# Study of $^{82}$Sr, $^{84}$Sr, and $^{86}$Sr with the $(p,t)$ Reaction*

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The $(p,t)$ reaction has been studied on the even stable isotopes of strontium at a proton energy of 31 MeV. Triton spectra were obtained with a magnetic spectrograph which yielded an over-all experimental resolution of 18 keV. The experimental angular distributions are compared with two-nucleon-transfer distorted-wave Born-approximation calculations to make spin-parity assignments for the observed levels and to extract enhancement factors. Energy level and transition intensity systematics are presented for the low-lying levels of these isotopes with particular emphasis on the $L=0$ transitions. A number of new spin-parity assignments are made for $^{86}$Sr and $^{84}$Sr and the previously unreported level structure of $^{82}$Sr is presented. The ground-state mass of $^{82}$Sr is also determined from the measured $Q$ values.

## I. INTRODUCTION

The level structure of nuclei in the $A=90$ mass region has been the subject of rather extensive theoretical treatment in terms of a rather small shell-model space based either on an inert $^{88}$Sr or $^{90}$Zr core. Except for the work of Talmi and Unna,[1] subsequent studies have concentrated on the nuclei with $N \geq 50$. Part of the reason for the lack of model calculations for the nuclei with $N < 50$ is the sparsity of detailed experimental information on many of the nuclei in this region. Recently, the strontium isotopes have been reexamined[2] in the same framework as Ref. 1. This very restricted model was employed again because the limited data available on the strontium isotopes precluded a more complete theoretical treatment.

The motivation for the present study was to provide additional data on the levels of $^{84}$Sr and to obtain information on the previously unreported level structure of $^{82}$Sr. In the case of $^{84}$Sr, the $(p,t)$ data augment the previous decay scheme[3] and inelastic scattering[4] studies and help to interpret those results as well as to provide new information on the location of $0^+$ states in this nucleus.

At the time this work was undertaken, a preliminary report of two studies of the $^{88}$Sr$(p,t)$ reaction had been noted.[5] It was therefore decided not to duplicate that work. In the course of the present study of the $^{84}$Sr$(p,t)^{82}$Sr reaction, a considerable amount of data on the $^{88}$Sr$(p,t)^{86}$Sr reaction was accumulated as a by-product of a significant presence of $^{88}$Sr in the $^{84}$Sr target. These data were also supplemented by $^{88}$Sr$(p,t)$ data previously obtained at this energy on a natural strontium target during the course of an investigation of $L=0$ transition strengths.[6] Since none of the $^{88}$Sr$(p,t)$ data have appeared subsequently in the literature, we have also included here our results on this reaction.

## II. EXPERIMENTAL RESULTS

The reactions were studied at an incident proton energy of 31 MeV. The proton beam was supplied by the Oak Ridge isochronous cyclotron and the tritons were detected by nuclear emulsions in the broad-range magnetic-spectrograph facility. Typical beam currents were 300 nA and the over-all average experimental resolution was 18 keV.

The strontium targets were produced by the Isotopes Target Laboratory of the Oak Ridge National Laboratory Isotopes Division by the reduction-distillation technique.[7] In each case $SrCO_3$ was heated under vacuum to convert the carbonate to the oxide. Fresh lanthanum filings were then admixed with the SrO (~10%) and the mixture transferred to a tantalum crucible. Reduction evaporation was conducted in vacuum and the distilled strontium collected on 30-$\mu$g/cm$^2$ carbon substrate. About 12 mg of SrO was required to pre-

TABLE I. Isotopic composition of the strontium targets.

| Target | Abundance (%) $^{84}$Sr | $^{86}$Sr | $^{87}$Sr | $^{88}$Sr |
|---|---|---|---|---|
| $^{84}$Sr | 82.24 | 3.71 | 1.56 | 12.49 |
| $^{86}$Sr | <0.05 | 97.6 | 0.68 | 1.73 |
| $^{nat}$Sr | 0.56 | 9.87 | 7.04 | 82.53 |

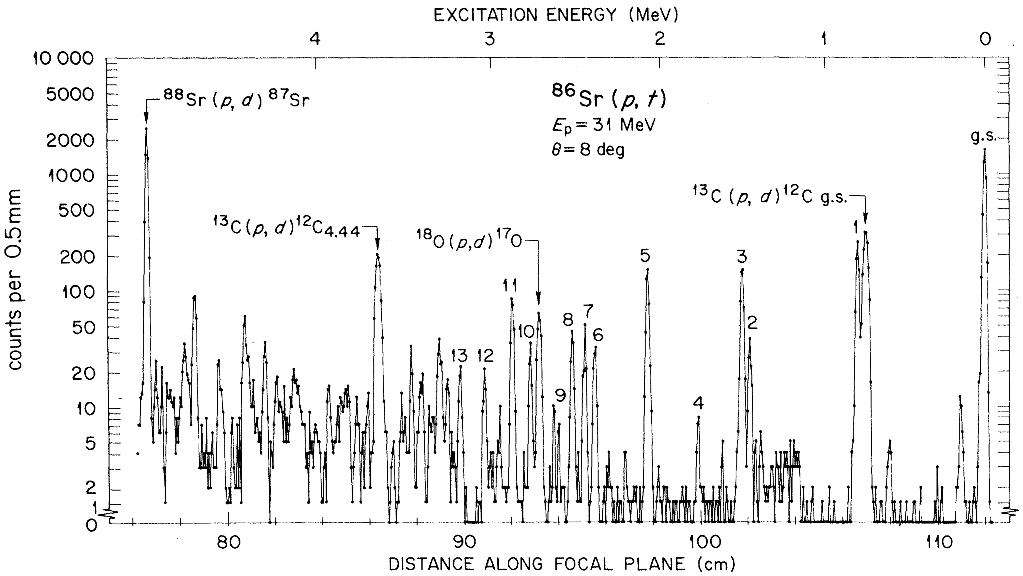


FIG. 1. Energy spectra of tritons observed at 8° from the interaction of 31-MeV protons with $^{86}$Sr.

pare, simultaneously, three 1.6-cm-diam targets of nominal thicknesses 150 $\mu g/cm^2$. The isotopic abundances of these targets are listed in Table I. Prior to use, the targets were stored in an argon atmosphere.

