Neutrons with energies of several MeV have a relatively large cross section, of the order of several hundred millibarns, for inelastic scattering on ^{51}V. This is an order of magnitude greater than that for 200-MeV pion inelastic scattering as determined by this experiment. Neutrons can thus contribute a substantial contamination component to the observed ^{51}V γ rays. Those originating outside of and inelastically scattering in the ^{51}V target and telescope will be randomly timed with respect to an incident pion in the beam telescope and will yield contaminating γ ray peaks predominantly in the non-beam-coincident spectra. Neutrons originating within the target, secondary target neutrons, will yield inelastic peak components that are beam coincident, as are the components arising from pion inelastic scattering. (The predominant coincident neutron contaminating component arises from secondary target neutrons rather than neutrons originating within the downstream beam telescope which had $<\frac{1}{5}$ the thickness, in g/cm^2 of the ^{51}V target. The upstream scintillator was ~1 m from the target.) However, the cross section for the peak component due to secondary target neutrons will vary with target size. In the case of a thin target (thickness negligible compared with width or height) the secondary neutron component will increase linearly with target thickness. (Such a shape yields maximum variation of secondary neutron cross section component with thickness.) The residual γ ray cross section, due only to incident pions, is then obtained by linearly extrapolating to zero target thickness the measured coincident γ ray cross sections versus target thickness. Two 10-cm diam disk ^{51}V targets were used, the smaller having 1.024-g/cm^2 thickness (1.6 mm), the larger having a thickness five times this amount, 5.120 g/cm^2.

As a further check, cross sections for six prominent spectra peaks arising from single and multiple nucleon emission were evaluated; see Table I. The negative Q values for the reactions producing these peaks varied from 20 to >70 MeV. These are sufficiently large to limit contributions induced by neutrons which are expected to have an evaporation spectrum with mean energy of only several MeV. It was found that the cross sections for these peaks had little variation with target thickness (Table I) and the peaks were prominent only in the beam-coincident spectra.

In view of the above qualitative results, cross sections for pion excitation of ^{51}V levels were evaluated as follows:

For both π^+ and π^-, beam-coincident and noncoincident spectrum areas were evaluated for five ^{51}V transitions that yielded discernible peaks; see Table I. Level and transition energies and branching ratios were obtained from Ref. 7. Areas in these spectra were also obtained for the six non-^{51}V peaks, arising predominately from the

TABLE I. Cross sections for γ transitions from ^{51}V level for a π^+ and π^- run sequence. Values have been rounded off to the nearest integer in mb. Cross section errors are $\pm 30\%$. R and R' are the ratios of five disk [$\sigma_\gamma(5)$] to one disk [$\sigma_\gamma(1)$] transition cross sections.

		π^-				π^+			
	E_γ (keV)	$\sigma_\gamma^-(1)$ (mb)	$\sigma_\gamma^-(5)$ (mb)	R, R'	$\sigma_\gamma^-(0)$ (mb)	$\sigma_\gamma^+(1)$ (mb)	$\sigma_\gamma^+(1)$ (mb)	R, R'	$\sigma_\gamma^+(0)$ (mb)
^{51}V	0.320	14	52	3.7	6	9	29	3.1	6
	0.928	7	15	2.2	5	5	13	2.5	4
	1.609	10	31	3.1	6	10	24	2.4	8
	1.813	5	17	3.1	3	4	11	2.7	3
	1.090	3	8	2.8	2	4	9	2.3	3
^{48}Ti	0.938	47	55	1.2		38	45	1.2	
	1.312	26	30	1.1		21	25	1.2	
^{46}Ti	0.889	26	29	1.1		27	35	1.3	
^{38}Ar	2.168	8	8	1.0		6	7	1.2	
^{44}Ca	1.157	20	22	1.1		13	22	1.7	
^{42}Ca	1.524	12	13	1.1		12	15	1.3	

first excited state to ground state transitions in residual even-even nuclei. Ratios for coincident to noncoincident areas for the five ^{51}V transitions were $\sim\frac{10}{1}$ and equaled, to within $\pm15\%$, corresponding ratios for the six non-^{51}V transitions. Peaks associated with non-beam-coincident γ rays, such as the 2223.3-keV $\gamma + p \rightarrow d + \gamma$ capture γ ray, 511-keV annihilation radiation, and the 2613-keV γ ray from the collimator ^{208}Pb 3^- to ground state transition, had ratios less than 0.5.

