PHYSICAL REVIEW C VOLUME 30, NUMBER 4 OCTOBER 1984

Brief Reports

Brief Reports are short papers which report on completed research or are addenda to papers previously published in the **Physical Review**. *A Brief Report may be no longer than 3½ printed pages and must be accompanied by an abstract.*

Observation of weak γ-ray transitions in ^{52}Cr using an efficient isotope identification technique for fusion-evaporation reactions

R. L. Kozub, C. B. Chitwood,* and D. J. Fields*
Department of Physics, Tennessee Technological University, Cookeville, Tennessee 38505

C. J. Lister† and E. K. Warburton
Brookhaven National Laboratory, Upton, New York 11973

(Received 23 December 1983; revised manuscript received 5 July 1984)

Gamma-ray transitions in ^{52,53}Cr and ^{54,55}Mn have been observed using ^{7}Li(^{51}V,$xnypz\alpha\gamma$) fusion-evaporation reactions and γ-particle coincidence techniques. The experiment involved the same reaction at the same center-of-mass energy as the earlier work of Poletti *et al.*, but with target and projectile interchanged. In the present work, eight additional transitions have been identified as occurring in ^{52}Cr. This provides corroboration of results obtained more recently via ^{50}Ti(α, 2nγ)^{52}Cr reaction studies. A simple, efficient approach to the spectroscopy of weakly populated nuclear states which provides for unambiguous isotopic assignments is thus demonstrated.

The γ-ray decay schemes of many nuclei have been deduced using fusion-evaporation reactions and γ-γ coincidence methods. However, while such data contain information necessary to determine energy levels, decay branches, etc., coincidence data acquisition using two germanium detectors is often very slow, owing primarily to low photon detection efficiency. Further, for nuclei about which little is known initially, unambiguous isotopic identification may not be possible. Particle-γ coincidence data can generally be acquired at a higher rate than γ-γ data, since particles incident on a detector can be detected with essentially 100% efficiency, provided their energies are above some threshold value. The overall system efficiency is further enhanced in the case of "inverted" heavy ion reactions, i.e., reactions in which the projectile is more massive than the target nucleus. In such cases, the high center-of-mass velocity ($v_{\mathrm{c.m.}}$) results in most of the evaporated light fragments being emitted forward in the laboratory. Thus, a particle detector system centered near 0° in the laboratory will intercept particles emitted within a center-of-mass solid angle which is significantly larger than the laboratory solid angle subtended, resulting in a very high particle counting efficiency. Experimental configurations similar to this have been used a number of times for the measurement of nuclear lifetimes.[1] In such cases, the reaction of interest usually involved the emission of only one light particle per event, so the discrete particle energy spectrum could be gated to control cascade feeding. In the present work, we demonstrate that this gating technique has other uses when applied to continuous, multiparticle evaporation spectra. Similar gating techniques have been used on neutron time-of-flight spectra by Fields *et al.*[2] and on charged particle spectra by Haenni *et al.*[3] in studies which, although similar to ours, involved less efficient, "normal" kinematics situations.

As a demonstration of this γ-particle coincidence technique, we used reactions of 180-MeV ^{51}V with ^{7}Li. This system and energy was chosen to match that studied by Poletti *et al.*,[4] who used γ-γ coincidence techniques and the corresponding "normal" reaction at the same center-of-mass energy, i.e., a ^{51}V target with 25-MeV ^{6,7}Li beams. An illustration of our experimental setup is shown in Fig. 1. The target consisted of 500-μg/cm^2-thick "natural" Li metal[5] on a 860-μg/cm^2-thick Ta backing, oriented with the backing facing the beam. ^{51}V^{15+} ions were accelerated in three stages to 200 MeV using the Brookhaven National Laboratory coupled MP tandems. After degradation by the target backing, the average energy in the Li target was approximately 180 MeV. A 46-mg/cm^2-thick Ta foil placed 12 mm downstream from the target served to stop the beam and heavy evaporation residues. This vacuum recoil distance corresponds to a flight time of approximately 600 ps,

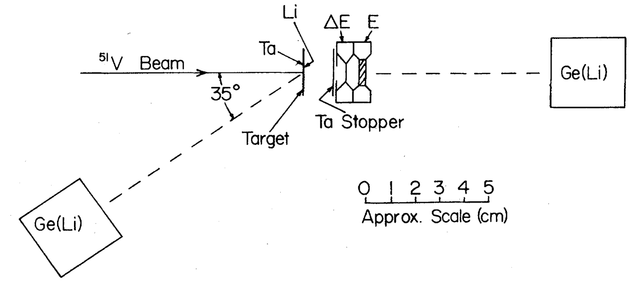

FIG. 1. Schematic drawing of the experimental setup. See text for further details.