An example of the spectra obtained for the $^{86}$Sr-$(p,t)^{84}$Sr reaction is shown in Fig. 1. Besides the two expected deuteron groups from the $(p,d)$ reaction on the $^{13}$C isotope present in the carbon backing, populating the ground and first excited states of $^{12}$C, we also observe a deuteron group from the ground-state transition of the $^{18}$O$(p,d)$-$^{17}$O reaction. This seems to imply significant oxidation of our targets despite the precautions taken by storing and transferring the targets in a dry argon atmosphere. However, no physical degradation of the foils was observed that would have affected the quality of the spectra. At the end of the experiment, the strontium deposits still had a bright metallic appearance. The $^{84}$Sr energy levels observed in this reaction and the excitation energies deduced are listed in Table II.

A spectrum obtained from the $^{84}$Sr target is shown in Fig. 2. The extraction of the $^{82}$Sr levels populated by the $^{84}$Sr$(p,t)$ was complicated by the presence of a significant isotopic impurity of $^{88}$Sr in this target. This difficulty was somewhat compensated by the fact that data for the $(p,t)$ reac-

TABLE II. Levels in $^{84}$Sr observed with the $^{86}$Sr$(p,t)$ reaction. Excitation energies are ±0.005 MeV. Assumed transitions: a: $(g_{9/2})_0^{10} \rightarrow (g_{9/2})_J^8$. b: $[(g_{9/2})_0^{10}(p_{3/2})_0^4]_0 \rightarrow [(g_{9/2})_{9/2}^9(p_{3/2})_{3/2}^3]_J$.

| Peak No. | $E^*$ (MeV) | $L$ | $J^\pi$ | Assumed trans. | $B^2(jjJ)$ | $\mathcal{E}$ |
|---|---|---|---|---|---|---|
| g.s. | 0.0 | 0 | $0^+$ | a | 1.0 | 13.0 |
| 1 | 0.795 | 2 | $2^+$ | a | 5.0 | 3.0 |
| 2 | 1.455 | (2) | $(2^+)$ | a | 5.0 | 0.4 |
| 3 | 1.505 | 0 | $0^+$ | a | 1.0 | 1.0 |
| 4 | 1.770 | (4) | $(4^+)$ | a | 9.0 | 0.4 |
| 5 | 2.075 | 0 | $0^+$ | a | 1.0 | 1.0 |
| 6 | 2.390 | 2 | $2^+$ | a | 5.0 | 0.5 |
| 7 | 2.450 | 3 | $3^-$ | b | 7.0 | 1.4 |
| 8 | 2.525 | (0) | $(0^+)$ | a | 1.0 | 0.4 |
| 9 | 2.600 | ⋯ | ⋯ | | | |
| 10 | 2.775 | (5) | $(5^-)$ | b | 11.0 | 0.3 |
| 11 | 2.880 | 2 | $2^+$ | a | 5.0 | 0.7 |
| 12 | 3.045 | (4) | $(4^+)$ | a | 9.0 | 1.3 |
| 13 | 3.175 | (2) | $(2^+)$ | a | 5.0 | 0.6 |

TABLE III. Levels in $^{82}$Sr observed with the $^{84}$Sr$(p,t)$ reaction. Excitation energies are ±0.005 MeV. Assumed transitions a and b as in Table II.

| Peak No. | $E^*$ (MeV) | $L$ | $J^\pi$ | Assumed trans. | $B^2(jjJ)$ | $\mathcal{E}$ |
|---|---|---|---|---|---|---|
| g.s. | 0.0 | 0 | $0^+$ | a | 1.0 | 15.8 |
| 1 | 0.575 | 2 | $2^+$ | a | 5.0 | 2.6 |
| 2 | 1.175 | 2 | $2^+$ | a | 5.0 | 1.0 |
| 3 | 1.310 | 0 | $0^+$ | a | 1.0 | 1.8 |
| 4 | 1.865 | 2 | $2^+$ | a | 5.0 | 0.2 |
| 5 | 2.195 | 2 | $2^+$ | a | 5.0 | 0.2 |
| 6 | 2.405 | 3 | $3^-$ | b | 7.0 | 0.9 |
| 7 | 2.665 | 0 | $0^+$ | a | 1.0 | 0.7 |
| 8 | 2.820 | (4, 5) | $(4^+, 5^-)$ | | | |
| 9 | 2.885 | (2) | $(2^+)$ | a | 5.0 | 0.8 |
| 10 | 2.920 | ⋯ | ⋯ | | | |

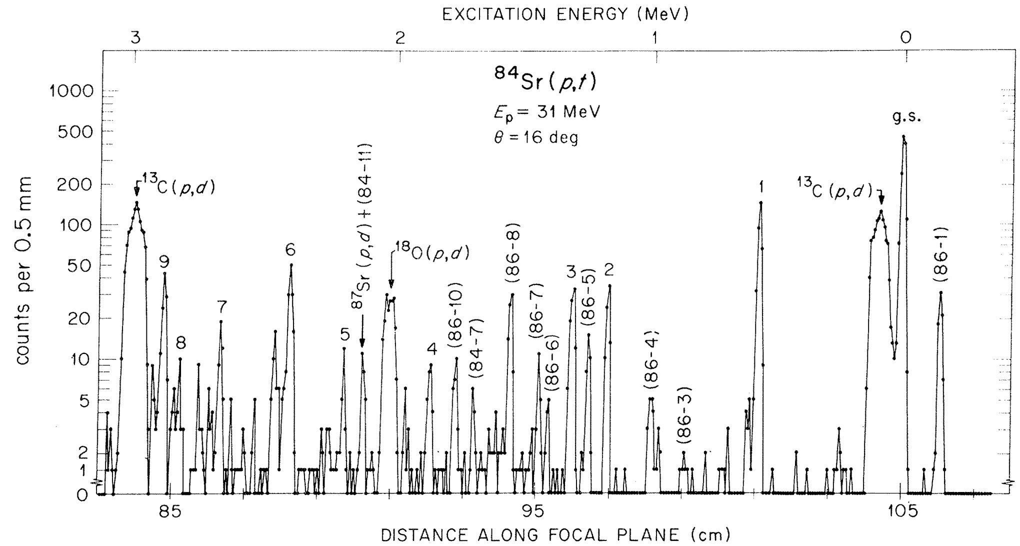


FIG. 2. Energy spectra of tritons observed at 16° from the interaction of 31-MeV protons with the $^{84}$Sr target. Peaks corresponding to states in $^{82}$Sr are labeled with the number referred to in Table III. Peaks arising from isotopic impurities are labeled by the final state $A$ and peak number (e.g., 86-1 is peak number 1 in Table IV).