Beam-coincident areas were then used to obtain cross sections for the 1.024- and 5.120-g/cm^2 targets formed, respectively, by one and five 10-cm diam$\times$1.6-mm vanadium disks, positioned at 45° with respect to the incident pion beam. After correcting the cross sections for target γ absorption, ratios R and R', for five disk /one disk cross sections were obtained for the six non-^{51}V and five ^{51}V levels, respectively. The former, with relatively good spectrum statistics, did not vary by more than $\pm10\%$ in most cases, and their average R_{av} was formed. This, when divided into the R' ratios, yielded ratios R'' normalized for variation of target—Ge(Li) detector distance with target size. Finally the five ^{51}V level cross sections were linearly extrapolated to zero target thickness by multiplying the one disk ^{51}V cross section $\sigma(1)$ by the factor $\frac{1}{4}(5-R'')$.

The ratio of the number of secondary target neutrons n_n to the number of incident pions n_{π^-} for one target disk can be obtained from the above and is

$$\frac{n_n}{n_{\pi^-}} = \frac{2\sigma^-(1)}{\sigma^V_{n,n'}} \frac{1}{4}(R''-1),$$

where the factor 2 accounts for secondary neutron scattering in $\frac{1}{2}$ the target, and $\sigma^V_{n,n'}$ is the ~3-MeV inelastic neutron scattering cross section to a ^{51}V level. $\sigma^-(1)$ and R'' values obtained for π^- to the first excited state of ^{51}V and $\sigma^V_{n,n'}$ to this state from Ref. 6 yielded $n_n/n_{\pi^-} \simeq 0.02$ per disk.

A less reliable estimate of n_n/n_{π^-} may be made by utilizing the area a of a 600-keV triangular shaped spectrum peak caused by inelastic neutron scattering to the first excited state of ^{74}Ge within the Ge(Li) detector.[8] (The internally converting 700-keV ^{72}Ge I – 0 triangular peak could not be used since its lifetime, 0.3 μs, caused it to appear mostly in the non-beam-coincident spectra.) A straightforward evaluation of n_n/n_{π^-} per disk using a yields

$$\frac{n_n}{n_{\pi^-}} = \frac{8\pi a}{n_{\pi^-}}\left(\frac{R^2}{\text{eff}\times\sigma_{\text{Ge}}(n,n')}\right)\left(\frac{A_{\text{Ge}}}{6\times10^{23}P_{\text{Ge}}\,\text{vol}_{\text{Ge}}}\right),$$
$$\simeq 0.01 \text{ per disk}$$

where R is the target-detector distance, eff is the Ge(Li) relative photopeak efficiency, $\sigma_{\text{Ge}}(n,n')$ is the ~2-MeV neutron inelastic cross section to Ge I state (Ref. 9), and all other symbols are conventional. n_n/n_{π^+} yield approximately half these values.

IV. PROTON CONTAMINATION

The contribution of secondary target protons to ^{51}V γ peaks is expected to be small since, at a proton energy $E_p \simeq 6$ MeV yielding the maximum in the inelastic proton cross section, the proton range in the target is only $\simeq 0.1$ g/cm^2, approximately $\frac{1}{10}$ the minimum target thickness. Furthermore, if the production of secondary target nucleons with energies <20 MeV is mainly by evaporation, the proton flux would be $<\frac{1}{20}$ the neutron flux.[10]

An estimation of secondary target proton contamination was made in a manner similar to that described in Ref. 11. It used a recent measurement[12] of proton emission from 235-MeV π^+ on Ni, displaying exponentially decreasing yield with E_p. An excitation curve for inelastic proton cross sections to the first excited (2^+) states for ^{54}Fe and ^{56}Fe for 3 MeV $\leq E_p \leq$ 50 MeV[13] was formed and also approximated exponentially. A double integration of the product of this fit and the Ni π^+ induced proton emission cross section over proton range and proton emission energy yielded an inelastic cross section to the first excited Fe states <0.1 mb. The path length of target secondary protons was set equal to the proton range and was not limited by target geometry. Proton contamination in the incident pion beam had an energy of ~40 MeV and was less than 5% of the pion flux, as determined by time of flight.

V. RESULTS

Table II lists values for $\pi^\pm$ cross sections obtained for the γ rays from levels of ^{51}V extrapolated to zero target thickness and corrected for branching and γ feeding from observed higher levels. Also shown for comparison are cross sections for 17.5-MeV protons and 42-MeV α particles.[14] A search of the spectra for γ decay of all other ^{51}V levels of $E_x \leq 3.5$ MeV to the ground state or excited states up through 1.61 MeV showed no peaks within the limits of experimental uncertainty of $\simeq 0.6$ mb extrapolated to zero target thickness.

