

## Gamma ray studies of neutron-rich *sd*f shell nuclei produced in heavy ion collisions

B. Fornal,\* R. H. Mayer, I. G. Bearden,<sup>†</sup> Ph. Benet,<sup>‡</sup> R. Broda,\* P. J. Daly, and Z. W. Grabowski  
*Chemistry and Physics Departments, Purdue University, West Lafayette, Indiana 47907*

I. Ahmad, M. P. Carpenter, P. B. Fernandez, R. V. F. Janssens, T. L. Khoo, T. Lauritsen, and E. F. Moore<sup>§</sup>  
*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439*

M. Drigert

*Idaho National Engineering Laboratory, Idaho Falls, Idaho 83415*

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Reanalysis of  $\gamma\gamma$  coincidence data acquired in studies of superdeformed bands in Hg and Tl nuclei has yielded spectroscopic information about light neutron-rich products of binary reactions of  $^{34}\text{S}$ ,  $^{36}\text{S}$ , and  $^{37}\text{Cl}$  beams on  $^{160}\text{Gd}$  targets. Gates set on known  $\gamma$  rays in  $A \sim 160$  products selected individual reaction channels and identified coincident  $\gamma$  rays in  $A \sim 36$  partner products. Transfers of protons from projectile to target and of neutrons from target to projectile were generally favored, leading to excited neutron-rich light nuclei, including some difficult to reach by other means. Notable results include the observation of  $\gamma$  ray cascades up to the highest known yrast states in four  $N=20$  isotones. In two  $N=19$  nuclei,  $^{33}\text{Si}$  and  $^{34}\text{P}$ , and the two  $N=22$  nuclei,  $^{38}\text{S}$  and  $^{39}\text{Cl}$ , previously unknown yrast states were identified.

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### I. INTRODUCTION

In an earlier study [1] of the  $^{92}\text{Mo}+^{60}\text{Ni}$  reaction just above the Coulomb barrier we found that thick target  $\gamma\gamma$  coincidence measurements using a Compton-suppressed Ge detector array can yield useful information about binary products of such heavy ion collisions. Noncollective excited states of moderately high spins in  $A \sim 60$  and  $A \sim 92$  product nuclei were seen to be populated by inelastic reaction processes, which typically involved exchange of several nucleons between target and projectile, with, in some cases, subsequent neutron evaporation from the excited primary products. Specific final nuclei could be identified with certainty through their known  $\gamma$  ray cascades. Important among the  $\gamma\gamma$  data recorded were the cross coincidences observed between  $\gamma$  rays emitted simultaneously from partner light and heavy reaction products. Analyses of these  $\gamma\gamma$  cross coincidence data showed that a given binary product may be associated in different events with two or more different partners, one the primary complementary partner nucleus itself, the other(s) secondary product(s) resulting from subsequent evaporation of one or more neutrons. The overall results of the  $^{92}\text{Mo}+^{60}\text{Ni}$  study [1] indicated that  $\gamma\gamma$

techniques might have potential for examining at high resolution some aspects of inelastic and/or transfer processes, and for exploring the yrast spectroscopy of certain neutron excessive nuclei that are inaccessible by fusion-evaporation reactions.

The main projects in recent years of the  $\gamma$ -ray program at the Argonne ATLAS accelerator have included the discovery and characterization of discrete superdeformed bands in nuclei of the  $A \sim 190$  region [2]. Many of the experiments performed have used beams of  $^{34}\text{S}$  or  $^{36}\text{S}$  ions on  $^{160}\text{Gd}$  targets (yielding light Hg nuclei by fusion evaporation) or  $^{37}\text{Cl}$  beams on  $^{160}\text{Gd}$  (yielding Tl products mainly). Since only a tiny fraction of the total fusion cross section leads to population of the superdeformed bands, these investigations have required long runs with the accumulation of high statistics  $\gamma$ -ray data—in a typical experiment more than  $10^8$   $\gamma\gamma$  coincidences. The information relating to superdeformed bands has come mainly from analyses of selected coincidence events of high  $\gamma$ -ray multiplicity.

It seemed to us that such top quality  $\gamma\gamma$  data might also be a source of worthwhile information about inelastic and/or transfer processes leading to yrast states in targetlike and projectilelike reaction products. We have therefore performed detailed analyses of lower-multiplicity subsets of the  $\gamma\gamma$  coincidence data for reactions of  $^{34}\text{S}$ ,  $^{36}\text{S}$ , and  $^{37}\text{Cl}$  beams on thick  $^{160}\text{Gd}$  targets. For many likely product nuclei near  $^{160}\text{Gd}$ , yrast  $\gamma$ -ray cascades were already well known up to high spins, but much less was known about  $\gamma$  rays in the less accessible nuclei around  $^{36}\text{S}$ . In the course of analysis, gates placed on known  $\gamma$  rays in specific  $A \sim 160$  products selected individual reaction channels and identified coincident  $\gamma$  rays in light product partners. Transfer of protons from

\*Permanent address: Institute of Nuclear Physics, PL-31342 Cracow, Poland.