tion on both $^{84}$Sr and $^{88}$Sr were obtained by analyzing the spectra from this target. The energy resolution obtained in the present study was sufficient that, over the angular region studied, the stronger triton groups originating from the two isotopes of Sr present could be distinguished easily by their different kinematic shift. In addition, triton spectra from a natural strontium target obtained at three angles were used to cross-check and confirm the $^{88}$Sr$(p,t)$ assignments. The energy levels deduced for $^{82}$Sr are given in Table III and the $^{86}$Sr levels observed are listed in Table IV.

The absolute calibration of the spectrograph system carries an uncertainty of about 100 keV. This uncertainty reflects itself, of course, in the absolute values determined for the reaction $Q$ values. In the present experiment, the presence of the two $^{13}$C$(p,d)$ and the $^{18}$O$(p,d)$ impurity peaks provided convenient calibration points to considerably improve the accuracy of the $Q$-value measurements. A small adjustment (65 keV) in the assumed value for the incident proton energy yielded $Q$ values for these three points all within 5 keV of the well determined values derived from the latest atomic mass evaluation.[8] With this calibration, the $(p,t)$ $Q$ values determined for the strontium isotopes

TABLE IV. Levels in $^{86}$Sr observed with the $^{88}$Sr$(p,t)$ reaction. Excitation energies are ±0.005 MeV. Also shown are levels summarized in a recent data compilation for this nucleus (Ref. 5). Assumed transitions a and b as in Table II.

| This work | | | | | | | Compilation | |
|---|---|---|---|---|---|---|---|---|
| Peak No. | $E^*$ (MeV) | $L$ | $J^\pi$ | Assumed trans. | $B^2(jjJ)$ | $\mathcal{E}$ | $E^*$ (MeV) | $J^\pi$ |
| g.s. | 0.0 | 0 | $0^+$ | a | 1.0 | 9.5 | 0.0 | $0^+$ |
| 1 | 1.075 | 2 | $2^+$ | a | 5.0 | 4.3 | 1.0766 | $2^+$ |
| 2 | 1.855 | (2) | $(2^+)$ | a | 5.0 | 0.9 | 1.8542 | $2^+$ |
| 3 | 2.100 | 0 | $0^+$ | a | 1.0 | 1.2 | (2.08) | $(0^+)$ |
| 4 | 2.230 | 4 | $4^+$ | a | 9.0 | 2.3 | 2.2297 | $2^+, 3^+, 4^+$ |
| 5 | 2.480 | 3 | $3^-$ | b | 7.0 | 1.4 | 2.4819 | $3^-$ |
| 6 | 2.635 | (2) | $(2^+)$ | a | 5.0 | 0.4 | 2.6419 | $(1^\pm, 2^+)$ |
| 7 | 2.675 | 5 | $5^-$ | b | 11.0 | 0.1 | 2.6728 | $3^-, 4^-, 5^-$ |
| 8 | 2.785 | 2 | $2^+$ | a | 5.0 | 4.2 | (2.789) | |
| | | | | | | | 2.8783 | $2^+, 3^+, 4^+$ |
| 9 | 2.860 | (5, 6) | $(5^-, 6^+)$ | | | | | |
| 10 | 2.995 | 3 | $3^-$ | b | 7.0 | 1.4 | 2.9973 | $3^-$ |

are listed in Table V. The corresponding two-neutron separation energies are also given in Table V and compared with the Mass Table values.[8] The agreement for the $^{88,87,86}$Sr isotopes seems quite satisfactory. For $^{84}$Sr, the present study represents the first experimental determination of this quantity and, therefore, the first determination of the $^{82}$Sr ground-state mass. From the Mass Table value for the $^{84}$Sr ground-state mass excess and our experimental two-neutron separation energy, we calculate a mass excess of $-75.991 \pm 0.010$ MeV for the ground state of $^{82}$Sr.

## III. DISTORTED-WAVE BORN-APPROXIMATION (DWBA) ANALYSIS

The angular distributions for the $^{84}$Sr levels observed in the $^{86}$Sr$(p, t)$ reaction are shown in Figs. 3 and 4. The angular distributions for the $^{82}$Sr levels from the triton spectra obtained from the $^{84}$Sr target are shown in Fig. 5 and those for the $^{86}$Sr levels, obtained from these same spectra, are shown in Fig. 6. Also shown in Fig. 6 are the cross sections obtained from the analysis of the natural strontium target spectra.

The main source of uncertainty in the absolute values of the cross sections shown in Figs. 3–6 arises from the lack of a precise determination of the target thicknesses. Since the physical form of the targets precluded measuring the thickness by weighing, the thicknesses were estimated by normalizing the measured elastic scattering cross sections, for the 31-MeV protons, to the cross sections predicted with the optical-model parameters discussed below. This matching was done in the angular range from 25 to 40° which covers the region of the first well-defined oscillation in the elastic angular distribution. This method should be reasonably accurate since the proton optical-model parameters are well determined in this energy and mass region. In similar studies of other nuclei in this mass region, we have found agreement within about 10% for thicknesses obtained in this way and thicknesses determined by weighing. The relative errors in the cross sections determined in this study should be somewhat better. Cross-checks between targets by means of reactions on the isotopic impurities and the relative cross sections measured with the natural strontium target all give values consistent to better than 5%.

