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# Nuclear Structure of $Sc^{43}$. I. Energy Levels and Decay Schemes

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The $Ca^{42}(p, \gamma)Sc^{43}$ reaction has been studied in the range $E_p=1200$–$2060$ keV in order to determine the properties of the excited states in $Sc^{43}$. Approximately 100 resonances due to this reaction were identified and located in proton energy to an accuracy of ±2 keV. Singles spectra were obtained at each of the resonances at $E_p=1235$, 1242, 1423, 1808, 1891, and 2037 keV using a large-volume Ge(Li) detector. These spectra were used to derive consistent $\gamma$-ray decay schemes and accurate level energies for the resonant and bound states of $Sc^{43}$. A new level in $Sc^{43}$ at 4.455 MeV was found. In addition, new results or results significantly different from earlier reports were obtained for the decay properties of most levels below 4 MeV in $Sc^{43}$. We also obtained a new value of $Q=4.929\pm0.002$ MeV for the $Ca^{42}(p, \gamma)Sc^{43}$ reaction. The resonance strengths were measured relative to the known strength of the $E_p=1842$-keV resonance in the $Ca^{40}(p, \gamma)Sc^{41}$ reaction.

## I. INTRODUCTION

The nuclear properties of $Sc^{43}$ were first investigated by Dubois and Broman[1] in 1963 using the $Ca^{42}(p, \gamma)Sc^{43}$ reaction in the energy range $E_p=780$–$1420$ keV. They studied the capture $\gamma$-ray spectra at nine resonances using NaI detectors and established the existence of six low-lying levels. Later work by Broman and Dubois[2] on the $Ca^{42}(p, \gamma)Sc^{43}$ reaction at seven resonances using both a NaI and a 0.5-cc Ge(Li) detector established the existence of 17 levels below 4 MeV in $Sc^{43}$ and provided the first information on the decay properties of these levels. Additional levels in $Sc^{43}$ have been found by Cujec,[3] by Phillips *et al.*,[4] and by Schwartz *et al.*[5] using the $Ca^{40}(\alpha, p)Sc^{43}$ reaction, by Schwartz and Alford[6] and by Broman[7] using the $Ca^{42}(He^3, d)Sc^{43}$ reaction, by Grandy *et al.*[8] using the $Ca^{42}(d, n)Sc^{43}$ reaction, and by Plendl *et al.*[9] using the $Ti^{46}(p, \alpha)Sc^{43}$ reaction. To date, approximately 41 excited states below 5 MeV in $Sc^{43}$ have been found.

The principal sources of level decay-scheme information have been the experiments of Broman and Dubois,[2] Phillips *et al.*,[4] and Schwartz *et al.*[5] Some spin-parity assignments have been made by Broman *et al.*[10] using the $Ca^{42}(p, \gamma)Sc^{43}$ reaction, by Phillips *et al.*[4] using the $Ca^{40}(\alpha, p\gamma)Sc^{43}$ reaction, and by Ward *et al.*[11] from internal-conversion-coefficients measurements. In addition, $l$-value assignments are available for certain levels from the $Ca^{42}(He^3, d)Sc^{43}$, $Ca^{40}(\alpha, p)Sc^{43}$, and $Ca^{42}(d, n)Sc^{43}$ reactions.[5,6,8] For a more complete review of previous work on $Sc^{43}$, the reader is referred to the recent review articles by Endt and van der Leun[12] and by Broman.[7]

We report on a study of the excited states of $Sc^{43}$ using the $Ca^{42}(p, \gamma)Sc^{43}$ reaction in the energy range $E_p=1200$–$2060$ keV. The objectives of the study were the following: (a) extend the $Ca^{42}(p, \gamma)Sc^{43}$ resonance yield curve, (b) verify the existence or nonexistence of certain doubtful levels in $Sc^{43}$, (c) resolve the ambiguity in the energy, $\gamma$-ray decay scheme, and branching-ratio measurements of many low-lying levels in $Sc^{43}$, (d) determine the spins and parities of the bound states in $Sc^{43}$, and (e) locate and study the isobaric analog states. In this paper, we will deal with (a)–(c). The results reported here provide the necessary information for the analysis of angular distribution and correlation measurements which we will deal with in subsequent papers. This work was greatly aided by the availability of a large volume (40 cc), high-resolution Ge(Li) detector.

In Sec. II, a brief account of the experimental procedures is given. Our experimental results are presented in Sec. III. A summary and discussion of the important results are contained in Sec. IV.

## II. EXPERIMENTAL PROCEDURE

The $Ca^{42}(p, \gamma)Sc^{43}$ reaction was initiated by a proton beam from the Aerospace Research Laboratories (ARL) 2-MeV Van de Graaff accelerator. For an accurate measurement of some resonance energies, the new ARL 8-MeV High-Voltage Engineering Corporation Insulating Core Transformer (HVEC-ICT) tandem accelerator was used. This new machine has a beam energy resolution of about 0.200 keV (see Sec. III C). The average beam current used in most of the present work was approximately 30 $\mu$A focused to a spot size of about 3 mm diam at the target. The energy resolution of the beam was approximately 1 keV.

