Nuclear γ Rays Associated with Stopped Kaons*

P. D. Barnes, R. A. Eisenstein, W. C. Lam, J. Miller, and R. B. Sutton
Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213

and

M. Eckhause, J. Kane, and R. E. Welsh
College of William and Mary, Williamsburg, Virginia 23185

and

D. A. Jenkins and R. J. Powers
Virginia Polytechnic Institute, Blacksburg, Virginia 24061

and

R. Kunselman
University of Wyoming, Laramie, Wyoming 82070

and

R. P. Redwine and R. E. Segel
Argonne National Laboratory, Argonne, Illinois 60439, and Northwestern University, Evanston, Illinois 60201

and

J. P. Schiffer
Argonne National Laboratory, Argonne, Illinois 60439, and University of Chicago, Chicago, Illinois 60637

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We have identified a large number of nuclear γ rays associated with negative kaons stopped in Ni, Cu, Si, and Al. Prominent among these for both the Cu and the Ni targets are transitions that take place in even-even nuclei lighter than the target by up to about twelve nucleons. In both cases, the total intensity of all of the identified nuclear γ rays amounts to about twice that of the strongest x ray.

The energies and relative intensities of nuclear γ rays associated with stopped kaons have been measured by use of the 800-MeV/c separated K beam at the Argonne zero-gradient synchrotron (ZGS). The signal obtained from the counter system upstream from the degrader corresponded to a beam purity of >95% kaons. The kaons were identified by signals from an appropriate Čerenkov counter, and about 4000 per ZGS pulse were incident on the degrader. For each target the range curve, taken with a veto counter downstream from the target, showed a peak at the expected degrader thickness. Spectra in time coincidence with the fast logic, without the veto signature, were then taken with a coaxial Ge(Li) detector having a volume of about 50 cm^3 and a beam-off resolution width of about 2.5 keV at 1.33 MeV. A calibration source, observed at the same time that the data were being accumulated, showed a width of ~3.5 keV.

A section of the spectrum of γ rays for the Ni target is shown in Fig. 1. Many distinct lines are seen and their energies are listed in Table I. The criterion for identifying the source of a line was that its energy should agree within 2 keV with that of a known[1] low-lying γ-ray transition of some nucleus between $A = 40$ and Ni. The nuclides identified in this way are shown in Fig. 2. For the Ni target, we note that γ rays corresponding to transitions in $^{46,(48)}$Ti, ^{50,52}Cr, and ^{54,56}Fe were seen, but that none could be identified from ^{58}Fe. Lines from ^{55}Fe and ^{57,59}Co were present but there was no indication of any odd-A isotope of Cr, Ti, Mn, or V.

For the Cu target, a very similar sequence was observed (Table I) except that the ^{60,62}Ni lines were clearly seen rather than ^{62,64}Ni. This suggests that removal of three nucleons is favored over proton removal. The decays from the first excited states of ^{56,58}Fe and $^{(50),52,54}$Cr were present while at most one weak Co line was seen. From both Ni and Cu targets, the strongest nuclear γ rays (not counting those due to inelastic scattering) are about half as intense as the $6 \to 5$