TABLE V. The $(p,t)$ reaction $Q$ values determined from the present study and the two-neutron separation energies derived therefrom. Relative errors are estimated as less than $\pm 0.005$ MeV and absolute values carry an uncertainty not exceeding $\pm 0.010$ MeV. Also shown for comparison are the two-neutron separation energies from the most recent atomic mass evaluation (Ref. 8). All energies are in MeV.

| Nucleus | This work $Q(p,t)$ | This work $S(2n)$ | Ref. $S(2n)$ |
|---|---|---|---|
| $^{88}$Sr | −11.060 | 19.542 | $19.542 \pm 0.001$ |
| $^{87}$Sr | −11.440 | 19.922 | $19.914 \pm 0.006$ |
| $^{86}$Sr | −11.535 | 20.017 | $20.013 \pm 0.004$ |
| $^{84}$Sr | −12.310 | 20.792 | 21.2 [a] |

[a] This mass table value was estimated from systematics since no determination of the $^{82}$Sr mass was available. From the present study, we obtain a value of $-75.991 \pm 0.010$ MeV for the mass excess of $^{82}$Sr.

The curves shown in Figs. 3–6 are the results of zero-range two-nucleon-transfer DWBA calculations performed with the computer program JULIE.[9] Since realistic shell-model wave functions are not available for the strontium isotopes, we have parametrized the observed experimental intensities by comparing them to the DWBA predictions for a one-configuration transition. In this case, where only a single two-neutron configuration is assumed to contribute to the cross section, the more complicated general expression[10] relating the experimental cross section to the output of the JULIE program reduces to the simple form

$$\sigma_{\exp}(\theta) = 2D_0^2 \mathcal{E} B^2\ (j_1 j_2 J)\sigma_{\mathrm{JULIE}}(\theta)\,.$$

In this expression, $D_0^2$ is the normalization factor introduced by the zero-range approximation, $B$ is the two-particle spectroscopic amplitude, and $\mathcal{E}$ is the enhancement factor which relates the observed $(p, t)$ intensity to the DWBA prediction.

The optical-model parameters used for these calculations are listed in Table VI. The proton parameters are taken from the results of a global analysis by Becchetti and Greenlees[11] and the triton parameters are from the work of Flynn *et al.*[12] A value of $D_0^2 = 29$ has been used which is consistent with the empirical normalization employed in previous calculations in this mass region with these same optical-potential parameter sets.[13] With this normalization, the enhancement factors derived from the comparisons shown in Figs. 3–6 are listed in Tables II–IV. Since it is not readily apparent that a particular configuration will dominate the observed transitions, nor how the amplitude of that configuration will change from isotope to isotope, we have chosen the value of $B^2$ in all cases to be that corresponding to removal of the neutrons from filled orbitals. Thus the $B^2$, for a given final-state spin-parity value, is the same irrespective of the isotope involved and the extracted enhancement factors reflect directly the change in $(p, t)$ intensity from isotope to isotope unmodified by any assumptions about changes in the structure of the wave functions. These $B^2$ values are also listed in Tables II–IV.

Obviously, DWBA calculations performed using structure amplitudes derived from realistic wave functions for the states involved should yield enhancement factors close to unity. The enhancement factors listed in Tables II–IV show quite dramatically the deficiencies of the simple wave functions assumed for these calculations. This is most apparent in the enhancement factors for the low-lying levels whose large values reflect the importance of the coherent addition of transfer strength from two or more configurations. With the present parametrization of the transfer strengths, the adequacy of any wave functions that become available for the strontium isotopes may be judged by computing the predicted theoretical enhancements relative to the single configurations used here and comparing with the experimental enhancements listed in the tables.

The quality of the DWBA fits to the angular distributions seems to deteriorate somewhat with decreasing $A$ value. This is most obvious for the $L=0$ transitions where the calculations produce more structure at forward angles than observed experimentally. This probably reflects an inadequacy in the triton optical-model parameters chosen for these calculations. The parameters listed in Table VI are those determined from triton scattering on zirconium and, although these parameters are observed to change rather slowly with $A$, the fits to the lighter strontium isotope data seem to indicate the effects of such an extrapolation. No