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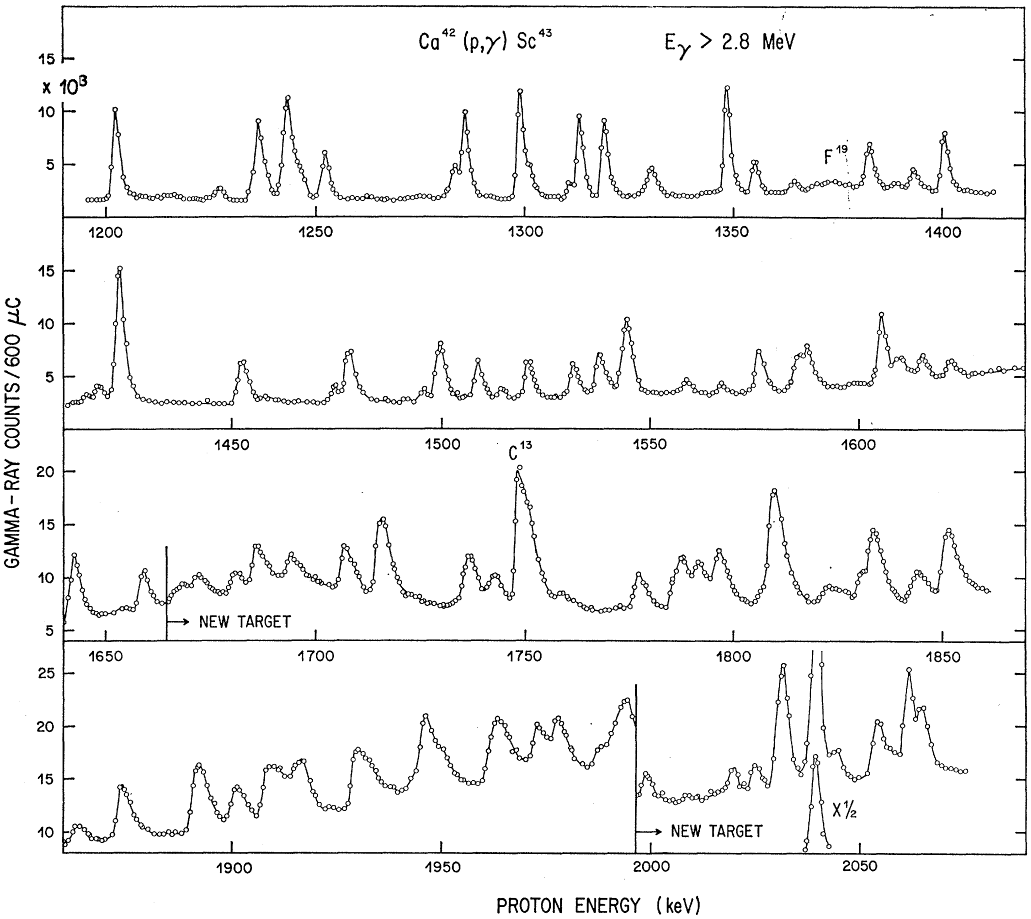

FIG. 1. Yield curve of the $Ca^{42}(p, \gamma)Sc^{43}$ reaction in the proton energy range of 1200–2060 keV, measured with an 8-in. NaI(Tl) detector at 55° to the beam direction. The first and last sections of the yield curve were measured using a 2-keV-thick target. The remaining part of the yield curve was measured using a 4–5-keV-thick target.

Targets were prepared from samples of $CaCO_3$ enriched in $Ca^{42}$.[13] The enriched $CaCO_3$ was evaporated onto a 10-mil-thick Ag target backing which was soldered onto a 0.0625-in.-thick brass cooling disk. With direct water cooling, targets prepared in this manner have withstood beam currents as large as 50 μA at 2 MeV with no appreciable deterioration. This method of target preparation was used for both the yield and spectra measurements, where the high counting rates and improved background ratio were of particular importance. Target thickness were typically 2–3 keV for the yield measurements and 3–5 keV for the spectra measurements.

An 8-in.-diam×8-in.-long NaI(Tl) detector placed at an angle of 55° with respect to the beam direction and at a distance of 6 in. from the target was used to locate the resonances. The resonance γ-ray yields were measured with the discrimination level set at $E_\gamma \geq 2.8$ MeV. The relative intensities of the resonances were determined by measuring the areas under the yield curve. The resonance strengths

$$[S=(2J+1)\Gamma_\gamma\Gamma_p/\Gamma_t]$$

reported here were determined from the resonance decay schemes and relative intensities. To obtain the absolute resonance strengths, a target[14] consisting of approximately 90% $Ca^{40}$ and 10% $Ca^{42}$ was used to compare the strengths of the $Ca^{42}$ resonances with that of the $E_p = 1842$-keV resonance in $Ca^{40}$ previously measured by Engelbertink and Endt.[15]

The γ-ray spectrum for each resonance was measured with a 40-cc Ge(Li) detector mounted with its axis at 55° with respect to the beam direction and at a distance of $1\frac{1}{8}$ in. from the target. The spectra were recorded in a 4096-channel analyzer and stored on

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[13] The enriched $Ca^{42}$ was obtained from Oak Ridge National Laboratory in the form of $CaCO_3$. Isotopic composition: $Ca^{40}$, 4.96%; $Ca^{42}$, 94.42%; $Ca^{43}$, 0.06%; $Ca^{44}$, 0.56%; $Ca^{46}$, <0.05%; $Ca^{48}$, <0.05%.

[14] This sample was also obtained from Oak Ridge National Laboratory as $CaCO_3$. Isotopic composition: $Ca^{40}$, 90.54%; $Ca^{42}$, 9.39%; $Ca^{44}$, 0.06%; $Ca^{46}$, <0.01%; $Ca^{48}$, <0.01%.

[15] G. A. P. Engelbertink and P. M. Endt, Nucl. Phys. **88**, 12 (1966).

TABLE I. Resonance energies and relative strengths.[a]