and was introduced to allow most of the residues to decay before slowing down or stopping, thereby reducing double peaking and the peak broadening from attenuated Doppler effects. Immediately downstream from the stopper foil, a particle detector telescope having 52.5- and 3000-μm-thick Si detectors for ΔE and E, respectively, was centered at 0°. The telescope subtended approximately 120 msr, and could thus detect particles leaving the target within 11° of the beam direction. Gamma radiation was detected using Ge(Li) detectors of 15% relative efficiency placed at 0° and 145°, each approximately 10 cm from the target. The average beam current was approximately 10 nA (0.67 particle nA), which resulted in counting rates of approximately 14 kHz for the Ge(Li) detectors and 7 kHz for the E detector in the telescope. Standard modular electronic devices were used to generate signals for all possible combinations of twofold γ-γ and γ-particle coincidences. The data were recorded event by event on magnetic tape.

Analysis of particle-γ coincidence data was performed by projecting our γ-ray spectra in coincidence with various two-dimensional regions of the ΔE-vs-E map. In particular, spectra of γ rays in coincidence with identified particles having energies in various 5-MeV intervals were generated for each Ge(Li) detector. Examples of two such spectra, one in coincidence with protons and one with α particles, are shown in Fig. 2. Mean recoil velocities were approximately

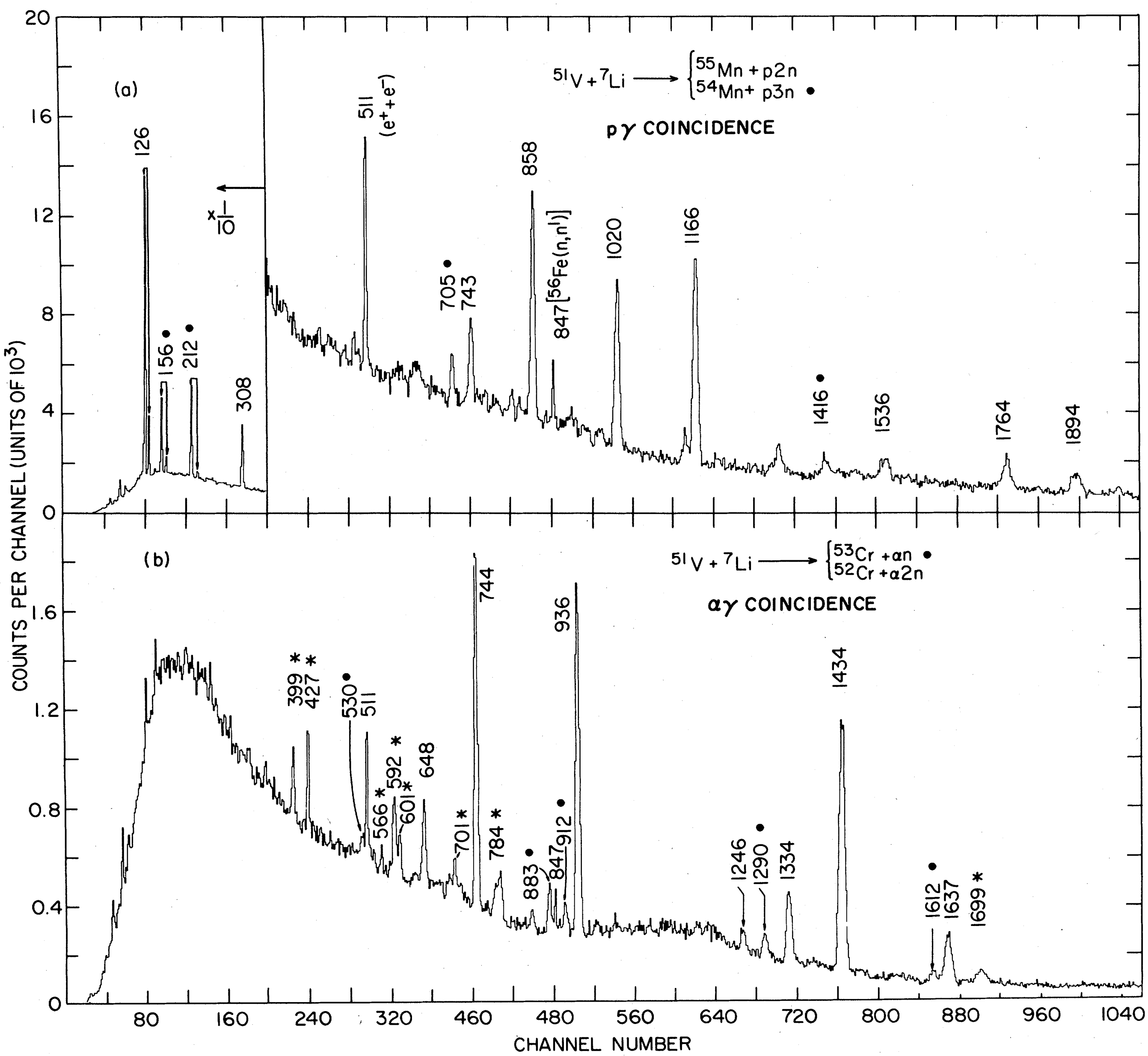

FIG. 2. Spectra of γ rays in coincidence with (a) protons having energies in the range 7.5–12.5 MeV, and (b) α particles having energies in the range 30–35 MeV. Energies are in keV, and lines labeled with an asterisk (*) in (b) are ^{52}Cr transitions not reported in Ref. 4. All peaks are fully Doppler shifted, except for three stopped peak components in (a) for the 126-, 156-, and 212-keV transitions, and the 511- and 847-keV lines. Unlabeled lines are transitions in ^{55}Mn and ^{52}Cr in (a) and (b), respectively.

