Absolute Cross Sections for Production of Prompt Nuclear γ Rays by Fast Pions*

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Cross sections have been measured for the production of prompt nuclear γ rays in the pion bombardment of Al, Ca, V, and ^{60}Ni. Several disagreements with values in the literature are noted.

Several experiments[1-3] examining prompt γ-ray spectra following fast ($\approx$ 100–400 MeV) pion bombardment have reported enhanced production of nuclei which correspond to the removal from the target of one or more α particles or, in the case of odd targets, to the removal of a triton plus α particles. None of the experiments appears to have been oriented towards accurate absolute cross-section measurements and the cross sections that have been published cover a wide range of values. The 382 mb (summed for the production of all nuclei differing from the target by an integral number of α particles) observed in the bombardment of ^{40}Ca with 220-MeV π^- is the largest such cross section reported. The present note gives the results of a series of measurements which overlap previous work and which were specifically designed to accurately determine absolute yields.

The work was done at the Clinton P. Anderson Meson Physics Facility, most of it at the low-energy-pion (LEP) channel and some at the higher-momentum channel, P^3 (pions for particle physics). Beam contamination in these channels is < 10% for the pion momenta used. Incident pion fluxes were measured by integrating the light from a scintillator placed in the beam, next to the target. The system was calibrated at low intensities by viewing the scintillator with a second phototube and directly counting the number of particles passing through. Linearity was checked with a light-emitting diode. The system is believed accurate to $\pm$ 2% up to instantaneous count rates of 10^9/sec, which is more than 100 times

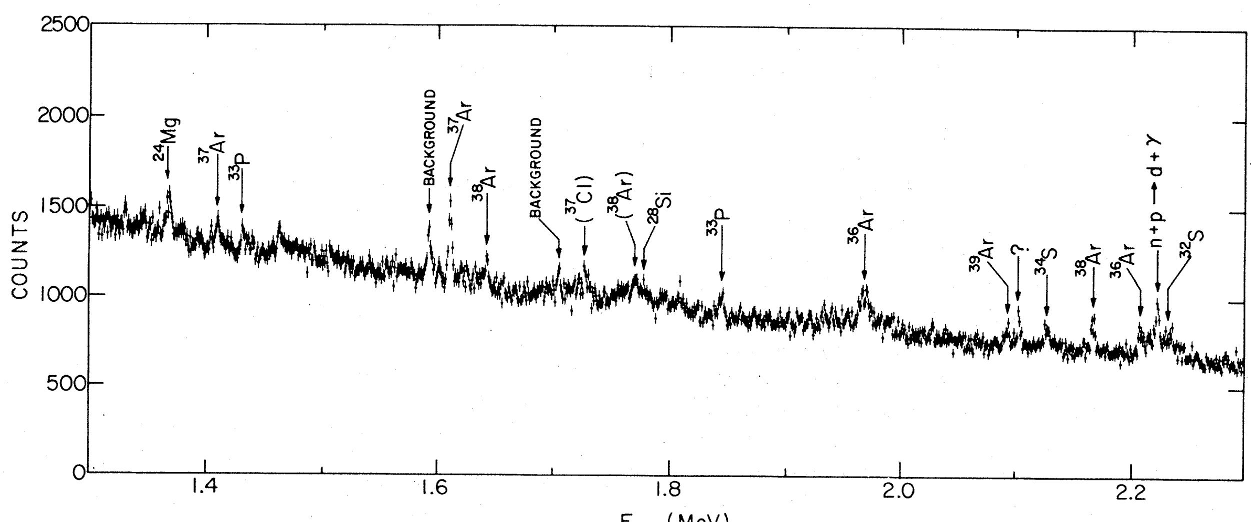

FIG. 1. Portion of the prompt γ-ray spectrum observed when a natural calcium target is bombarded with 220-MeV negative pions.

greater than any rates used in the present work. Halo counters were used to check that the beam remained focused on the monitor-target system. The substantial dead-time and pileup losses (~ 30%) in the Ge(Li) circuitry were monitored by feeding a pulser, triggered by scattered pions, into the Ge(Li) preamplifier and comparing the pulser peak in the spectrum with the number of triggers. Pulses from the Ge(Li) were processed by conventional electronics with good quality spectra obtained in 3–6 h. Production cross sections were determined from the spectra at 90° under the assumption of isotropic γ decay.