| $E_p$ (keV) | Relative intensity | $E_p$ (keV) | Relative intensity | $E_p$ (keV) | Relative intensity | $E_p$ (keV) | Relative intensity |
|---|---|---|---|---|---|---|---|
| 1201 | 105 | 1415 | 10 | 1623 | 23 | 1850 | 142 |
| 1214 | 7 | 1418 | 22 | 1643 | 100 | 1862 | 33 |
| 1226 | 13 | 1422.8[b] | 202 | 1656 | 6 | 1873 | 111 |
| 1234.8[b] | 109 | 1452 | 70 | 1660 | 49 | 1891 | 163 |
| 1241.9[b] | 148 | 1459 | 13 | 1667 | 24 | 1900 | 63 |
| 1245 | 27 | 1474 | 20 | 1673 | 41 | 1908 | 148 |
| 1250 | 74 | 1478 | 85 | 1680 | 21 | 1916 | 135 |
| 1274 | 6 | 1491 | 3 | 1685 | 58 | 1929 | 177 |
| 1282 | 42 | 1496 | 13 | 1693 | 31 | 1945 | 185 |
| 1285 | 91 | 1500 | 85 | 1706 | 75 | 1949 | 47 |
| 1290 | 6 | 1509 | 53 | 1714 | 195 | 1962 | 183 |
| 1298 | 121 | 1515 | 15 | 1735 | 99 | 1972 | 113 |
| 1300 | 14 | 1521 | 50 | 1741 | 51 | 1977 | 107 |
| 1310 | 13 | 1532 | 49 | 1776 | 63 | 1987 | 34 |
| 1312 | 91 | 1538 | 61 | 1786 | 47 | 1993 | 183 |
| 1318 | 91 | 1545 | 128 | 1788 | 64 | 1996 | 52 |
| 1329 | 46 | 1559 | 22 | 1792 | 77 | 2006 | 4 |
| 1343 | 7 | 1567 | 9 | 1797 | 95 | 2017 | 37 |
| 1348 | 116 | 1576 | 56 | 1806 | 40 | 2022 | 37 |
| 1354 | 36 | 1586 | 53 | 1808.3[b] | 255 | 2029 | 221 |
| 1364 | 13 | 1588 | 53 | 1821 | 41 | 2036.6[b] | 301 |
| 1382 | 59 | 1600 | 5 | 1825 | 16 | 2042 | 30 |
| 1388 | 4 | 1606 | 92 | 1829 | 48 | 2052 | 110 |
| 1393 | 34 | 1610 | 38 | 1832 | 127 | 2059 | 190 |
| 1400 | 71 | 1616 | 34 | 1843 | 57 | 2063 | 87 |

[a] Intensities are normalized to the relative intensity assigned to the 1421.4-keV resonance in Ref. 2.

[b] Resonance energies of selected resonances determined with the ICT-tandem accelerator after correction for relativistic effects. The uncertainty in the energy is approximately 0.5 keV at these selected resonances.

magnetic tape for subsequent processing in an IBM 7094 computer. Off-resonance spectra were obtained in order to identify those $\gamma$ rays which did not belong to transitions in $Sc^{43}$. Background $\gamma$ rays were found at energies of 0.309, 0.324, 0.414, and 0.423 MeV from the Coulomb excitation of the Ag isotopes in the target backing, 0.439 and 1.63 MeV from the $Na^{23}(p, p'\gamma)Na^{23}$ and $Na^{23}(p, \alpha\gamma)Ne^{20}$ reactions, respectively, 4.43 MeV from the $N^{15}(p, \alpha\gamma)C^{12}$ reaction, and 6.13 MeV from the $F^{19}(p, \alpha\gamma)O^{16}$ reaction.

The $\gamma$-ray energies were determined using a least-squares technique. The accurately known energies of the annihilation $\gamma$ ray and the background $\gamma$ rays, 1.63 and 6.13 MeV from the $Na^{23}(p, \alpha\gamma)Ne^{20}$ and $F^{19}(p, \alpha\gamma)O^{16}$ reactions, respectively, were used as calibration points. The energy differences between the photopeak, single- and double-escape peaks were used as constraints in the fitting procedure. The center position of each line was first determined assuming that all lines have a Gaussian shape. The energies of the center positions were then determined by fitting them with a third-order polynomial in the channel number. The $\gamma$-ray energies of the primary transitions were all corrected for Doppler shifts due to the motion of the nucleus during $\gamma$-ray emission.

The relative intensities of the transitions were determined from the relative photopeak, single- or double-escape peak intensities in the spectrum. The intensity calibration of the 40-cc detector was estimated to be accurate to about 15% on a relative basis over the energy range that is of importance in this study.

## III. RESULTS

### A. Yield Curve

The $\gamma$-ray yield from the $Ca^{42}(p, \gamma)Sc^{43}$ reaction measured with the 8-in. NaI(Tl) detector at 55° to the beam direction is shown in Fig. 1. The strong resonances of $F^{19}$ and $C^{13}$ are indicated in the figure. The resonance energies and relative strengths are given in Table I. The resonance energies given here are accurate to $\pm 2$ keV unless otherwise stated (see Sec. C). The proton energy was calibrated using the $E_p = 991.90 \pm 0.04$-keV resonance[16] in the $Al^{27}(p, \gamma)Si^{28}$ reaction as the reference point.

Dubois and Broman have measured the excitation curve for the $Ca^{42}(p, \gamma)Sc^{43}$ reaction in the energy region $E_p = 800$–$1420$ keV. In the overlap region, $E_p = 1200$–$1420$ keV, there appears to be good agreement on resonance energies and relative strengths.

Recently, a report on the study of isobaric analog states in $Sc^{43}$ using the elastic scattering reaction has appeared.[17] The split analog states reported at 1792, 1802, and 1817 keV could not be identified in the yield curve shown in Fig. 1 because of target thickness. For this reason, the yield measurement was repeated for the energy region 1780–1840 keV using a 1-keV-thick target. The results are presented in Fig. 2. The analog resonances reported around 1800 keV can probably

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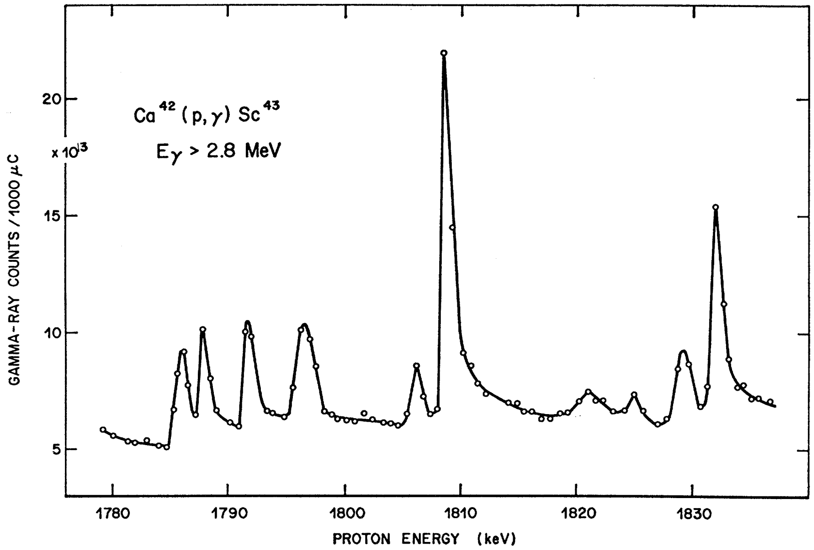