Relative to each other, the cross sections for these five levels follow the same general pattern for both $\pi^\pm$ and also for proton and α excitation. The 320-keV $\frac{5}{2}^-$ level has the largest cross section, with the 1610- and 930-keV levels somewhat less; each of the two other levels observed has a considerably smaller cross section. Since, as noted above, shell model calculations of the inelastic cross sections for the five strongly excited levels reasonably reproduce the proton and α data, the pion data indicates a reaction apparently proceeding similarly. However, the ratios of the π^+ to π^- cross sections listed in Table II are approximately equal. Since these ratios should be $\frac{9}{1}$ on an extreme

TABLE II. Cross sections $\sigma^\pm$ for the production of ^{51}V levels by 200-MeV $\pi^\pm$ inelastic scattering, obtained by averaging $\sigma_\gamma^\pm(0)$ over two run sequences. They have been corrected for branching and γ feeding from higher levels and have errors $\pm 30\%$. Also shown are inelastic proton and α cross sections for comparison.

E_x (MeV)	J^P	σ^+ (mb)	σ^- (mb)	σ^+/σ^-	$\frac{d\sigma(p,p')}{d\Omega}$ [a]	$\frac{d\sigma(\alpha,\alpha')}{d\Omega}$ [a]
0.32	$\frac{5}{2}^-$	9	13	0.7	1.2	3.6
0.93	$\frac{3}{2}^-$	6	6	1.0	0.4	1.0
1.61	$\frac{11}{2}^-$	3	5	0.6	1.0	2.8
1.81	$\frac{9}{2}^-$	4	4	1	0.5	1.6
2.70	$\frac{15}{2}^-$	4	3	1.3	0.2	···

[a] Differential cross section in mb/sr at $\theta_{c.m.} = 35°$ for protons, $\theta_{c.m.} = 20°$ for α particles. $E_p = 17.5$ MeV, $E_\alpha = 42$ MeV. Protons had similar angular distribution shapes with the maximum at $\theta_{c.m.} = 35°$. α particles also had similar shapes with the second maximum at $\theta_{c.m.} = 20°$. Data are from Ref. 14.

no-distortion direct-interaction basis as noted above, the measured ratios are, on this basis, unexpectedly small by a factor of ~9.

Several effects may appreciably modify the above simple interaction basis, in particular multiple scattering of the incident pion and appreciable nuclear distortion of the pion wave function. This has been shown to produce a strong nuclear surface reaction yielding diffraction-like inelastic angular distributions.[15] In connection with the latter, a distorted wave impulse approximation calculation[16] showed great sensitivity of the magnitude of the pion inelastic scattering cross section to small charges in the outer slope of the nuclear form factor. An increase of ~50% in the latter produced a tenfold increase in the former. The presence of the closed $(1f_{7/2})^8$ neutron shell could then be important. A π^+/π^- cross section ratio calculated by simply assuming that all nucleons outside the ^{40}Ca incoherently participate in the reaction yields

$$\sigma(\pi^+)/\sigma(\pi^-) = (1\times 8 + 9\times 3)/(9\times 8 + 1\times 3) = 1/2.2\,.$$

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*Work supported by the National Science Foundation, NASA, and HEW.

[1]J. D. McCullen, B. F. Bayman, and L. Zamick, Phys. Rev. 134, B515 (1964).
[2]R. N. Horoshko, D. Cline, and P. M. S. Lesser, Nucl. Phys. A149, 562 (1970).
[3]B. A. Brown *et al.*, Phys. Rev. C 9, 1033 (1974).
[4]A. S. Goodman and D. J. Donahue, Phys. Rev. C 5, 875 (1972).
[5]B. J. Lieb *et al.*, Phys. Rev. C 14, 1515 (1976).
[6]A. W. Barrows *et al.*, Nucl. Phys. A107, 164 (1968).
[7]C. Rossi-Alvarez and G. B. Vingiani, Nuovo Cimento 17A, 731 (1973); J. N. Mo *et al.*, Nucl. Phys. A147, 129 (1970); A. S. Goodman and D. J. Donahue, Phys. Rev. C 5, 875 (1972); R. N. Horoskho *et al.*, Nucl. Phys. A149, 562 (1970); G. L. Borchert *et al.*, Z. Naturforsch. 30a, 274 (1975).
[8]C. Chasman *et al.*, Nucl. Instrum. Methods 37, 1 (1965).

[9]K. C. Chung *et al.*, Phys. Rev. C 2, 139 (1970).
[10]E. Vogt, Advan. Nucl. Phys. I, 261 (1968).
[11]H. Funsten *et al.* (unpublished).
[12]P. G. Bizzeti *et al.*, Nuovo Cimento 26A, 25 (1975).
[13]F. D. Seward, Phys. Rev. 114, 514 (1959); K. Amor and R. Smith, Nucl. Phys. A226, 519 (1974); P. G. Greaves *et al.*, *ibid.* A179, 1 (1972).
[14]R. J. Peterson, Ann. Phys. (N.Y.) 53, 40 (1969); Phys. Rev. 172, 1098 (1968).
[15]H. J. Weber (private communication).
[16]T. H. Lee and F. Tabakin, Nucl. Phys. A226, 253 (1974).
[17]B. M. Preedom *et al.*, Phys. Rev. C 2, 166 (1970).