0.062*c* and 0.066*c* for events in coincidence with α particles and protons, respectively. As expected from the ^{7}Li+^{51}V results of Poletti *et al.*,[4] the dominant evaporation channels are p2n, p3n, αn, and α2n, leading to γ-decaying states in ^{55}Mn, ^{54}Mn, ^{53}Cr, and ^{52}Cr, respectively.

In Figs. 3–5 the relative yields for some of the transitions observed at $\theta_\gamma = 145°$ are plotted versus energy of the evaporated charged particle. Here, the relative yield is defined as the number of coincidence events in a γ-ray peak (I_γ) divided by the total number of events in the entire γ-ray spectrum containing that peak (I_T). It is clear by comparing Fig. 3 with Fig. 4, and by inspection of Fig. 5, that isotopic identification can be made very easily for both p*x*n- and α*x*n-evaporation channels, even though the neutrons are not detected. The observed effects are to be expected from energy conservation considerations, i.e., protons (α particles) from the p2n (αn) evaporation channel will have a higher average energy than those from the p3n (α2n) channel, owing to the combined effects in the latter case of a more negative Q value and the sharing of kinetic energy with an extra neutron. Also, there is some tendency for γ-ray transitions originating at higher excitation energies in ^{52}Cr to be peaked at lower particle energies (Fig. 3), an effect which can be understood in terms of the sharing and conservation of energy within the α2n channel. Finally, it

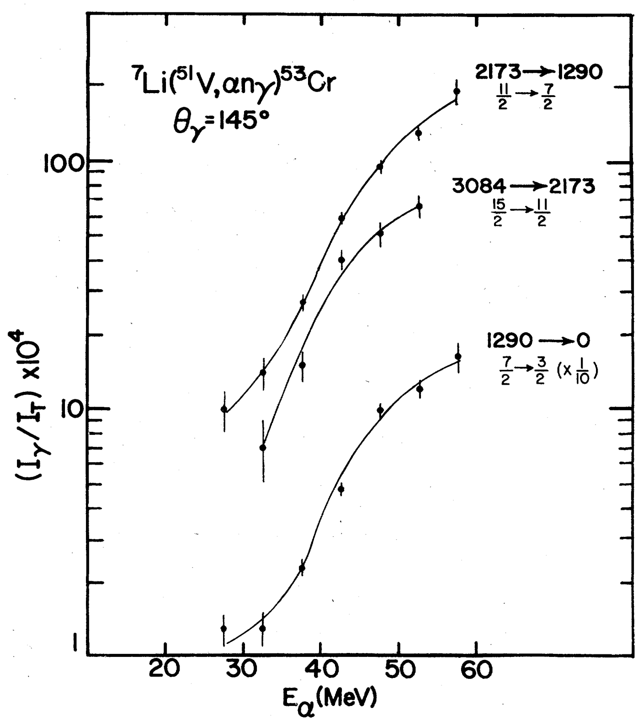

FIG. 4. Relative peak yields for ^{53}Cr γ-ray transitions vs energy of coincident α particles. See caption of Fig. 3 for further details.