FIG. 2. Yield curve of the $Ca^{42}(p,\gamma)Sc^{43}$ reaction in the proton energy range of 1780–1840 keV, measured with an 8-in. NaI(Tl) detector at 55° to the beam direction. The target thickness was less than 1 keV.

be identified as the 1797-, 1806-, and 1821-keV resonances in the $Ca^{42}(p,\gamma)Sc^{43}$ reaction.

### B. Resonance Decay Schemes

In this section, we present our results for the decay schemes of the six resonances at 1235, 1242, 1423, 1808, 1891, and 2037 keV. Figure 3 shows a typical example of the high-resolution Ge(Li) spectra obtained in this experiment. The level energy assignments given here are determined from the Ge(Li) spectra.

### *1. 1235-keV Resonance*

The decay scheme resulting from the analysis of several spectra taken at this resonance is presented

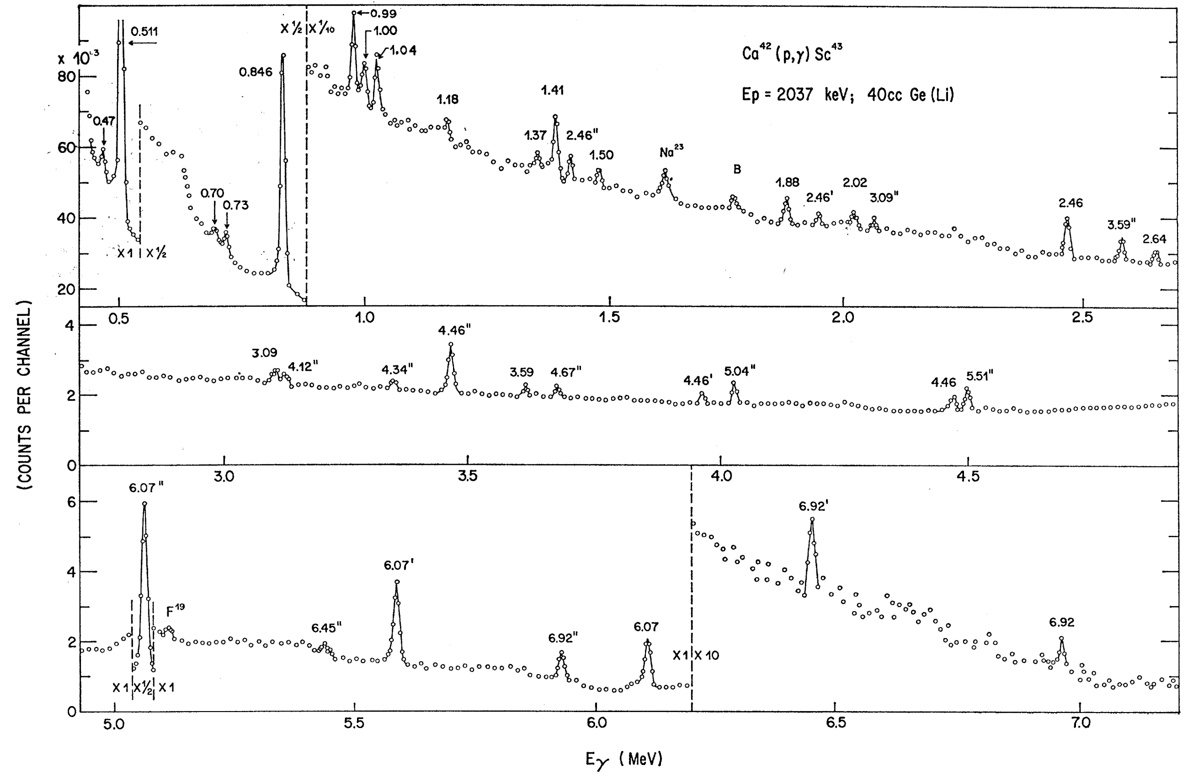

FIG. 3. γ-ray spectrum at the 2037-keV resonance in $Ca^{42}(p,\gamma)Sc^{43}$, taken with a 40-cc Ge(Li) detector at an angle of 55° to the beam direction. The peaks are labeled by the corresponding γ-ray energies; primes and double primes indicate single- and double-escape peaks, respectively. In the flat areas between peaks, the average of each four consecutive channels was plotted.