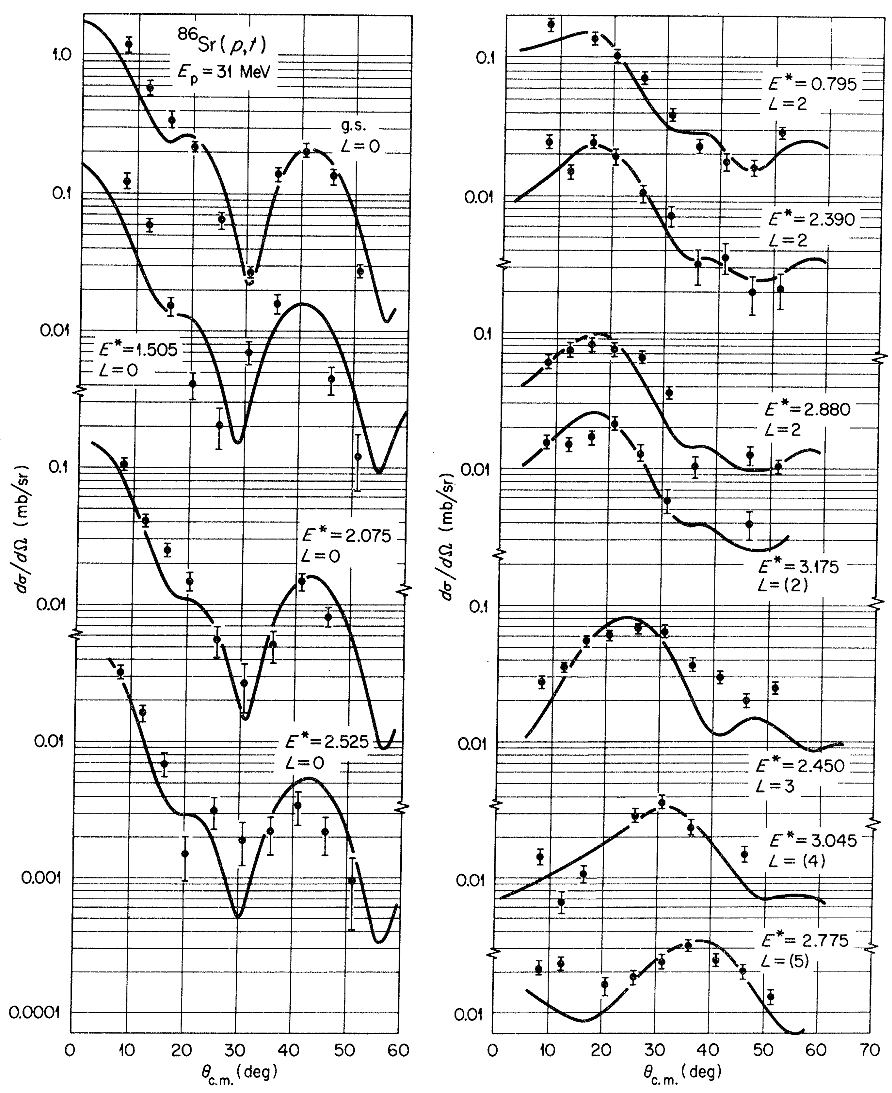


FIG. 3. Angular distributions for triton groups observed in the $^{86}Sr(p,t)^{84}Sr$ reaction. The curves are results of DWBA calculations for the indicated $L$-transfer values.

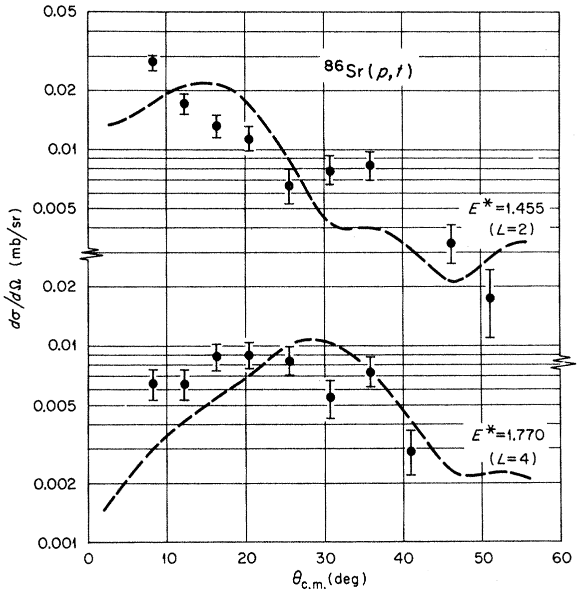


FIG. 4. Angular distributions of two levels observed in the $^{86}$Sr$(p, t)^{84}$Sr reaction which could not be well reproduced by the DWBA predictions. The calculations most nearly resembling the data are indicated by the dashed curves.

attempt was made to arbitrarily change the triton parameters to improve the quality of the fits to the $(p, t)$ angular distributions since this was deemed unnecessary for the purposes of the present study.

TABLE VI. Optical-model parameters used in the DWBA calculations. The notation is the same as that of Satchler [see G. R. Satchler, Nucl. Phys. A92, 273 (1967)]. Multiple values are for $^{84,86,88}$Sr, respectively.

| | Protons (Ref. 11) | Tritons (Ref. 12) | Neutrons |
|---|---|---|---|
| $V$ (MeV) | 54.6, 55.1, 55.5 | 170.7 | a |
| $r_0$ (fm) | 1.12 | 1.16 | 1.25 |
| $a$ (fm) | 0.78 | 0.752 | 0.65 |
| $W$ (MeV) | 4.14 | 21.5 | |
| $W_D$ (MeV) | 5.17, 5.42, 5.66 | 0.0 | |
| $r_0'$ (fm) | 1.32 | 1.498 | |
| $a'$ (fm) | 0.58, 0.59, 0.60 | 0.817 | |
| $V_s$ (MeV) | 6.2 | 0.0 | $\lambda=25$ |
| $r_s$ (fm) | 0.98 | 0.0 | |
| $a_s$ (fm) | 0.75 | 0.0 | |
| $r_c$ (fm) | 1.20 | 1.25 | |

[a] Adjusted to bind each neutron with one half of the two-neutron separation energy plus one half of the excitation energy for the appropriate final state.

## IV. DISCUSSION

### A. $L=0$ Transitions

These transitions are of particular interest since the observed $0^+$ levels are not readily observed by other experimental methods. In addition the $(p, t)$ transition intensities reflect the pairing correlations introduced into the wave functions of those levels by the strong pairing component of the nu-

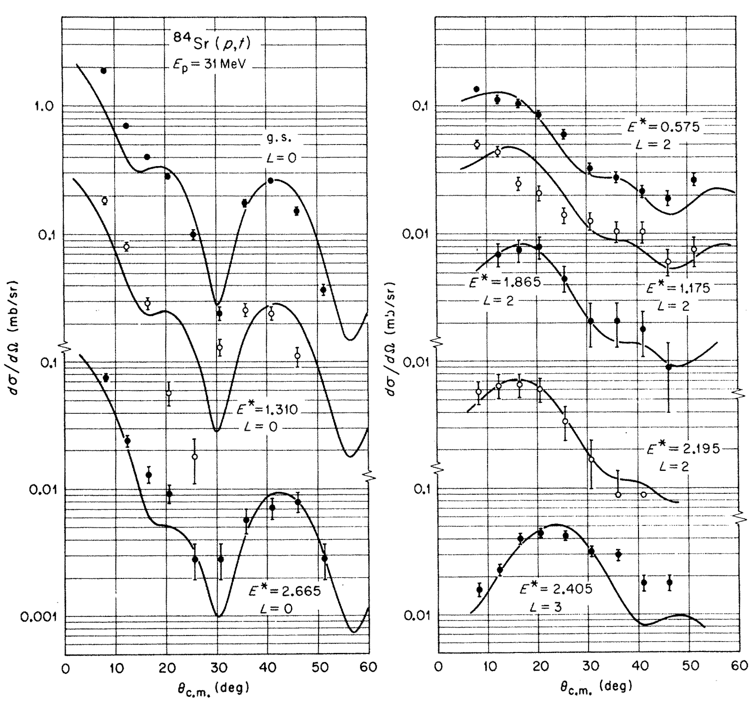


FIG. 5. Angular distributions for the triton groups observed in the $^{84}$Sr$(p, t)^{82}$Sr reaction.