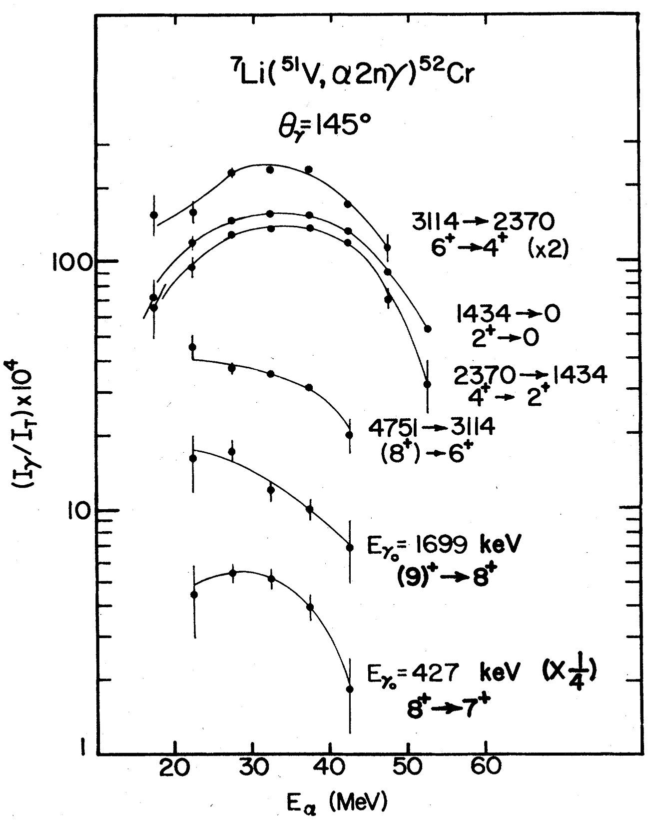

FIG. 3. Relative peak yields for ^{52}Cr γ-ray transitions vs energy of coincident α particles. I_γ is the number of coincidence events in the γ-ray peak and I_T is the number of events in the γ-ray spectrum for each α-particle energy window. No corrections for Ge(Li) detector efficiency have been made. γ-ray energies are in keV. The 427- and 1699-keV transitions were not reported in Ref. 4.

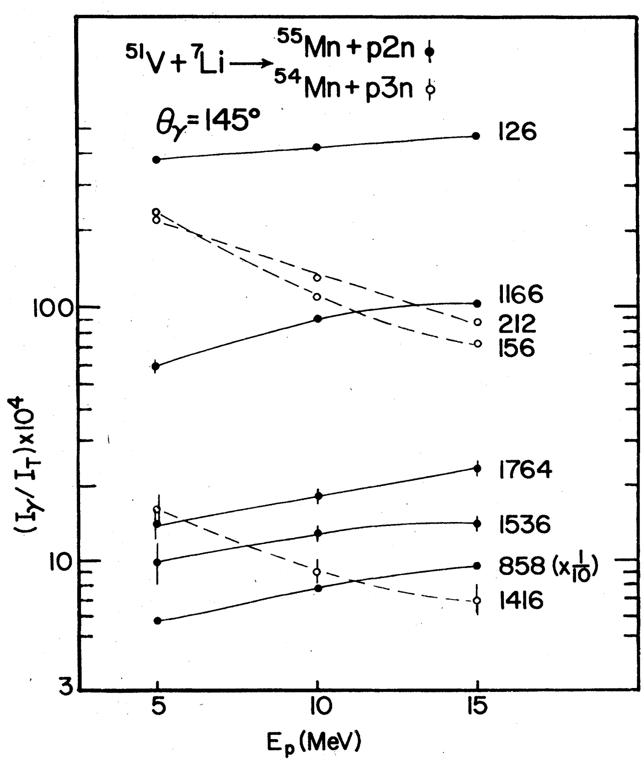

FIG. 5. Relative peak yields for ^{55}Mn and ^{54}Mn γ-ray transitions vs energy of coincident protons. See caption of Fig. 3 for further details.