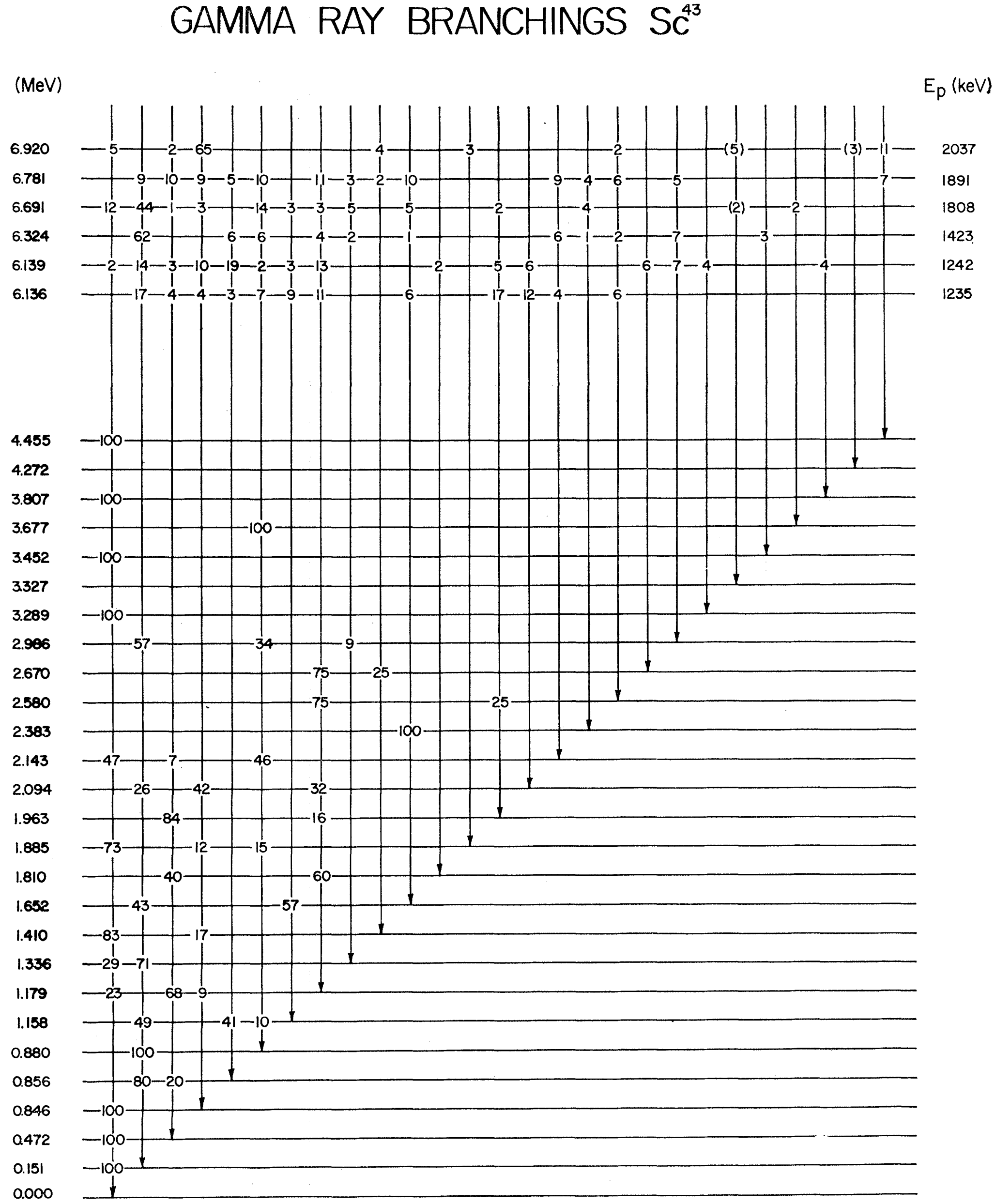

FIG. 4. The decay schemes and branching ratios of all resonances and bound states studied in this work. Typical errors for the branching ratios range from 50% for weak ($\leq 3\%$) $\gamma$ rays to about 10% for $\gamma$ rays with intensities of $\approx 50\%$.

in Fig. 4. The previous measurements of this resonance by Broman and Dubois[2] are considerably different from our results. In our high-resolution Ge(Li) spectra, we find transitions from the resonance to the 0.472-, 0.846-, 0.856-, 0.880-, 1.158-, and 1.652-MeV levels which were not found in previous work. The presence of a 5.285-MeV $\gamma$ ray in our spectra confirms the existence of a level at 0.856 MeV. We do not find transitions from the resonance to levels at 2.676, 2.979, 3.297, and 3.809 MeV as reported by Broman and Dubois. The resonance branching ratios quoted here are also different than those reported by Broman and Dubois.

We find that the 0.472- and 0.846-MeV levels decay completely to the ground state and that the 0.880-MeV level decays completely to the 0.151-MeV level in agreement with earlier work.[2,4,5] The decay of the 0.856-MeV level has only recently been established. We find that the 0.856-MeV level decays strongly (80%) to the 0.151-MeV level and weakly (20%) to the 0.472-MeV level, in agreement with Schwartz *et al.*[5] We find that the 1.158-MeV level decays to the 0.151-, 0.856-, and 0.880-MeV levels, whereas, Phillips *et al.*[4] report decays to the 0.151- and 0.880-MeV levels, and Schwartz *et al.*[6] report decays to the 0.151- and 0.846-MeV levels. A possible decay of the 1.158-MeV level to the 0.846-MeV level would be hidden under the high Ag-background $\gamma$ rays from our target backing. However, from intensity considerations, we can say that such a transition should be less than 10% of the total decay of this level. We find that the 1.179-MeV level has a strong decay to the 0.472-MeV level in agreement with previous work, but we also find weak transitions to the ground state and to the 0.846-MeV level. We find that the 1.652-MeV level decays to the 0.151- and 1.158-MeV levels with equal intensity. We found no ground-state transition for this level. The energy resolution of the detector was good enough to separate a possible ground-state transition from the 1.63-MeV background peak. This result is in disagreement with earlier work,[2,4,5] which all report a ground-state transition for this level. We find that the 1.963-MeV level decays strongly to the 0.472-MeV level and weakly to the 1.179-MeV level and does not decay to the ground state as reported in Ref. 2.

In addition, we also find that the decay of the 2.094-, 2.143-, and 2.580-MeV levels is considerably different from that reported in Ref. 2. The level at 2.580 MeV decays strongly to the 1.179-MeV level, weakly to the 1.963-MeV level, and not to the 0.472-MeV level.

### 2. *1242-keV Resonance*

The analysis of several spectra taken at this resonance leads to the decay scheme presented in Fig. 4. Our results for the decay scheme of this resonance are in reasonable agreement with the previous measurements of Broman and Dubois.[2] However, we find additional transitions from the resonance state to the ground, 0.856-, 1.158-, 1.810-, 3.289-, and 3.807-MeV states.