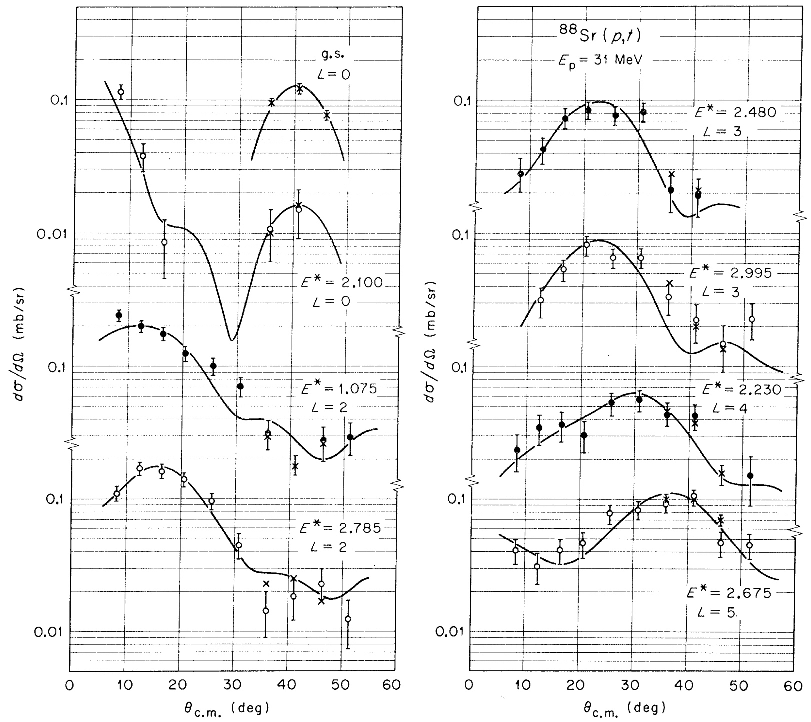


FIG. 6. Angular distributions for triton groups observed from the $^{88}$Sr($p,t$)$^{86}$Sr reaction. The circles are data obtained from the $^{84}$Sr target and the crosses are data from the natural Sr target. The error bars associated with the crosses are smaller than those for the circles and are shown in a few cases where these data alone were used.

clear two-body force.[14,15]

The effect of the strong two-neutron correlations in the ground states of these isotopes manifests itself in the large enhancement factor extracted for the ground-to-ground-state transitions. The kinematic factors associated with the ($p,t$) reaction mechanism favor the formation of a triton by picking up two $2p_{1/2}$ neutrons by about a factor of 4 over the pickup of the two $1g_{9/2}$ neutrons assumed in extracting the enhancements in Tables II–IV. However, the large enhancements observed cannot be accounted for by assuming the coherent addition of strength from these two orbitals alone, and a considerable portion of the $2p_{3/2}$ $L=0$ strength must also appear in these ground-state transitions.

The $0^+$ levels observed in the present study and the relative ($p,t$) transition intensities to these states are summarized in Fig. 7. The position of the lowest excited $0^+$ level in $^{88}$Sr has also been included in the figure to complete the energy systematics. This state has been reported from a study of the $^{86}$Sr($t,p$) reaction.[16]

The ground-to-ground-state transition intensities seem to increase rather smoothly away from the closed shell at $^{88}$Sr. The behavior of the $L=0$ strength to the excited states appears more erratic. The total strength to low-lying excited $0^+$ states is about the same for both the $^{86}$Sr($p,t$) and $^{84}$Sr($p,t$) reactions with more strength going into the lower state as it drops in excitation energy away from the closed $N=50$ shell. The strength observed to excited $0^+$ states in the $^{88}$Sr($p,t$) reaction is, how-

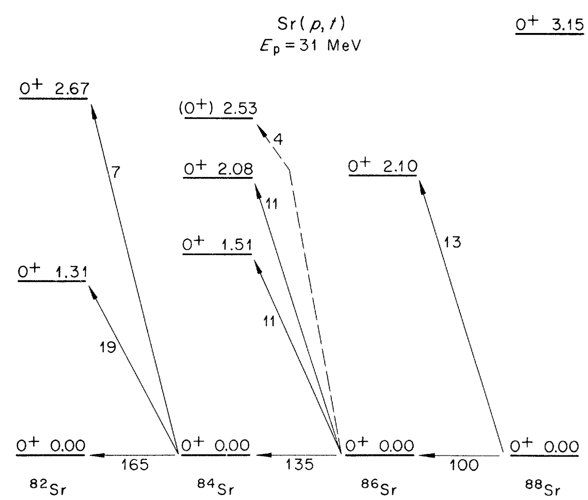


FIG. 7. Systematics of the low-lying $0^+$ levels observed in the strontium isotopes. The relative ($p,t$) transition intensities are indicated by the numbers labeling the appropriate arrows. Excitation energies for the excited states are in MeV. The position of the excited $0^+$ in $^{88}$Sr is taken from Ref. 16.

ever, significantly less. No other excited $0^+$ level was observed in this reaction in the excitation energy region below 3.5 MeV. The data of Fig. 7 should provide a rather stringent test on the wave functions obtained from any model of the neutron structure of these nuclei.

### B. Levels in $^{86}$Sr

The low-lying levels of $^{86}$Sr have been extensively studied and have been summarized in a recent compilation.[5] Although it was not the intention of the present study to examine this nucleus in detail, a comparison of the present results with the compilation assignments allows a number of previous ambiguities to be resolved.

A tentative excited $0^+$ level based on the preliminary ($p,t$) results quoted in Ref. 5 is confirmed and placed at an excitation energy of 2.100 MeV by the present study. A level at 2.230 MeV previously assigned as $2^+$, $3^+$, or $4^+$ can now be definitely assigned as $4^+$ and a level at 2.675 MeV can now be assigned definitely as $5^-$. A level at 2.64 MeV which was previously assigned $1^\pm$ or $2^+$ is most likely $2^+$ on the basis of the present results and a previously unassigned level at 2.79 MeV can now be assigned as $2^+$. A level at 2.88 MeV which was previously assigned $2^+$, $3^+$, or $4^+$ was not observed in the present experiment. The fact that unnatural-parity states are not allowed by the ($p,t$) selection rules favors the $3^+$ assignment but this is an extremely weak argument.