When the 220-MeV π^- beam bombarded a calcium target, Doppler-broadened lines (Fig. 1) were seen for the $2_1^+ \to 0_1^+$ transitions in nuclei differing from ^{40}Ca by 1, 2, and 3 α particles. The energy 1.970 MeV (^{36}Ar $2_1^+ \to 0_1^+$) lies at the center of a structure spread out over 50 keV which we attribute to Doppler-shifted ^{36}Ar γ rays. The 2.230-MeV ^{32}S line is one of several sitting on a broad bump and while the entire 35-keV wide bump is attributed to the ^{32}S line, this intensity determination must be regarded as particularly uncertain. Finally, the 1.779-MeV ^{28}Si line is not only broadened but also mixed with a 1.771-MeV line (^{36}Ar $2_2^+ \to 2_1^+$?) and so its intensity is also subject to considerable error. Because of the difficulties in the ^{40}Ca data caused by the Doppler broadening, any conclusions about the importance of α removal are perhaps better based on other nuclei. However, as can be seen from Table I, even for the sharp 1.409-MeV ^{37}Ar line, our value is about a factor of 3 lower than that of Ref. 2.[4] In contrast, our value for the ^{48}Ti 2^+-0^+ transition from a ^{51}V target is in good agreement with that of Ref. 2.

Data were also taken with 100-MeV π^+ on ^{27}Al in order to compare with Ref. 3. As can be seen in Table I, present values are nearly a factor of 2 higher. Additional data taken with 380-MeV π^+ bombarding ^{60}Ni are compared in Table I with earlier data for 380-MeV π^- on ^{60}Ni.[1,5] While the cross sections found here are much larger than those of Ref. 1, they are similar to more recent results from 380-MeV π^- on ^{60}Ni.[5] "α removal" cross sections obtained for other nuclei during the present experiment[6] are similar in magnitude to those reported here.

Recent measurements of kaonic x-ray yields[7] indicate that in nickel the $6 \to 5$ x-ray yield is only 14%, and in copper 22%, instead of the 30% previously assumed in both cases. Normalized to these newer results, the nuclear γ-ray spectra from capture of stopped kaons suggest that about 25–40% of the interactions end in "α removal" nuclei, instead of the ~ 70% implied[8] by the earlier kaonic x-ray data.

It now appears that nowhere does "α removal" account for more than about 20% of the total reaction cross section in pion-induced reactions. It remains an open question as to whether the observed degree of "α removal" can be explained without requiring a preferential interaction of pions (or kaons) with α clusters.

TABLE I. Comparison of present cross sections with previously reported values. Present cross sections are believed accurate to ±15%, except for most of the ^{40}Ca lines where, because of the Doppler broadening, errors are $^{+15}_{-50}$%.

Target and projectile	Gamma line (MeV)	Previous σ (mb)	Present σ (mb)
^{27}Al, 100-MeV π^+	^{26}Al 0.417	6.6[a]	13.6
	^{23}Na 0.440	14.8[a]	20
	^{23}Mg 0.585	6.6[a]	22
	^{22}Ne 1.275	5.2[a]	15.1
	^{24}Mg 1.369	17.3[a]	26
	^{26}Mg 1.809	12.2[a]	24
^{51}V, 220-MeV π^-	^{48}Ti 0.983	95[b]	105
^{40}Ca, 220-MeV π^-	^{24}Mg 1.369	36.2[b,c]	14.0
	^{37}Ar 1.409[d]	21.7[b,c]	6.8
	^{28}Si 1.778	66.1[b,c]	23
	^{36}Ar 1.970	137.9[b,c]	61
	^{32}S 2.230	114.8[b,c]	42
^{60}Ni, 380-MeV π^-	^{56}Fe 1.238	5,[e] 44[f]	
	^{52}Cr 1.434	7,[e] 34[f]	
^{60}Ni, 380-MeV π^+	^{56}Fe 1.238		40
	^{52}Cr 1.434		40