We find that the level at 2.094 MeV decays to the 0.151-, 0.846-, and 1.179-MeV levels. The reported decay of this level to the 0.880- and 1.652-MeV levels[2] could not be confirmed. From intensity considerations we can say that a decay to the 0.880-MeV level should be less than 10% of the total decay of the 2.094-MeV level. New decay schemes have been established for the 1.810-MeV level, which decays to the 0.472- and 1.179-MeV levels, the 2.670-MeV level which decays to the 1.179- and 1.410-MeV levels, and the two levels at 3.289 and 3.807 MeV, which both decay completely to the ground state. The level at 1.810 MeV observed here for the first time in proton-capture work is probably the level at 1.810 MeV observed by Schwartz *et al.*,[5] rather than the level reported at 1.827 MeV. Schwartz found the 1.810-MeV level to be $l=1$, whereas, there is some evidence[7] for an $l=5$ assignment for the 1.827-MeV level. It is very unlikely that an $l=5$ level would be populated by a resonance formed by the capture reaction at such a low energy. In addition, our decay-scheme results for the 1.810-MeV level are in general agreement with those found by Schwartz *et al.*[5]

$\gamma$ rays found in the spectra at the energies of 1.916 and 2.287 MeV could not be placed in the decay scheme of this resonance.

### 3. *1423-keV Resonance*

The 1423-keV resonance has been studied previously by Broman and Dubois.[2] The values of the $\gamma$-ray energies and intensities obtained from several spectra measurements together with the resonance decay scheme are presented in Fig. 4. Our results are in general agreement with the previous work. The reported decay of the resonance to the 0.846- and 3.807-MeV levels could not be confirmed. However, we found transitions from the resonance to the levels at 0.856, 1.336, 1.652, 2.383, 2.580, and 3.452 MeV, which were not seen in the previous work.

The level at 1.336 MeV has not been observed in previous proton-capture work. Our results for the decay of this level are in agreement with Phillips *et al.*,[4] except for a reported transition from this level to the 0.880-MeV level which we do not observe. Broman and Dubois report that the 2.143-MeV level decays entirely to the ground state, however, our data are consistent only with the decay of this level to the ground, 0.472- and 0.880-MeV levels. New decay schemes have been established for the levels at 2.383, 2.986, and 3.452 MeV.

$\gamma$ rays found in the spectra at the energies 1.372, 1.445, 2.044, 2.242, 2.292, and 3.466 MeV could not be placed in the decay scheme of this resonance.

### 4. *1808-keV Resonance*

The decay scheme resulting from the analysis of several spectra taken at the 1808-keV resonance is presented in Fig. 4. This resonance has not been previously investigated. The main decay of the resonance is to the first excited state. There are weak decays to other levels; the decay to the ground and 0.880-MeV level being the most prominent.

A detailed analysis of the $\gamma$-ray spectra taken at this resonance confirms the decay schemes of the 1.652- and 2.383-MeV levels which were derived from the spectra taken at the 1235- and 1423-keV resonances, respectively. A small decay of the resonance level to the 3.677-MeV level was found. This level decays completely to the 0.880-MeV level.

$\gamma$ rays found in the spectra at the energies 0.955, 1.442, 1.532, 1.598, 2.226, 2.688, and 3.555 MeV could not be placed in the decay scheme of this resonance.

### 5. *1891-keV Resonance*

The decay scheme obtained from the analysis of several spectra taken at the 1891-keV resonance is presented in Fig. 4. This resonance has not been previously investigated. This resonance has no dominant decay mode, but instead decays to many lower levels with essentially equal probability. Perhaps the only interesting characteristic of this resonance is the absence of a ground-state decay.

A detailed analysis of the $\gamma$-ray spectra taken at this resonance confirms the decay schemes of many levels previously obtained from spectra taken at other resonances. The level at 1.410 MeV has not been observed in previous proton-capture work. A discussion of the decay of the 1.410-MeV level will be given in Sec. III B *6* which deals with a resonance having a larger branching ratio to the 1.410-MeV level.

Two $\gamma$ rays with energies of 2.342 and 4.447 MeV were observed in the spectra taken at this resonance. The presence of these two $\gamma$ rays would indicate the existence of a level at either 4.447 or 2.342 MeV. We have placed the level at 4.455 MeV because there is clear evidence in the spectra taken at the 2037-keV resonance for a level at this energy.

$\gamma$ rays found in the spectra at the energies 1.964, 1.995, 2.392, 2.432, 2.475, 2.498, 2.560, 2.607, and 2.919 MeV could not be placed in the decay scheme of this resonance.

### *6. 2037-keV Resonance*

The decay scheme resulting from the analysis of several spectra (see Fig. 3 for a typical spectrum) taken at the 2037-keV resonance is presented in Fig. 4. This resonance has not been previously investigated. The main decay of the resonance is to the 0.846-MeV level.

In all spectra taken at the 2037-keV resonance, we observe two $\gamma$ rays with energies of 2.461 and 4.463 MeV. The presence of these $\gamma$ rays in our spectra clearly establishes a level at 4.455 MeV.[18] This is the same level indicated in the data taken at the 1891-keV resonance. In addition, we observe two $\gamma$ rays in our spectra which have the correct energy to be transitions from the resonance to levels at 3.327 and 4.272 MeV. However, the decay of these levels could not be established.