<sup>†</sup>Present address: Niels Bohr Institute, Risø, DK-4000 Roskilde, Denmark.

<sup>‡</sup>Present address: 11 rue de bondues, F-59200 Tourcoing, France.

<sup>§</sup>Present address: Physics Dept., North Carolina State University, Raleigh, NC 27708.

projectile to target, with or without exchange of neutrons, was found to be generally favored, leading to excited neutron-rich light nuclei, some difficult to reach by other spectroscopic methods. Results include the observation of  $\gamma$ -ray cascades up to the highest known yrast states in the four  $N = 20$  isotones  $^{34}\text{Si}$ ,  $^{35}\text{P}$ ,  $^{36}\text{S}$ , and  $^{37}\text{Cl}$ . In two  $N = 19$  isotones,  $^{33}\text{Si}$  and  $^{34}\text{P}$ , and two  $N = 22$  isotones,  $^{38}\text{S}$  and  $^{39}\text{Cl}$ , previously unknown yrast states have been identified. These results serve to test the predictions of up-to-date shell model calculations.

## II. EXPERIMENTAL PROCEDURE AND DATA ANALYSIS

The experiments were performed at the Argonne superconducting linear accelerator ATLAS using beams of 159 MeV  $^{34}\text{S}$ , 159 MeV  $^{36}\text{S}$ , and 167 MeV  $^{37}\text{Cl}$  ions. Targets of  $1.0 \text{ mg/cm}^2$   $^{160}\text{Gd}$  (98% enriched) backed by  $\sim 15 \text{ mg/cm}^2$  of evaporated gold were bombarded at different times with these beams, and  $\gamma$  rays were detected with the Argonne-Notre Dame BGO  $\gamma$ -ray facility, which consists of 12 Compton-suppressed Ge detectors and a 50-element bismuth germanate (BGO) array. The data were recorded event by event with a trigger requiring the prompt firing of at least two Ge detectors in coincidence with at least four BGO elements of the array. Each event stored Ge energy and timing data as well as information from the array, which included sum energy and fold  $k$ . As mentioned,  $k \geq 4$  was a condition for data acquisition in all three experiments. For the setup used, the coincidence efficiency of the Ge detectors dropped off rather sharply for  $\gamma$ -ray energies below  $\sim 140 \text{ keV}$ .

In the original analyses of these data, the  $\gamma$ -ray cascades deexciting high-spin states in Hg and Tl fusion-evaporation product nuclei were relatively enhanced by gating on higher folds in the array, such as  $k > 10$ . For the present investigations, however,  $\gamma\gamma$  correlation matrices produced with the fold condition  $4 \leq k \leq 9$  proved to be much more suitable. These matrices were found to include most of the events associated with deep inelastic processes, while the limits imposed on  $k$  sharply reduced contributions from fusion-evaporation products and also excluded low-multiplicity events arising mainly from Coulomb excitation and quasielastic processes.

Yrast cascades in most of the deformed even-even nuclei around  $^{160}\text{Gd}$  are known up to fairly high spins. Analysis of the data for each reaction was started by setting gates on the  $4^+ \rightarrow 2^+$   $\gamma$  rays in these nuclei and determining the intensities of higher ground band transitions in the coincidence spectra. From efficiency-corrected coincidence intensities for the different  $4^+ \rightarrow 2^+$  and  $6^+ \rightarrow 4^+$   $\gamma$ -ray pairs, relative yields of various products could be estimated, as is shown in Table I for the  $^{160}\text{Gd}+^{37}\text{Cl}$  reaction. Similar patterns were observed in the other two reactions, with  $^{160,162,164}\text{Dy}$  and  $^{156,158,160}\text{Gd}$  being strongly populated (typically up to  $I \sim 14$ ), but little, if any, production of Sm nuclei or  $^{162}\text{Gd}$ . Clearly, the favored processes are those involving addition of protons to the  $^{160}\text{Gd}$  target (with or without neutron transfer) or removal of neutrons from  $^{160}\text{Gd}$ . Unfortunately, this investigation could not be extended

TABLE I. Relative coincidence yields determined for the main  $A \sim 160$  even-even products of the  $^{160}\text{Gd}+^{167} \text{MeV } ^{37}\text{Cl}$  reaction. For each nucleus the  $4^+ \rightarrow 2^+$  transition is the gating  $\gamma$  ray and the  $6^+ \rightarrow 4^+$   $\gamma$  ray is detected in coincidence. Corrections for  $\gamma$ -ray detection efficiency have been applied.

