^{84}Sr(x, x') and ^{84}Sr(x, $x'\gamma$) Measurements with 13-MeV Protons, 12-MeV Deuterons, and 18-MeV α Particles

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Inelastic scattering experiments, using the ^{84}Sr(α, α'), ^{84}Sr(α, $\alpha'\gamma$), ^{84}Sr(p, p'), and ^{84}Sr-(p, $p'\gamma$) reactions, were performed on 82.2% enriched ^{84}Sr targets with solid-state detectors. The 18-MeV α-particle inelastic scattering measurements resulted in the identification of excited states at 0.793, 1.454, 1.767, 2.07, 2.447, 2.62, 2.75, 2.81, 2.87, (3.01), 3.16, 3.24, 3.32, 3.46, 3.52, 3.65, 3.96, 4.25, 4.36, 4.55, 4.66, and 4.74 MeV, whereas the 13-MeV proton measurements resulted in identification of excited states at 0.793, 1.454, (1.502), 1.767, 2.07, 2.447, 2.76, (2.81), 2.88, (3.02), 3.18, (3.24), (3.34), 3.40, (3.48), and (3.53) MeV. Angular distributions of 13-MeV deuterons inelastically scattered from the 0.793- and 2.447-MeV states were measured with an Enge magnetic spectrograph and were fitted by $L=2$ and $L=3$ distorted-wave Born-approximation angular-momentum-transfer curves, respectively. Deformation parameters $\beta_2=0.150$ and $\beta_3=0.129$ were deduced.

I. INTRODUCTION

Until recently, only a small amount of data on the nuclear structure of ^{84}Sr has been published. This has been largely due to the fact that ^{84}Sr is a rather rare isotope (0.56% natural abundance) and is on the very edge of the neutron-deficient side of the valley of stability. Yamazaki *et al.*[1] first identified the radioactive isotope ^{84}Y and studied its decay to the levels of ^{84}Sr with NaI(Tl) detectors. More recent studies of this decay with Ge(Li) detectors have been reported by Zaitseva *et al.*,[2] by Konijn *et al.*,[3] and by Doron and Blann.[4]

In early Coulomb-excitation work, Alkhazov *et al.*[5] established that the first excited 2^+ state of ^{84}Sr lay at approximately 0.80 MeV and reported that its measured lifetime was about 38×10^{-13} sec. Davies *et al.*[6] have reported preliminary results of ^{86}Sr(p, t)^{84}Sr measurements, and Inamura *et al.*[7] have studied the γ rays from the reaction ^{76}Ge(^{12}C, $4n$)^{84}Sr. No inelastic scattering studies of ^{84}Sr have been reported in the literature.

We initiated the present work for several reasons. First, it would serve as a useful complement to our radioactive-decay work.[3] The shell model predicts that the ground-state spin and parity of ^{84}Y are probably 4^- or 5^-; hence many low-spin states of the ^{84}Sr daughter would be populated only weakly, if at all, from this decay. These low-spin states should be readily excited by inelastic scattering of particles from a ^{84}Sr target. In addition, we wanted to identify and study the 3^- collective octupole state in this nucleus. Identification of this state from the radioactive-decay work[3] proved to be difficult, whereas it was readily shown to be at 2.447 ± 0.001 MeV from the present work. Finally, the preliminary work of Davies *et al.*[6] suggested that a (0^+) state lay at 1.46 ± 0.03 MeV, whereas our radioactive-decay experiments[3] clearly indicated the existence of a 1.4536 ± 0.0001-MeV (2^+) level depopulated by a ground-state transition. It was hoped that inelastic scattering experiments would shed light on this discrepancy. Indeed, evidence was found for the existence of a new level in ^{84}Sr at 1.502 ± 0.002 MeV, which could be the (0^+) level reported by Davies *et al.*[6]

II. TARGET PREPARATION

82% enriched ^{84}Sr, prepared in the chemical form $SrCO_3$ by the Isotopes Development Center of Oak Ridge National Laboratory, had the following isotopic composition:

Mass	Atoms (%)
84	82.2
86	3.7
87	1.6
88	12.5

Targets were prepared by the method of Sauer.[8] The $SrCO_3$ was coverted to SrO by heating the material to 1000°C *in vacuo*. Four parts of SrO were mixed with one part of Al powder; the mixture was then pressed into pellets of about 5 mg each. For each target, two of the pellets were placed in a small tantalum *chimney* evaporation apparatus. The following reaction takes place at 800°C:

$$3SrO + 2Al \overset{\Delta}{=} Al_2O_3 + 3Sr\uparrow .$$

The ^{84}Sr metal liberated was collected on a 20-$\mu g/cm^2$-thick carbon film placed on a glass slide just above the opening of the chimney. The film was then remounted on an Al target frame. Targets approximately 150 $\mu g/cm^2$ thick for the α- and p-scattering experiments and about 20 $\mu g/cm^2$ thick for the d-scattering experiment were produced.