TABLE II. Resonance energies, excitation energies, and absolute strengths. All strengths were measured relative to the strength of the 1842-keV resonance in the $Ca^{40}(p, \gamma)Sc^{41}$ reaction which was known from previous work (see text).

| Resonance energy (keV) | Excitation energy (keV) | $(2J+1)\Gamma_p\Gamma_\gamma/\Gamma$ (eV) |
|---|---|---|
| 1234.8±0.5 | 6136.4±1.0 | 0.68±0.14 |
| 1241.9±0.5 | 6139.1±1.0 | 0.92±0.18 |
| 1422.8±0.5 | 6323.9±1.0 | 1.37±0.27 |
| 1808.3±0.5 | 6691.1±1.0 | 2.18±0.44 |
| 1891.0±2.0 | 6781.4±1.0 | 1.47±0.29 |
| 2036.6±0.5 | 6920.4±1.0 | 3.01±0.60 |

TABLE III. Energy levels of $Sc^{43}$ (in keV).

| This work | $(p, \gamma)$ [a] | $(\alpha, p)$ [b] | $(He^3, d)$ [c] |
|---|---|---|---|
| 150.9±0.7 | 150±1 | 151±2 | 152±8 |
| 472.3±0.6 | 472±1 | 472±2 | 475±6 |
| 845.7±0.5 | 844±2 | 849±2 | 846 |
| 855.6±1.0 | | | 856±10 |
| 880.5±0.4 | 877±2 | 880±2 | 882 |
| 1158.3±0.4 | 1150±10 | 1158±3 | 1154 |
| 1178.9±0.5 | 1175±4 | 1181±3 | 1180±7 |
| 1336.4±0.5 | | 1341±4 | 1335 |
| 1410.0±0.8 | | 1414±4 | 1418 |
| 1652.0±0.9 | 1649±7 | 1644±5 | 1647 |
| 1809.7±1.0 | | | 1812±6 |
| | | | 1827 |
| 1885.0±0.6 | | | 1877 |
| | | | 1928 |
| 1962.7±0.5 | 1959±7 | | 1962±6 |
| 2094.3±0.3 | 2089±7 | | 2100±9 |
| 2143.2±0.5 | 2137±7 | | |
| | 2200±7 | | |
| | | | 2294±5 |
| 2382.8±0.5 | 2382±10 | | |
| 2580.4±1.0 | 2587±10 | | |
| 2669.6±1.0 | 2676±10 | | 2679±15 |
| 2985.8±1.1 | 2979±10 | | 2992±15 |
| 3288.8±1.6 | 3297±10 | | |
| 3326.7±1.5 | | | 3337±15 |
| 3451.7±1.0 | | | 3462±15 |
| | | | 3618±15 |
| 3676.9±0.5 | | | 3673±15 |
| 3806.6±0.7 | 3809±10 | | |
| | | | 3992±10 |
| | | | 4238±8 |
| | | | 4380±10 |
| 4454.7±2.8 | | | |

[a] See Ref. 2.
[b] See Ref. 4.
[c] See Refs. 5 and 6.

There is considerable theoretical interest in the decay scheme of the 1.410-MeV level.[19] In order to establish this decay scheme, a coincidence experiment with the 40-cc Ge(Li) detector and the 8-in. NaI detector was performed. The 1.410-MeV level was found to decay to the ground state and the 0.846-MeV level in agreement with the work of Phillips *et al.*,[4] but in disagreement with Schwartz *et al.*[5] who report only a ground-state transition. We have looked for the transition from the 1.410- to the 0.472-MeV level, with negative results. We estimate that this transition can be no greater than 10% of the total decay of the 1.410-MeV level. A coincidence experiment was also performed to establish the decay schemes of the 1.885- and 4.455-MeV levels. The 1.885-MeV level was found to decay to the 0.846- and 0.880-MeV levels in addition to a ground-state transition. However, the decay to the 0.880-MeV level is questionable because of the presence of a background $\gamma$ ray at 1.014 MeV which appeared in all spectra taken at this resonance. The 4.455-MeV level was found to decay completely to the ground state.

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[18] The level energy 4.455 MeV is the average of the values obtained from the data taken at the 1891- and 2037-keV resonances.