Product	Gating $\gamma$ ray (keV)	Observed $\gamma$ ray (keV)	Relative coincidence yield
$^{160}\text{Gd}$	173	266	100
$^{158}\text{Gd}$	182	278	65(6)
$^{156}\text{Gd}$	199	297	25(3)
$^{162}\text{Dy}$	185	283	91(9)
$^{160}\text{Dy}$	197	297	20(3)
$^{164}\text{Dy}$	169	259	22(3)

in any satisfactory way to possible odd- $A$  or odd-odd products in the  $A \sim 160$  region, mainly because of poor detection sensitivity for low-energy  $\gamma$  rays.

Inspection of summed coincidence spectra gated on "clean"  $\gamma$  rays of a strong  $A \sim 160$  product usually revealed some cross-coincidence  $\gamma$  rays from its light reaction partner. An example for the  $^{160}\text{Gd}+^{37}\text{Cl}$  reaction is illustrated in Fig. 1. Here the upper spectrum gated on  $^{158}\text{Gd}$  lines shows in coincidence not only  $^{158}\text{Gd}$   $\gamma$  rays, but also known  $\gamma$  rays in its partner product  $^{39}\text{Cl}$ . In the lower spectrum, gated on  $^{39}\text{Cl}$  transitions, the  $^{39}\text{Cl}$   $\gamma$  rays (including one new one) are relatively much stronger.

In thick target measurements such as those described, only  $\gamma$  rays emitted from stopped nuclei are observed as narrow lines. For the light products, Doppler broadening essentially prevents the observation of transitions deexciting short-lived ( $T_{1/2} < 1 \text{ ps}$ ) states, except when their population involves longer feeding times. In view of the incompleteness of observation arising from this limitation, a general estimation of light product reaction yields was impossible. The following sections summarize the  $\gamma$ -ray spectroscopic results obtained for light neutron-rich product nuclei with neutron numbers  $N = 22-18$ .

## III. SPECTROSCOPY OF NEUTRON-RICH NUCLEI NEAR $N = 20$

### A. $N = 22$ isotones $^{38}\text{S}$ and $^{39}\text{Cl}$

The  $^{38}\text{S}$  nucleus has been studied previously by means of  $(t, p)$  and  $(t, p\gamma)$  reactions [3-5], and excited states with  $I^\pi = 2^+$ ,  $4^+$ , and  $5^-$  or  $6^+$  have been located. For the  $^{39}\text{Cl}$  nucleus, a combination of  $(t, p\gamma)$  and  $^{39}\text{S}$   $\beta$  decay studies [6,7] has identified levels up to an  $I^\pi = \frac{9}{2}^+$  state at 2424 keV, which deexcites mainly by a cascade of 638, 485, and 1301 keV transitions to the  $^{39}\text{Cl}$   $\frac{3}{2}^+$  ground state. Both of these  $N = 22$  isotones were produced quite strongly in the present experiments.

As shown for the  $^{160}\text{Gd}+^{37}\text{Cl}$  reaction in Fig. 1(a), known  $^{39}\text{Cl}$   $\gamma$  rays appeared in coincidence with yrast cascade  $\gamma$  rays of  $^{158}\text{Gd}$ , and gating on  $^{39}\text{Cl}$  transitions [Fig. 1(b)] sharply enhanced the prominence of the  $^{39}\text{Cl}$  coincidence peaks. The 685 and 410 keV  $\gamma$  rays, clearly

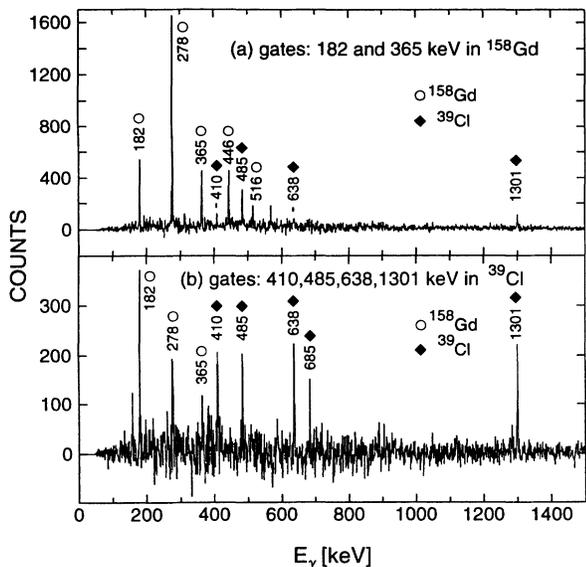


FIG. 1. Representative  $\gamma\gamma$  coincidence spectra for  $^{158}\text{Gd}$  and  $^{39}\text{Cl}$  products of the reaction  $^{160}\text{Gd}+^{167}\text{MeV } ^{37}\text{Cl}$ .