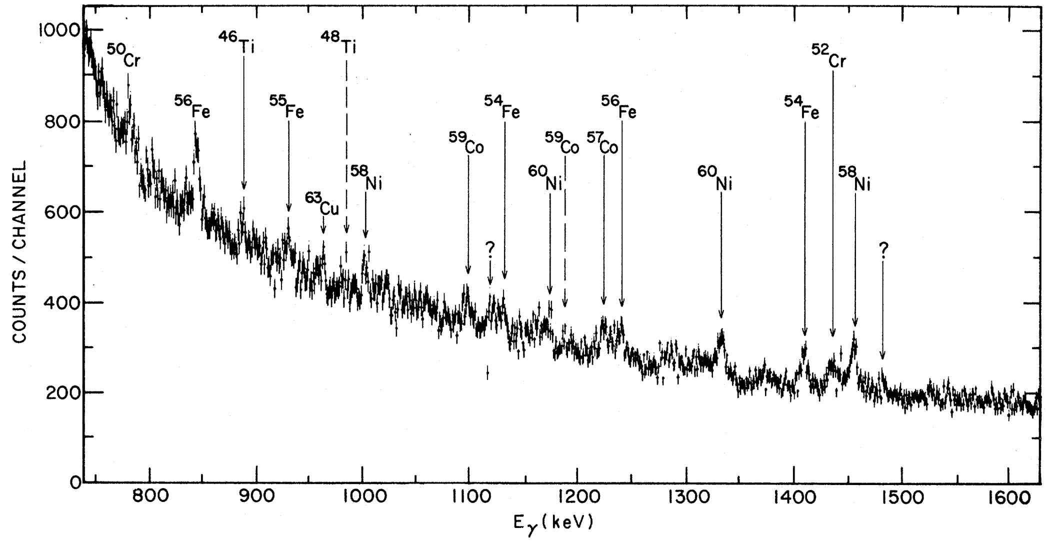

FIG. 1. Pulse-height spectrum for a Ge(Li) detector viewing the Ni target in which K^-'s were stopped.

K^- x rays, which have been reported to occur for ~30% of the stopped kaons.[2]

Data have also been obtained in shorter runs with ^{28}Si and ^{27}Al targets. These γ-ray data are less striking, but still the spectrum accumulated with the Si target showed ^{24}Mg and possibly ^{20}Ne lines (as well as lines in ^{27}Al, ^{25}Mg, and ^{23}Na) and the Al spectrum had lines in ^{26}Mg, ^{23}Na, and ^{19}F. For these lighter nuclei, removal of a single proton appears to be the strongest process; a relatively large number of lines remain unassigned. The presence of the ^{57,59}Co lines from the Ni target shows single-proton removal to be comparable to other processes; the failure to observe ^{64}Ni from the Cu target indicates that in Cu a single-proton removal is, at most, a weak branch. No indication of single-neutron removal was seen for any target, as expected from the fact that at low energies the K^-n interaction is only about $\frac{1}{6}$ as strong as the K^-p.

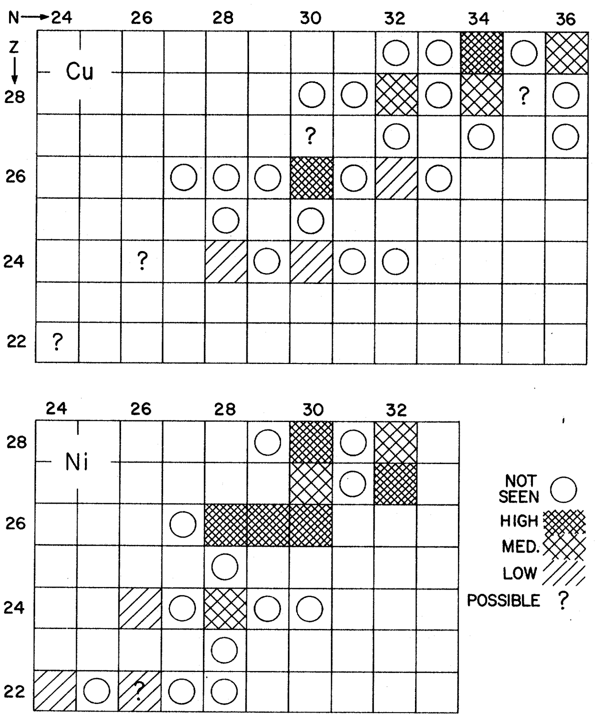

FIG. 2. Nuclei whose radiations were observed when K^- mesons were brought to rest in Cu and Ni targets. For a nucleus designated "high," the intensity of the observed γ radiations is greater than 50% of the density of the last unattenuated x ray; for "medium," the γ-ray intensity is 40–50%; for "low," the observed intensity is ≤ 30%.