[a] Ref. 3.
[b] Ref. 2.
[c] An error has recently been found in the analysis of the data which reduces all the Ca cross sections in Ref. 2 by a factor of 2.4.
[d] While a stronger line at 1.611 MeV, believed to be from ^{37}Ar, is also seen in the present work, the 1.409-MeV line was the only one used in Ref. 2 in evaluating the amount of ^{37}Ar made.
[e] Ref. 1.
[f] Ref. 5.

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[3]D. Ashery *et al.*, Phys. Rev. Lett. 32, 943 (1974).
[4]The authors of Ref. 2 have recently uncovered an error which, when corrected, lowers their calcium results by a factor of 2.4. Only their calcium data are affected.
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Surface Electric Field Model for the Beam–Tilted-Foil Interaction

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It is shown that the experiments on the polarization of the light emitted after beam–tilted-foil interaction are compatible with a surface electric field model.

Following the theory of Macek, the experimental work of Andrä[1] has shown that the atoms or ions which are produced in excited states by passing an accelerated beam of ions through a thin carbon foil normal to the beam are aligned; i.e., they emit light partially linearly polarized. More recently, after a theoretical suggestion of Fano and Macek[2] and of Ellis,[3] Berry, Curtis, Ellis, and Schectman[4] have shown experimentally that when the foil is tilted relative to the beam, an orientation of the excited levels appears in the direction Ox perpendicular both to the beam direction Oz and the foil normal Oz'. This orientation leads to the emission of partially circularly polarized light. Several authors[5-7] have suggested that the orientation could be caused by the action on the excited state emerging from the foil of an electric field at the final surface of the foil. They have pointed out the similarity of such a mechanism with a previous observation of Giroud and Lombardi.[8,9] In this last experiment, an electric field of a few hundred volts per centimeter was applied to a set of atoms excited and aligned by electron bombardment. It was then shown that an orientation perpendicular both to the electric field and to the electron beam appeared whenever the beam and the field were neither parallel nor perpendicular and when the phase $\varphi = \tau\Delta E/\hbar$ was of the order of unity (ΔE is the Stark splitting, τ = 30 nsec is the lifetime of the level). If $\varphi \ll 1$, the field has no time to act during the lifetime; if $\varphi \gg 1$, the orientation oscillates rapidly and is averaged out.

Eck[5] has made an explicit calculation of such an effect under very restrictive assumptions. He has calculated the effect of a second-order Stark Hamiltonian (or, equivalently, of a first-order electric gradient interaction) upon a $J = 1$ level aligned along the beam in the bulk of the foil. He showed first that the maximum of orientation should occur when the tilt angle α of the foil is 45°, second that the fractional polarization percentage f_p (with the notations of Ref. 4) is constant when one tilts the foil. These two predictions have been shown to be in contradiction with experiment by Berry, Curtis, and Schectman.[10] The main purpose of this Comment is to demonstrate that this does not rule out the interpretation of the phenomenon by surface electric field, but only the too restrictive assumptions of Eck.[5]

In the tilted-foil configuration, one has first to account for the existence of a surface electric field. As suggested by Eck,[5] it may be due to the image charge of the ion in the foil, but in that case one can hardly explain the similarity observed between the results in neutral He and various ionic species. Another possible field source is the direct electrostatic interaction of the incoming ion with the last layer of atoms in the foil. That possibility is not ruled out by surface corrugations either at the atomic (1 Å) or microscopic (1 μm) level. Indeed, even if the electric-field direction is distributed evenly in the forward half-space of the foil, the $\sin\alpha$ and $\cos\alpha$ terms in the formulas below are reduced only by a factor of 2. If one uses a more realistic, somewhat forward peaked, distribution of the electric fields, the other terms with higher multiples of α are also preserved, only somewhat reduced. However, in the hypothesis of a last-layer interaction, the