seen in Fig. 1(b), were found to occur in cascade feeding the known  $\frac{9}{2}^+$  yrast state in  $^{39}\text{Cl}$ ; of these, the 410 keV transition was already observed in the  $(t, p\gamma)$  study [6], but the 685 keV  $\gamma$  ray was not seen before. The main  $\gamma$ -ray deexcitation cascade observed for  $^{39}\text{Cl}$  is displayed on the right side of Fig. 2.

Likewise, for the  $^{160}\text{Gd}+^{36}\text{S}$  reaction  $\gamma$  rays of the  $2n$  transfer product partners  $^{158}\text{Gd}$  and  $^{38}\text{S}$  were observed in coincidence. Known 1292 keV  $2^+ \rightarrow 0^+$ , 1533 keV  $4^+ \rightarrow 2^+$ , and 1513 keV  $2^+ \rightarrow 2^+$   $^{38}\text{S}$  transitions were clearly seen as well as a fairly strong 849 keV  $\gamma$  ray which feeds the  $4^+$  state from a level at 3674 keV. The decay scheme is shown with observed intensities on the left side

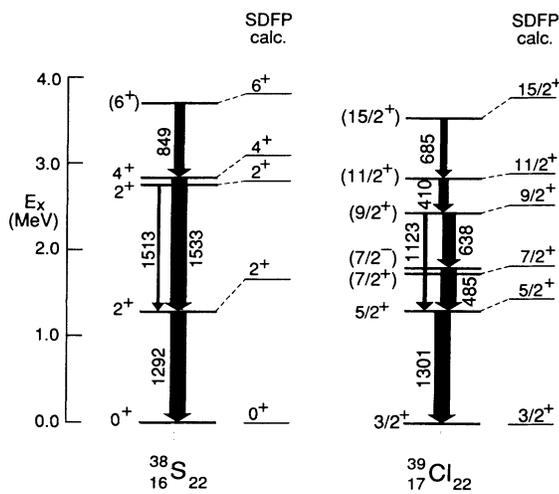


FIG. 2. Decay schemes of  $^{38}\text{S}$  and  $^{39}\text{Cl}$  nuclei from  $^{160}\text{Gd}+^{36}\text{S}$  and  $^{160}\text{Gd}+^{37}\text{Cl}$  reactions, respectively. Arrow widths reflect the relative  $\gamma$ -ray intensities observed in coincidence with the lowest transition in each nucleus, but are otherwise arbitrary. Calculated level spectra are from Refs. [4,7].

of Fig. 2. It is highly likely that the 3674 keV level is identical to the one located in the  $(t, p)$  study of  $^{38}\text{S}$  at  $3690 \pm 16$  keV and given a tentative  $I^\pi = 6^+$  assignment.

The nucleus  $^{38}\text{S}$  has two valence neutrons outside the  $N = 20$  closed shell, and  $(\nu f_{7/2})^2$  seniority-2  $2^+$ ,  $4^+$ , and  $6^+$  yrast states are thus expected. In  $^{39}\text{Cl}$ , which has a  $\pi d_{3/2}(\nu f_{7/2})^2$   $v = 3$  states with  $I^\pi$  values up to  $\frac{15}{2}^+$ . A comparison in Fig. 2 with results of calculations [4,7] in an *sd*f*p*-shell model space shows generally good agreement between experimental and predicted energies for yrast states in both  $N = 22$  nuclei.

### B. $N = 20$ isotones $^{34}\text{Si}$ , $^{35}\text{P}$ , $^{36}\text{S}$ , and $^{37}\text{Cl}$

The  $\gamma$  rays deexciting known [8] yrast states up to  $I \sim 6$  in the  $N = 20$  products  $^{34}\text{Si}$ ,  $^{35}\text{P}$ ,  $^{36}\text{S}$ , and  $^{37}\text{Cl}$  were observed in these reactions with the coincidence intensity patterns shown in Fig. 3. Each isotone was produced with similar yields in at least two of the reactions studied.