Up to the 3 MeV of excitation energy covered in this present study, there are no conflicts between our results and previous assignments.[5,17,18] A level is observed at 2.86 MeV that does not appear in the final accepted level scheme of the compilation. This level probably corresponds to the level reported[2] at this energy, populated by $l=4$ transfer in the $^{87}$Sr($p,d$) reaction, and suggested as $6^+$. Such an assignment would be consistent with our results.

*Note added in proof:* This assignment is also supported by the on-line $\gamma$-ray studies of Ishihara *et al.*[18a] and by the $^{86}$Y$^m$ decay scheme results of Simpson *et al.*[18b]

### C. Levels in $^{84}$Sr

The present results from Table II are compared in Fig. 8 with previous results from inelastic $\alpha$-

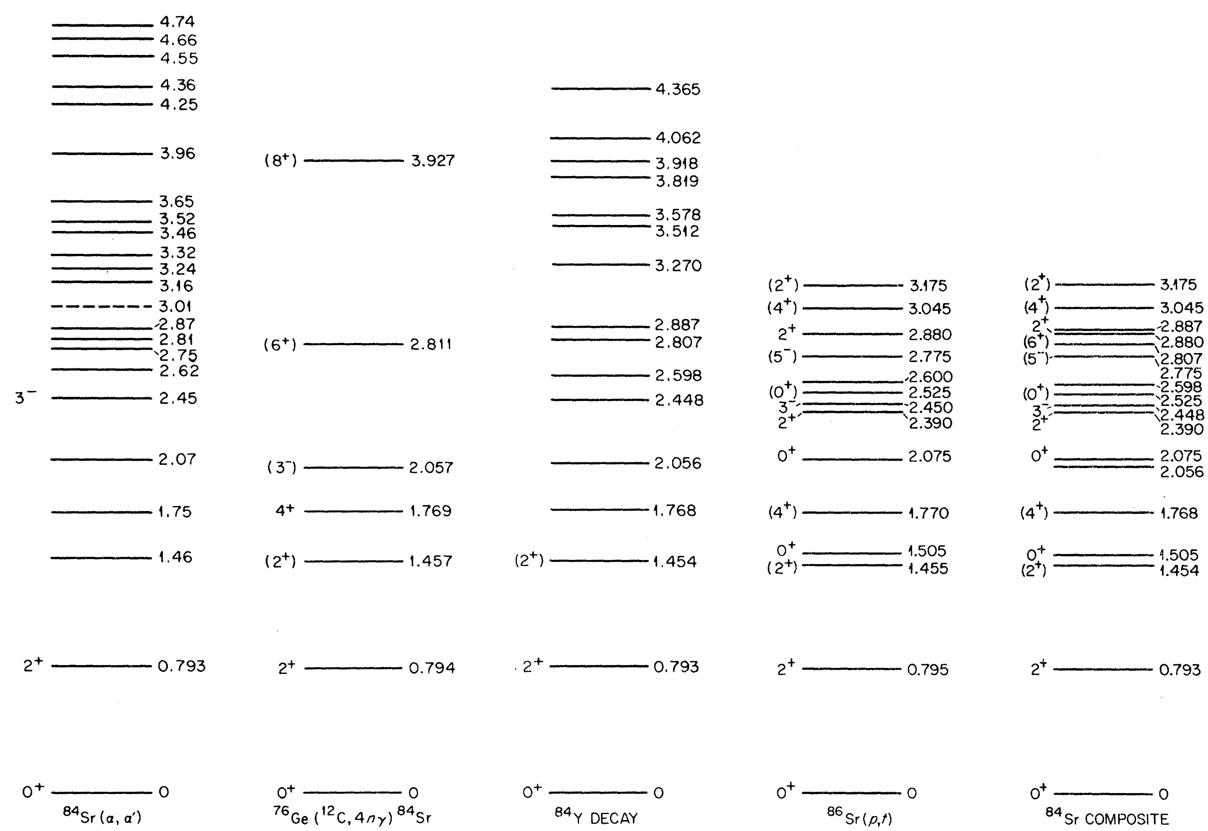


FIG. 8. The level structure of $^{84}$Sr as observed with several reactions. The ($\alpha,\alpha'$) data are taken from Ref. 4, the ($^{12}$C,$4n\gamma$) data from Ref. 19, the decay data from Ref. 20, and the ($p,t$) data are from the present work. At the far right is shown a composite level spectrum for $^{84}$Sr constructued from this comparison.

particle scattering,[4] the $^{76}$Ge($^{12}$C, $4n\gamma$) reaction,[19] and the $^{84}$Y decay scheme.[20] The $(p, t)$ reaction yields considerable new information on this nucleus. Three new $0^+$ levels are identified at 1.505, 2.075, and 2.525 MeV. A new level at 2.39 MeV is assigned as $2^+$ and the proposed $3^-$ assignment[4] to a level at 2.45 MeV is confirmed. In addition, several assignments are suggested for higher-lying levels. A final composite level scheme suggested for $^{84}$Sr, up to an excitation energy of 3 MeV, is also shown in Fig. 8.

The angular distributions for the 1.455 and 1.770 MeV states were shown separately in Fig. 4, since they did not agree well with any of the DWBA predictions. The state at 1.455 MeV, tentatively assigned $2^+$, is a factor of 2 weaker than the corresponding state in $^{86}$Sr and the 1.770 MeV ($4^+$) is about six times weaker than the lowest first excited $4^+$ in $^{86}$Sr. It is interesting that such "two-phonon-like" levels, which do not agree well with the DWBA two-neutron-transfer calculations, when studied by inelastic scattering reactions are also found to be fitted poorly by the DWBA predictions.[21]

### D. Levels in $^{82}$Sr

The levels for $^{82}$Sr are summarized in Table III. The only other information on this nucleus is a preliminary report of $\gamma$ rays observed following the $^{74}$Ge($^{12}$C, $4n$) and $^{68}$Zn($^{16}$O, $2n$) reactions.[19,22] These authors suggest a first excited, $2^+$ level in good agreement with the present $(p, t)$ results. Except for this state, none of the remaining levels in Table III have been observed previously.