TABLE I. Weak γ-ray transitions in ^{52}Cr.

E_γ[a] (keV)	Transitions[b] (keV)	Reference
399.3 ± 0.8	$2768.1 \pm 0.3 \rightarrow 2369.8 \pm 0.3$; $4015.42 \rightarrow 3615.84$ $4_2^+ \rightarrow 4_1^+$ $5_2^+ \rightarrow 5_1^+$	4,9
427.1 ± 1.0	$5822.8 \rightarrow 5395.5$ $8^+ \rightarrow 7^+$	7
566 ± 3	$4038 \rightarrow 3471.2$ $4^+ \rightarrow (3,5)$	7
591.8 ± 1.6	$5395.5 \rightarrow 4804.5$ $7^+ \rightarrow 6^+$	7
600.9 ± 1.1	$4015.42 \rightarrow 3415.27$ $5_2^+ \rightarrow 4_3^+$	9
701 ± 3	$3471.2 \rightarrow 2767.3$ $(3,5) \rightarrow 4_2^+$	7
784.3 ± 1.5	$7231 \rightarrow 6448.9$; $7238 \rightarrow 6454$ $? \rightarrow 9$ $(10^+) \rightarrow (9)^+$	7,8
1699 ± 3	$6448.9 \rightarrow 4748$; $6454 \rightarrow 4750$ $9 \rightarrow 8^+$ $(9)^+ \rightarrow 8^+$	7,8

[a]Energies of γ rays observed in the present work but not reported in Ref. 4.
[b]Energies, spins, and parities of levels are taken from the references shown in the right-hand column. The two sets of results shown for the 784- and 1699-keV transitions reflect a discrepancy between the energy scales of Refs. 7 and 8.

should be noted that our proton-γ coincidence analysis (Fig. 5) was limited to protons having energies ≤ 17.5 MeV, owing to interference in the ΔE-E array from protons having ranges in Si in excess of our counter telescope thickness (3052 μm, or about the range of a 23-MeV proton). Families of curves similar to those in Figs. 3–5 were also obtained for $\theta_\gamma = 0°$.

In the case of ^{52}Cr and ^{55}Mn, we observed all transitions reported by Poletti *et al.*[4], as well as the $4206 \rightarrow 2312$ keV transition in ^{55}Mn observed by Nathan *et al.*,[6] via the ^{48}Ca(^{11}B,$4n\gamma$)^{55}Mn reaction. Most of the ^{54}Mn data of Ref. 4 were acquired with a ^{6}Li beam, so no direct comparison is possible for this isotope; we see evidence for six transitions in ^{54}Mn in our spectra, all of which are reported in Ref. 4. As for ^{52}Cr, we observe, in addition to all transitions reported in Ref. 4, the eight decays listed in Table I, all of which have been seen by Berinde *et al.*,[7] in a study of the ^{50}Ti(α,$2n\gamma$)^{52}Cr reaction. In another study, using the same reaction, Styczen *et al.*[8] observed six of these transitions, the exceptions being the 566- and 701-keV lines. The initial and final states shown in Table I are taken from Refs. 7 and 8. Unfortunately, the γ-γ coincidence data of the present work were insufficient for independent assignments to be made.

In summary, the technique described herein does not eliminate the need for γ-γ coincidence experiments. However, the data presented here were acquired in approximately 16 h of accelerator time. For twofold coincidence data, this rate could be increased by an order of magnitude by increasing the effective detector solid-angle product by that factor with larger (but commercially available) particle and γ-ray detectors and using high-counting-rate electronics. Indeed, even γ-γ-particle triple coincidence experiments would be quite feasible with such improvements. Also, the general approach demonstrated here would be very useful for a large number of light-target–heavy-projectile combinations, as the Q values for different evaporation channels are generally quite different for a given compound system.

S. G. Menees and T. J. Theiss of Tennessee Technological University assisted in analyzing the data. The visitors from Tennessee Technological University (TTU) appreciate the hospitality and assistance provided by the Brookhaven National Laboratory (BNL) tandem laboratory staff. This research was supported by the U.S. Department of Energy under Contracts No. DE-AS05-79ER-10335 (TTU) and No. DE-AC02-76H00016 (BNL).

*Present address: National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824.
†Present address: Department of Physics, Schuster Laboratory, The University of Manchester, Manchester M13 9PL United Kingdom.

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