Care was taken to ensure that background radiation had been taken into account properly, since past experience had shown that radiations from extraneous structural material (often containing Fe, Ni, or Cu) can be a source of background lines in the spectra of exotic atoms. The 964-keV line from the Ni target was seen whenever a Cu degrader was used. A fairly strong line appeared at 843.9 keV in Al and at 844.5 keV in Si, and these peaks are attributed to the 843.7-keV first excited state of ^{27}Al. It is felt that the energy calibration was good enough to assign these peaks in the spectra from the lighter targets to ^{27}Al rather than to the 846.8-keV line of ^{56}Fe seen in the Cu and Ni spectra. None of the other peaks that were seen in the Cu and/or Ni spectra were identified in the other spectra, although it is pos-

TABLE I. Nuclear γ rays observed when K^-'s were stopped in Cu and Ni targets. In determining the γ-ray intensities, the detector efficiency and the self-absorption in the target have been taken into account.

Copper target			Nickel target		
Energy[a] (keV)	Identification[b]	Intensity[c]	Energy[a] (keV)	Identification[b]	Intensity[c]
134.6	x ray 6 → 5	(100)	126.5	x ray 6 → 5	(100)
783.2	^{50}Cr[d]	10	413.1	^{55}Fe	30
808.9	^{58}Fe or (^{63}Ni)[e]	30	572.7		40
			603.5		50
827.4	^{60}Ni*[d]	10	783.7	^{50}Cr	20
835.3	^{54}Cr[f]	30	846.2	^{56}Fe	60
846.2	^{56}Fe	60	889.0	^{46}Ti	20
889.3	(^{46}Ti)[d]	10	931.8	^{55}Fe	40
946.3	(^{63}Ni)[e]	20	964.0	^{63}Cu	40
962.7	^{63}Cu	70	985.1	(^{48}Ti)[d]	20
1115.1	^{65}Cu	40	1003.6	^{58}Ni*	30
1121.9		20	1097.9	^{59}Co	40
1164.0	^{62}Ni*	50	~1125	broad	
1173.5	^{62}Ni or ^{60}Ni*	70	~1170	broad	
			1189.5	(^{59}Co)[d]	20
1221.9	(^{57}Co)[g]	10	1223.2	^{57}Co	50
1236.7	^{56}Fe*	20	1238.4	^{56}Fe*	40
1327.7		30	1331.9	^{60}Ni	40
1332.7	^{60}Ni	30	1408.0	^{54}Fe	60
1411.4	^{63}Cu	20	1433.6	^{52}Cr	40
1435.5	^{52}Cr	20	1453.5	^{58}Ni	70
1480.0	^{65}Cu	30	1480.3		20

[a] Measurements believed accurate to ~ 2 keV.

[b] Identification usually implies that the γ-ray energies agree to better than 2 keV. An asterisk implies a transition between excited states. γ rays below ~ 550 keV are usually not given. Only a few of these are seen and mainly x rays have been identified in this energy range. The region between 620 and 700 keV was blocked out by the calibration procedure.

[c] Normalized to 100 for the 6→ 5 x-ray transition. The values are accurate to ± 30% or ± 10 in these units, whichever is larger.

[d] These lines seem to be present but are on the edge of statistical significance.

[e] The ^{63}Ni line would have to originate on ^{65}Cu, and there should be corresponding ^{61}Ni lines from ^{63}Cu. Since these are *not seen*, the assignment is dubious.

[f] Could be contaminated by the 835-keV line from Ge(n,n').

[g] No other line is seen from ^{57}Co nor any from ^{59}Co. Hence the assignment is dubious.

sible that a weak background line ($I \approx 20$ in Table I) could have been missed in the Si and Al spectra.

The observed spectra can be compared with what would be expected if evaporation of nucleons were the primary decay mode, much as is the case in the interaction of protons or α particles of ~100 MeV. In such reactions, the evaporation of successive neutrons, or several neutrons and one or two protons, seems to be the rule.[3] Reactions in which only α particles are emitted must be much less probable. Thus in Cu, for instance, one might have expected that the γ-ray lines resulting from kaon absorption would originate in nuclides centered somewhere among the neutron-poor Ni, Co, and Fe isotopes. Instead of such a statistical spread, our data suggest possibly a simpler direct mechanism which somehow removes one, two, or three α particles in Ni and a triton or a triton plus one or two α particles in Cu. The probability of one of these processes occurring is high—the sum total of the probabilities is about twice as high as the next-to-last x-ray transition. However, if the absolute x-ray intensity were to be very much lower than we assumed here (~5% of the stopped kaons instead of 30%), then it may be that the lines we see are the result of a statistical process in which even-A nuclei tend to stand out because of their simpler level schemes. It would still be somewhat difficult to account for the absence of the ^{58}Fe, ^{54}Cr, and ^{50}Ti γ rays with the Ni target as well as those corresponding to ^{58,64}Ni and ^{54}Fe, with the Cu target.