The  $^{34}\text{Si}$  nucleus was observed as a product in both  $^{34}\text{S}$  and  $^{36}\text{S}$  induced reactions, and some typical  $\gamma\gamma$  data for the  $^{160}\text{Gd}+^{36}\text{S}$  reactions are presented in Fig. 4. The upper spectrum [Fig. 4(a)], recorded in coincidence with  $\gamma$  rays of the  $2p$  transfer product  $^{162}\text{Dy}$ , is fairly complicated, but one can still pick out the 3326, 929, and 125 keV transitions known to depopulate yrast states with  $I^\pi$  values of  $2^+$ ,  $3^-$ , and  $(4,5)^-$  in the reaction partner  $^{34}\text{Si}$ . The spectrum obtained by gating on the 3326 keV  $2^+ \rightarrow 0^+$  transition in  $^{34}\text{Si}$  is much cleaner [Fig. 4(b)], and the 929 and 125 keV  $\gamma$  rays, as well as a few  $^{162}\text{Dy}$  transitions, are clearly visible. The same three  $^{34}\text{Si}$  transitions were also seen in the  $^{160}\text{Gd}+^{34}\text{S}$  reaction, but this time in coincidence with  $\gamma$  rays from the  $^{160}\text{Dy}$  partner product. The excitation process here involves net exchange of two neutrons for two protons between target and projectile.

A rather similar decay pattern was found for the  $^{36}\text{S}$  nucleus, which was an observed product in all three of the reactions studied. The known  $5^- \rightarrow 4^- \rightarrow 3^- \rightarrow 2^+ \rightarrow 0^+$  cascade of 185, 827, 902, and 3291 keV  $\gamma$  rays was seen clearly, and for the  $^{34}\text{S}$  and  $^{36}\text{S}$  induced reactions these  $\gamma$  rays appeared in coincidence with transitions in their heavy reaction partners.

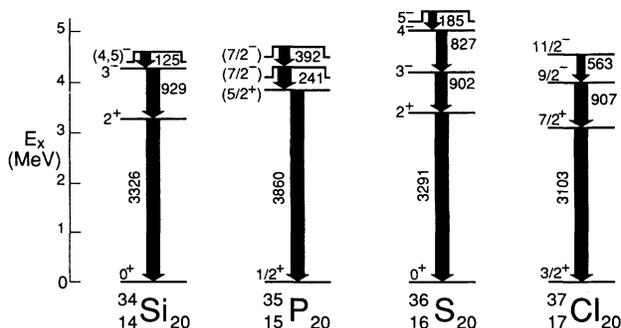


FIG. 3. Decay schemes for four  $N = 20$  isotones. See the caption to Fig. 2 regarding the widths of transition arrows.

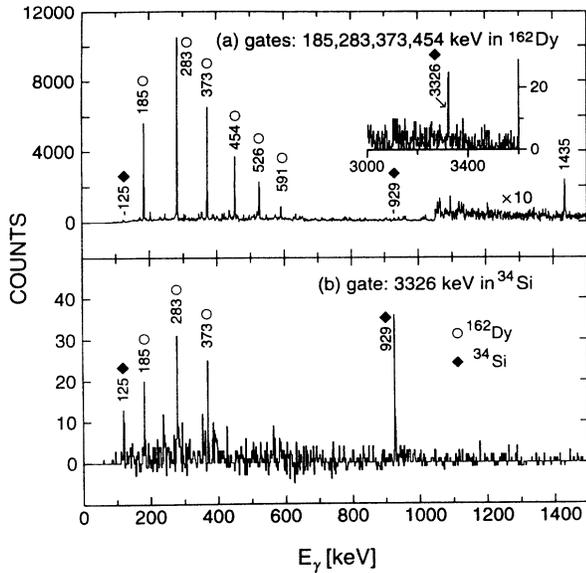


FIG. 4. Coincidence  $\gamma$ -ray spectra for  $^{162}\text{Dy}$  and  $^{34}\text{Si}$  products of the  $^{160}\text{Gd}+162\text{ MeV }^{36}\text{S}$  reaction.