[19] I. P. Johnston and G. L. Payne, Nucl. Phys. **A124, 217 (1969).**

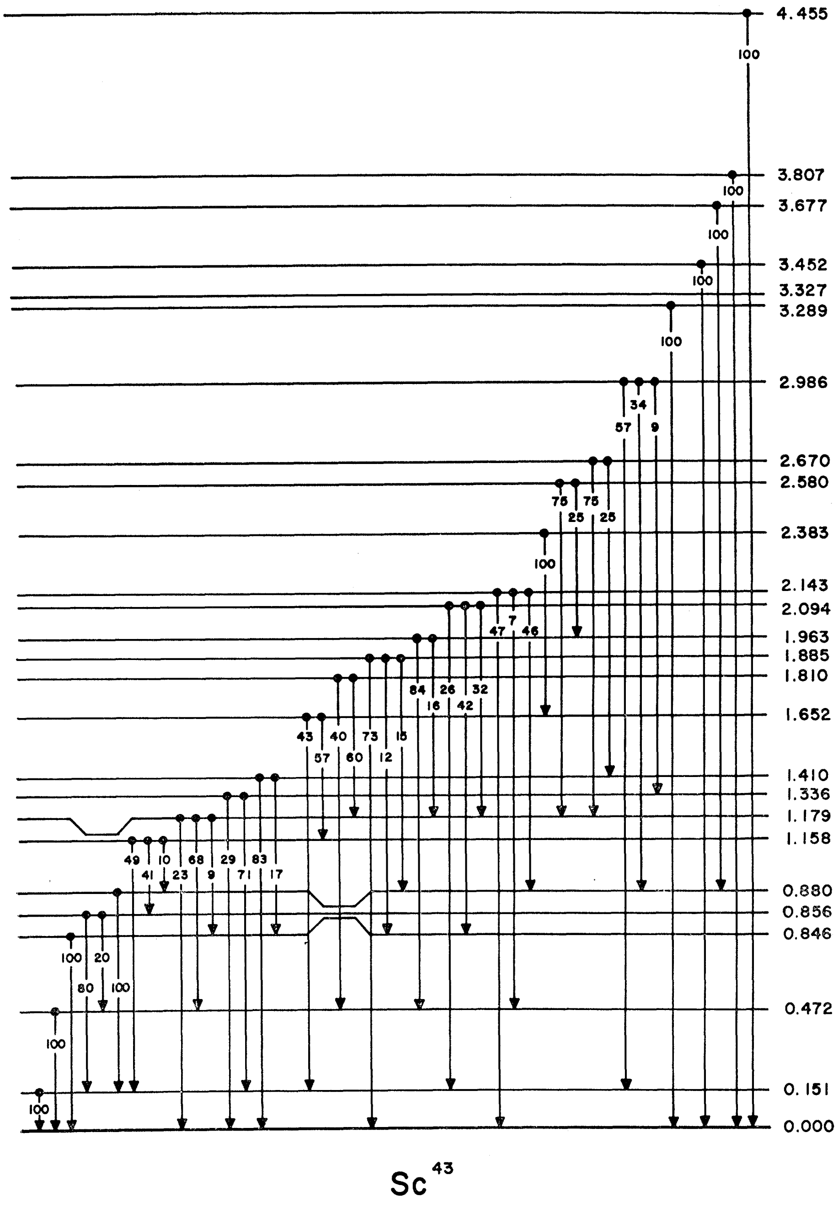

FIG. 5. The decay scheme of all bound levels below 5 MeV observed in the present work. There is some evidence that the levels at 3.327 and 4.270 MeV are populated, however, the decay schemes of these levels could not be established. In addition, the decay of the 1.885-MeV level to the 0.880-MeV level is questionable (see text). Typical errors for the branching ratios range from 50% for weak ($\leq 3\%$) $\gamma$ rays to about 10% for $\gamma$ rays with intensities of $\approx 50\%$.

$\gamma$ rays found in the spectra at the energies 0.809, 0.869, 1.014, 1.372, 1.775, 1.972, 2.022, 3.025, 3.106, and 3.658 MeV could not be placed in the decay scheme of this resonance.

### C. Resonance Strengths and Level Energies

The results of the strength measurements for the six resonances studied in the present work are given in Table II. For a discussion of the techniques used in our strength measurements see Sec. II.

The excitation energies of the selected resonances with standard deviations less than 1 keV were obtained by averaging several independent measurements. For an accurate determination of the $Q$ value, it was necessary to know the proton energies of the resonances more accurately than was possible with the ARL 2-MeV Van de Graaff. For this reason, the proton energies were measured with the ARL ICT-tandem accelerator using the well-known $E_p = 991.90 \pm 0.04$-keV resonance in the $Al^{27}(p,\gamma)Si^{28}$ reaction as the calibration point.[16] These accurate proton-energy measurements together with the excitation energies obtained from the spectra studies provide a reaction $Q$ value of $4.929 \pm 0.002$ MeV. This value is approximately 6 keV higher than the value given in the 1964 mass table.[20]

Rather precise level energies were obtained from the Ge(Li) spectra using the calibration procedure

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[20] J. H. E. Mattauch, W. Thiele, and A. H. Wapstra, Nucl. Phys. **67**, 32 (1965).

described in Sec. II. In many cases, the energy of a given level could be determined in several ways because the level was involved in several different cascades. In addition, many levels were populated by more than one resonance, which allows one to make several independent measurements of the level energy. The final level energies, after appropriate averaging, are presented in Table III together with the values previously reported by other authors. In general, our results are in agreement with previous values.

## IV. SUMMARY AND DISCUSSION

The $\gamma$-ray branchings of all bound levels observed in the present investigation are presented in Fig. 5. Most values are the average of results obtained at several different resonances.

A summary of all results obtained in the present work can be found in Tables I–III. Figure 5 summarizes our results for the decay properties of all bound levels observed in the present work below 5.0 MeV in Sc$^{43}$. As was indicated in the preceding discussions, we have made significant changes in the reported decay schemes of most levels as a result of our high-resolution Ge(Li) work. We have revised the previously reported decay schemes for the resonance levels at 1235, 1242, and 1423 keV. We have obtained decay schemes for the resonance levels at 1809, 1891, and 2037 keV. These levels have not been studied in previous work. Decay properties of bound levels over 2.0 MeV for which no previous data was available were also determined.

A new bound level at 4.455 MeV has been established, since there is clear evidence for this level in the decay of two resonances studied in this work. There are many levels observed in other reactions which were not populated in our Ca$^{42}(p,\gamma)$Sc$^{43}$ work. Most notable among them are the 1.930-MeV level (there is some evidence that this may be an $l=4$ level[21]) and the $l=5$ levels at 1.827 and 2.620 MeV observed by Bernstein.[22] Other levels below 4 MeV not observed in the present work are the levels at 3.485, 3.520, 3.955, and 3.994 MeV. It may be that all these levels below 4 MeV not observed in the proton-capture work have $l \geq 4$.

One of the principal reasons for selecting the resonances studied in the present work was the possibility that some may be isobaric analog states. The $l=1$ levels in Ca$^{43}$ at 2.048 and 2.607 MeV both have large spectroscopic factors (3.0 and 0.3, respectively). In addition, the level at 2.673 MeV appears to be an $l=3$ level and has a reasonably large spectroscopic factor (0.14). The elastic-scattering work of Browne *et al.*[17] clearly establishes the 1242-keV resonance as the isobaric analog state of the 2.048-MeV level and the three resonances at 1797, 1806, and 1821 keV as possible candidates for the analog of the 2.607-MeV level in Ca$^{43}$. One would then expect the analog of the 2.673-MeV level in Ca$^{43}$ to appear around $E_p=$ 1890 keV in the Ca$^{42}+p$ reaction. The search for this analog state, as well as other analog states, is in progress. In addition, decay-scheme studies of the analog resonances around 1800 keV are underway.

We have refrained from comparing our experimental results with the abundant theoretical predictions available for Sc$^{43}$ because we intend to include such considerations in a subsequent paper dealing with our spin-parity measurements for the levels in Sc$^{43}$.

Finally, it is perhaps worthwhile to reemphasize the versatility for spectroscopic studies of the $(p,\gamma)$ reaction using large-volume high-resolution Ge(Li) detectors. $\gamma$-ray decay schemes of resonances and bound levels can be determined with precision and in complete detail without resorting to coincidence studies using NaI detectors. Unlike other charged-particle reactions, the availability of many $(p,\gamma)$ resonances with totally different decay properties allows one to investigate almost all bound levels.

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[21] W. R. Phillips (private communication).

[22] A. M. Bernstein (private communication), quoted in Ref. 7.