Perhaps the most surprising result of the present study is the failure to observe a low-lying $4^+$ level. The work of Refs. 19 and 22 suggests such a level at an energy nearly degenerate with the $0^+$ level observed by the $(p, t)$ reaction at 1.31 MeV. We see no evidence for another level in this region of excitation, even at a scattering angle of 25° where the $L=0$ distribution is at a minimum and the $L=4$ distribution should be nearly at a maximum. Thus an upper limit to the cross section of an $L=4$ angular distribution at this excitation energy is about 1 $\mu$b/sr. This is an order of magnitude weaker than the intensity to the proposed $4^+$ level at 1.77 MeV in $^{84}$Sr.

### E. Level Systematics

The levels populated by the $(p, t)$ reaction for the even isotopes of strontium are summarized in Fig. 9. The figure shows the low-lying levels in the final nuclei up to 3 MeV of excitation. Also included for completeness are the levels of $^{88}$Sr, for this same region of excitation, as observed with the $^{86}$Sr$(t, p)^{88}$Sr reaction.[16] These levels have not been studied with the $(p, t)$ reaction since $^{90}$Sr is not stable.

The most dramatic feature of the systematics exhibited in Fig. 9 is the steady compression of

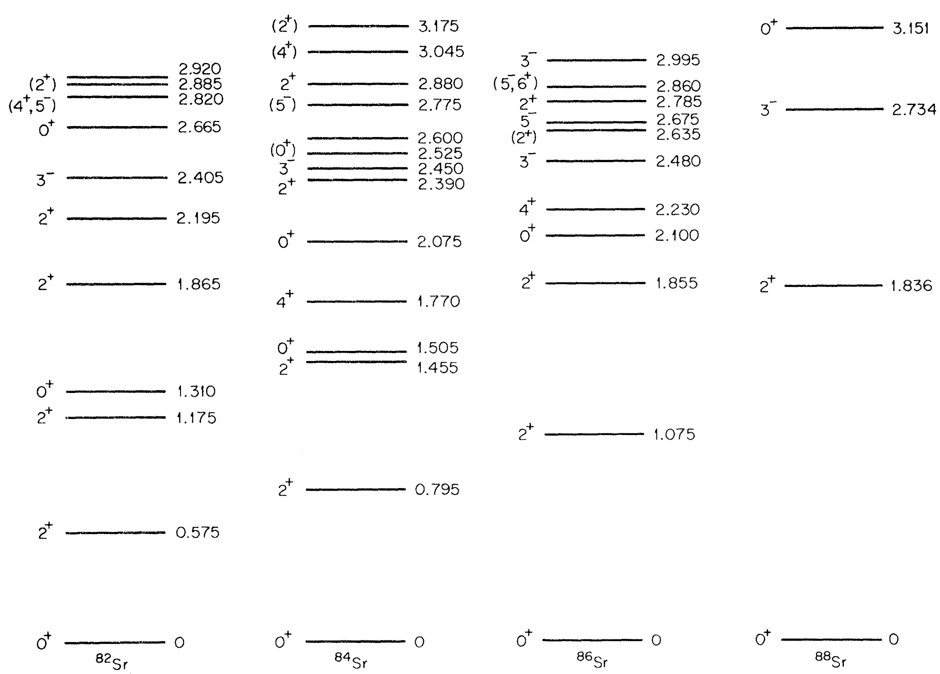


FIG. 9. Energy systematics for the low-lying levels of the even stronium isotopes observed with the $(p, t)$ reaction. The known levels of $^{88}$Sr, for this same region of excitation energy, have been included to extend the comparison.

the lowest level sequence as the neutron number decreases from the shell closure at $N=50$. For the three "non-closed-shell" isotopes, the lowest level sequence appears to be $0^+$(g.s.), $2^+$, $2^+$, $0^+$, $(4^+)$. This sequence, and in particular its harmonic energy spacing, suggests strongly that a vibrational model description[23] of these nuclei would be appropriate. The decreasing phonon energy with removal of neutrons from the closed shell is also in agreement with such a description.[24] It is also quite striking that where similar levels are known in the isotonic Zr and Kr nuclei (two protons more and two protons less), their excitation energies show remarkable agreement with these low-lying levels observed in the Sr isotopes. The marked decrease in level spacing, observed from $^{86}$Sr to $^{82}$Sr, immediately precludes a meaningful analysis in terms of shell-model calculations which consider only the $2p_{1/2}$ and $1g_{9/2}$ neutron orbitals with interactions for which seniority is conserved. Even releasing the condition of seniority conservation will obviously be inadequate since this model space cannot yield two $2^+$ levels for $^{86}$Sr. In addition, the number of $0^+$ levels observed, as well as the large ground-to-ground-state transition intensities, point to the need for a larger set of basis states in shell-model calculations for these nuclei.

It is interesting to note that the lowest $3^-$ level observed in these nuclei remains quite stable in excitation energy and does not show any appreciable lowering from $^{86}$Sr to $^{82}$Sr. Such a behavior is consistent with these levels arising from the collective octupole vibration of these nuclei. It should also be noted that, whereas the first excited $0^+$ level decreases in excitation energy in a similar fashion to the first and second $2^+$ levels, the second excited $0^+$ level shows a sharp rise in excitation energy from $^{84}$Sr to $^{82}$Sr. This behavior suggests that the basic structure of this second $0^+$ state is significantly different from the lower-lying levels in these spectra.

Finally, the disappearance of $(p,t)$ strength to the first excited $4^+$ level remains very puzzling. The evident sharp decrease in intensity with falling excitation energy is not found in the case of the low-lying $2^+$ levels.

In summary, the present data considerably extend available information on the low-lying level structure of the even strontium nuclei. An investigation of the $\gamma$-decay properties of $^{82}$Sr would give additional important information in establishing a detailed description of these nuclei.

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