However, in those cases where  $\gamma$  rays of  $^{35}\text{P}$  and  $^{37}\text{Cl}$  were detected, direct  $\gamma\gamma$  cross coincidences between primary products were not observed. The  $^{35}\text{P}$   $\gamma$ -ray cascade shown in Fig. 3 was seen in the  $^{160}\text{Gd}+^{37}\text{Cl}$  reaction, but the  $\gamma$  rays of the  $^{162}\text{Dy}$  reaction partner did not appear in coincidence; instead, the  $\gamma$  rays of  $^{160}\text{Dy}$  and  $^{35}\text{P}$  appeared together, indicating evaporation of two neutrons in each event. In the same  $^{160}\text{Gd}+^{37}\text{Cl}$  reaction, the  $\gamma$  rays of  $^{37}\text{Cl}$  (Fig. 3) were found to be coincident with  $\gamma$  rays of  $^{158}\text{Gd}$  (and not those of the direct partner product  $^{160}\text{Gd}$ ), demonstrating that  $2n$  evaporation occurred also in these events.

### C. $N = 19$ isotones $^{33}\text{Si}$ , $^{34}\text{P}$ , and $^{35}\text{S}$

Little is known about yrast excitations in the hard to reach  $N = 19$  isotones  $^{33}\text{Si}$  and  $^{34}\text{P}$ , and the situation is not much better in the more accessible isotone  $^{35}\text{S}$ . The present studies yielded some information about the spectroscopy of these three  $N = 19$  nuclei. Figure 5 shows for the  $^{160}\text{Gd}+^{37}\text{Cl}$  reaction the coincidence spectrum obtained with gates set on yrast transitions of the  $2p$  transfer product  $^{162}\text{Dy}$ . No  $^{35}\text{P}$   $\gamma$  rays were observed in cross coincidence (as noted in the preceding section); however, two fairly strong  $\gamma$  rays of 429.1 and 1876 keV did appear [Fig. 5(a)], and the first of these was recognized to be identical with the 429.1 keV ground-state transition in  $^{34}\text{P}$  known from  $^{34}\text{Si}$   $\beta$ -decay studies [9]. The 1876 and 429 keV transitions occur in cascade [Fig. 5(b)], and they are placed in the  $^{34}\text{P}$  level scheme shown in Fig. 6. The observation in the  $^{160}\text{Gd}+^{37}\text{Cl}$  reaction of  $^{34}\text{P}$   $\gamma$  rays in coincidence with those of  $^{162}\text{Dy}$  implies that a neutron was evaporated from one of the primary products, which could have been either  $^{34}\text{P}+^{163}\text{Dy}$  or

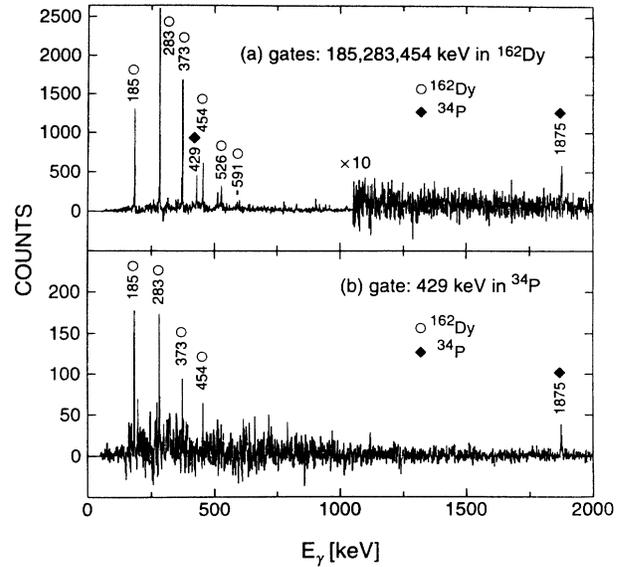


FIG. 5. Coincidence  $\gamma$ -ray spectra for  $^{162}\text{Dy}$  and  $^{34}\text{P}$  products of the  $^{160}\text{Gd}+167\text{ MeV }^{37}\text{Cl}$  reaction.

$^{35}\text{P}+^{162}\text{Dy}$ . The 429, 1876 keV  $\gamma$ -ray cascade was observed in the  $^{34}\text{S}$  and  $^{36}\text{S}$  induced reactions as well, but there was little possibility of detecting cross coincidences with  $\gamma$  rays in Tb nuclei.