The x-ray cascade in an exotic atom terminates with a strong interaction between the meson or baryon and the nucleus. This interaction is unique in that (1) the rather large amount of energy that is released is deposited far out on the nuclear surface and (2) no momentum transfer is associated with this energy. Wilkinson[4] has suggested that α clustering may be especially probable at the outer surface of the nucleus and that kaon capture by a nucleus might be used to probe this. Although such considerations may provide a plausible explanation for the removal of one α particle (or triton), the apparent high probability of removing more than one remains a puzzle. The probability of exciting the relevant nuclear levels with the secondary pions from kaon capture may be dismissed as requiring an even less plausible reaction mechanism.

There have been a number of studies of K^--capture stars in emulsions or heavy-liquid bubble chambers.[5] Multiple-prong stars have been observed, with some of the prongs identified as "protons" (tracks that were too heavy to be pions and did not decay). Apparently, they might also have been α particles. Short-range hyperfragments were also often indistinguishable.

It is conceivable that the mechanism that gives rise to the apparent "α-particle removal" seen here is quite sensitive to such effects as (a) the height of the Coulomb barrier, (b) the extent of a possible neutron tail, which may extend significantly further beyond the protons in Br and Ag than in the Ni region, and (c) the binding energy per nucleon, which has its maximum around $A \approx 56$.

Very little other experimental information on nuclear γ rays from exotic atoms is available for comparison with the present results. Poelz *et al.*[6] reported some nuclear γ rays following pion capture, but since their spectrometer covered only a limited range of γ-ray energies (100 −650 keV), many lines would have been missed —in particular, those in even-even nuclei. Recently published work by Wiegand, Gallup, and Godfrey[7] on γ rays from kaon capture by S and Cl is even more restricted in the energy interval observed. For the Cl target, they report a weak 78-keV line (~5% per stopped kaon) which they assign to a transition in ^{32}P; and for the S target an even weaker (1%) line at 197 keV was attributed to ^{19}F.

To summarize, the nuclear γ-ray spectra following K^- capture in Ni and Cu show a pattern that implies that the removal of one, two, or three α particles is the favored mode. This conclusion is not inconsistent with any previous work on the interaction between stopped kaons and complex nuclei. However, far more than the present fragmentary data will be required before a mechanism can be definitely established. We would like to thank the ZGS staff for their help and assistance in the course of this experiment.

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Magnetic Moments of ^{3}He and ^{3}H†

R. V. Gerstenberger and Y. Nogami
Department of Physics, McMaster University, Hamilton, Ontario, Canada

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The electromagnetic structure of a nucleon in a nucleus is different from that of a free nucleon. This difference is examined for the two-pion part of the form factor by considering interactions with other nucleons in the course of pion emission and absorption, but without exchanging charge. For ^{3}He and ^{3}H, the isovector part of the magnetic moment increases by an amount which is comparable to the outstanding discrepancy between the experimental and theoretical values.

The purpose of this note is to show that the magnetic moment of an individual nucleon in the trinucleon systems ^{3}He and ^{3}H is modified by a mechanism different from the conventional exchange-current effect, to the extent that the bulk of the outstanding discrepancy between the theoretical and experimental values of the magnetic moments of these nuclei can be explained.

To begin with, let us summarize the background of the problem. The static magnetic moments of ^{3}He and ^{3}H are known very accurately. For a theoretical analysis it is convenient to introduce the isovector and isoscalar parts of the magnetic moment, defined by

$$\mu_v = \tfrac{1}{2}[\mu(^3\mathrm{He}) - \mu(^3\mathrm{H})], \tag{1}$$

$$\mu_s = \tfrac{1}{2}[\mu(^3\mathrm{He}) + \mu(^3\mathrm{H})]. \tag{2}$$