In  $^{34}\text{P}$ , the  $1^+$  ground state and 429 keV  $2^+$  state are assigned to the  $\pi s_{1/2}\nu d_{3/2}$  configuration. Promotion of the odd neutron across the  $N = 20$  gap should give rise to yrast states of the type  $\pi s_{1/2}\nu f_{7/2}$ , with  $I^\pi = 3^-$  and  $4^-$ , and candidates for these states have been located at 2.23 and 2.31 MeV in studies of the  $^{34}\text{S}(t,^3\text{He})^{34}\text{P}$  and  $^{36}\text{S}(d,\alpha)^{34}\text{P}$  reactions [10,11]. The 2305 keV level es-

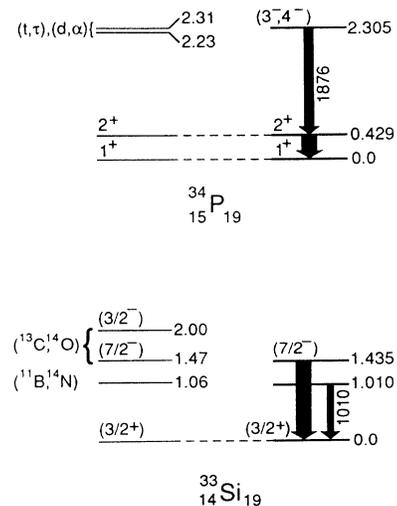


FIG. 6. Proposed decay schemes for  $^{34}\text{P}$  and  $^{33}\text{Si}$ . Here the arrow widths denote relative  $\gamma$ -ray coincidence intensities observed with gates on transitions in the reaction partner. On the left are shown levels located previously in the specified transfer reactions.

established in the present work and the  $2309 \pm 10$  keV level populated in the ( $t, ^3\text{He}$ ) reaction are almost certainly the same state (with  $I^\pi = 3^-$  or  $4^-$ ), but no  $\gamma$  ray(s) deexciting a  $^{34}\text{P}$  level around 2.23 MeV could be detected. One possibility is that a fast  $3^- \rightarrow 2^+$   $\gamma$  ray may have been obscured by Doppler broadening, whereas the much slower  $4^- \rightarrow 2^+$   $\gamma$  ray should be seen as a narrow line.

The simultaneous production of  $^{34}\text{P}$  and  $^{162}\text{Dy}$  described above for the  $^{160}\text{Gd} + ^{37}\text{Cl}$  reaction suggested that in the  $^{36}\text{S}$  induced reaction one might similarly observe coincidences between  $^{33}\text{Si}$  and  $^{162}\text{Dy}$   $\gamma$  rays. The big problem here is the total lack of information about transitions in the  $^{33}\text{Si}$  nucleus—approximate energies of only the few excited levels shown in Fig. 6 are known from studies [12,13] of the exotic transfer reactions  $^{34}\text{S}(^{13}\text{C}, ^{14}\text{O})$  and  $^{36}\text{S}(^{11}\text{B}, ^{14}\text{N})$ . Inspection of the appropriate  $\gamma$ -ray coincidence spectrum gated on  $^{162}\text{Dy}$  lines [Fig. 4(a)] revealed, in addition to the known  $^{34}\text{Si}$  transitions, a single strong 1435 keV  $\gamma$  ray that we interpret as a ground state transition in  $^{33}\text{Si}$ , deexciting the ( $\frac{7}{2}^-$ ) level first located at  $\sim 1.47$  MeV in the ( $^{13}\text{C}, ^{14}\text{O}$ ) study [12]. A second but much weaker 1010 keV  $\gamma$  ray is also tentatively placed in the  $^{33}\text{Si}$  scheme (Fig. 6). In the  $^{160}\text{Gd} + ^{34}\text{S}$  reaction, the same 1435 and 1010 keV transitions appeared with similar intensities in coincidence with known  $^{160}\text{Dy}$   $\gamma$  rays.

A third  $N = 19$  isotone,  $^{35}\text{S}$ , was also produced in the reactions studied. In this nucleus, an  $I^\pi = \frac{7}{2}^-$  yrast state at 1991 keV is well known from ( $d, p\gamma$ ), ( $n, \gamma$ ) and  $^{35}\text{P}$   $\beta^-$ -decay studies [14–16]. In fact, the previously discussed 1435 keV ground state transition in  $^{33}\text{Si}$  is an ostensible counterpart of the established 1991 keV  $\frac{7}{2}^- \rightarrow \frac{3}{2}^+$  transition in  $^{35}\text{S}$ . The ( $d, p\gamma$ ) results included higher-lying  $^{35}\text{S}$  levels at 3818 and 4022 keV that decay exclusively to the 1991 keV  $\frac{7}{2}^-$  state; either of these could be the  $\frac{9}{2}^-$  yrast state calculated in Ref. [16] at 3.91 MeV. The present data from both the  $^{34}\text{S}$  and  $^{37}\text{Cl}$  induced reactions showed clean coincidences between 1991 and 2031 keV  $\gamma$  rays but no trace of a 1827 keV transition (from the proposed 3818 keV level). This result confirms the level at 4022 keV in  $^{35}\text{S}$  as a likely candidate to be the expected  $\frac{9}{2}^-$  yrast excitation.

#### D. $N = 18$ isotones $^{32}\text{Si}$ and $^{34}\text{S}$

The  $\gamma$  rays deexciting all known [8] states in  $^{34}\text{S}$  up to a  $5^-$  state at 5689 keV were observed in the reaction  $^{160}\text{Gd} + ^{34}\text{S}$ , but no new transitions were identified. In the same reaction, two-proton transfer yielded an yrast  $\gamma$ -ray cascade in  $^{32}\text{Si}$  consisting of previously known [8] 1941 and 3562 keV  $\gamma$  rays and a new 402 keV transition. This cascade appeared also in the  $^{36}\text{S}$  induced reaction, with appropriate Dy  $\gamma$ -ray families showing in cross coincidence in both reactions. For the 402, 3562, 1941 keV cascade in  $^{32}\text{Si}$ , systematics suggest the  $I^\pi$  sequence ( $5^-$ )  $\rightarrow$  ( $4^+$ )  $\rightarrow$   $2^+ \rightarrow 0^+$ .

## IV. REACTION YIELDS

The present  $\gamma$ -ray analysis has identified with certainty many product nuclei excited to moderately high spins and energies in both the target and projectile regions, and it raises questions about the cross sections and mechanisms of the excitation processes involved. The data consist of  $\gamma\gamma$  coincidence intensities, but these cannot generally be converted into reaction cross sections for individual exit channels. However, for even-even product nuclei a reasonable comparison of yrast yields could be based on the available  $\gamma\gamma$  coincidence intensities for  $6^+ \rightarrow 4^+ \rightarrow 2^+$  cascades in the  $A \sim 160$  region and for  $4^+ \rightarrow 2^+ \rightarrow 0^+$  cascades in the light products. The results demonstrate a similar overall pattern of reaction yields for each of the three reactions studied in this work. Unfortunately, no satisfactory method for including odd- $A$  and odd-odd product yields in these semiquantitative surveys could be devised.

As a representative example, the results for the  $^{160}\text{Gd} + ^{36}\text{S}$  reaction are presented in Fig. 7, where square symbols for the even-even product nuclei are drawn proportional to the observed  $\gamma\gamma$  coincidence intensities. Asterisks label other products that were positively identified through their  $\gamma$  rays. It is apparent that transfers of protons from projectile to target and of neutrons from target to projectile are generally favored. In this reaction the ratio  $N/Z$  is substantially larger for target than for projectile, and so these findings are in keeping with the expected tendency [17] toward mass and charge equilibration of the colliding ions. Indeed, the observed yield pattern correlates well with the minimum nuclear potential energy contours [17] calculated for this system (Fig. 7). Some shift in average yields toward lower masses can be attributed to neutron evaporation from primary frag-

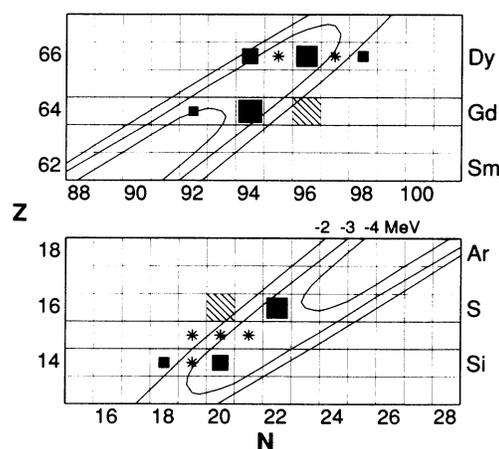


FIG. 7. Relative yields of even-even products of the reaction  $^{160}\text{Gd} + 162$  MeV  $^{36}\text{S}$  are represented by squares having areas directly proportional to the observed  $\gamma\gamma$  coincidence intensities. Target and projectile nuclei are indicated by crosshatching, while asterisks label odd- $A$  and odd-odd products that were positively identified. The  $-2$ ,  $-3$ , and  $-4$  MeV potential energy contours in the regions around target and projectile are shown for the  $^{160}\text{Gd} + ^{36}\text{S}$  dinuclear system.

ments, but at these low energies the effect may be a small one.

Gamma-ray coincidence studies such as those described here open possibilities for exploring to a limited extent the spectroscopy of certain neutron-rich products of deep-inelastic heavy ion reactions. Since the production method unavoidably delivers many product nuclei with comparable yields, the data analysis is often difficult. Obviously, such investigations would benefit con-

siderably from the enhanced sensitivity and selectivity of the newer, larger  $\gamma$ -ray detector arrays.

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