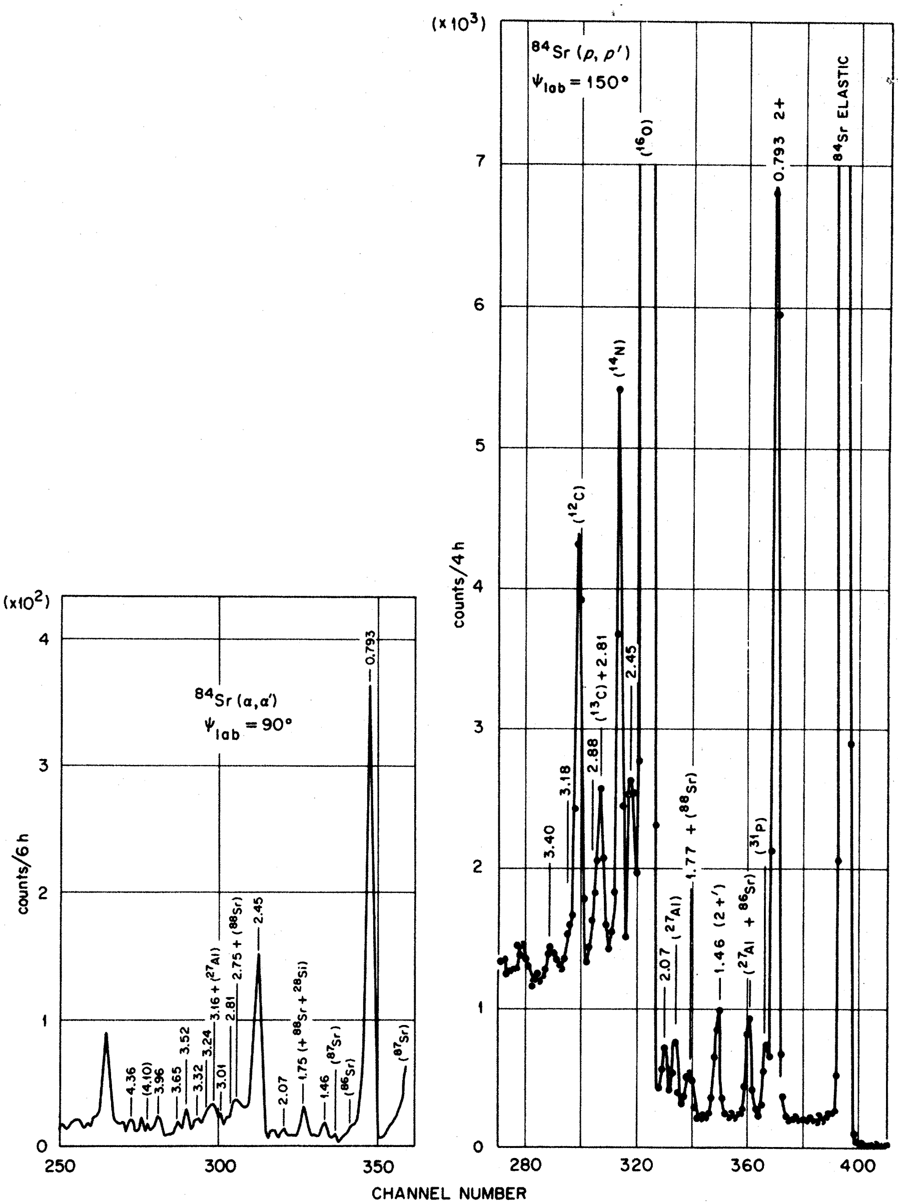

FIG. 1. ^{84}Sr(α,α') and ^{84}Sr(p,p') spectra.

III. ^{84}Sr(α,α') AND ^{84}Sr(p,p') MEASUREMENTS

A. Experimental Procedure

Beams of 18.36-MeV α particles and 13.13-MeV protons were produced by the 6-MV tandem Van de Graaff accelerator of the University of Utrecht for the present work. In both the (α, α') and (p,p') experiments, the beam current was approximately 200 nA, focused onto a spot about 1 mm in diameter at the target site. In the (α, α') measurements, six 200-μm surface-barrier detectors were employed, one being fixed at 70° as a monitor and five being movable. For 16.41-MeV α particles, the system had a resolution of 66 keV full width at half maximum (FWHM). Four 2000-μm surface-barrier detectors were employed in the (p,p') measurements, one detector being fixed at 150° and three being movable. This system had a resolution of 78 keV FWHM for 12.57-MeV protons. For both sets of measurements, the detectors were located 18 cm from the target. With the addition before the detectors of apertures and small magnets for deflecting electrons, each detector saw a solid angle of about 9×10^{-3} sr. An 800-V positive potential was applied to the target in each experiment as a further aid in the reduction of electron background. The targets were oriented to an angle of 50° with respect to the beam axis.

The data from the detectors were collected in a Laben 4096-channel analyzer. By means of a routing system, the data from each detector were allotted 512 channels in the memory. Each run from each detector was calibrated separately from the energies of the ground-state and first-excited-state peaks of ^{84}Sr and the very strong ground-state peaks of ^{12}C and ^{16}O contaminants. Typical α' and p' spectra are shown in Fig. 1.

B. ^{84}Sr(α,α') and ^{84}Sr(p,p') Results

The results obtained from the analysis of the α' and p' singles measurements are shown in the

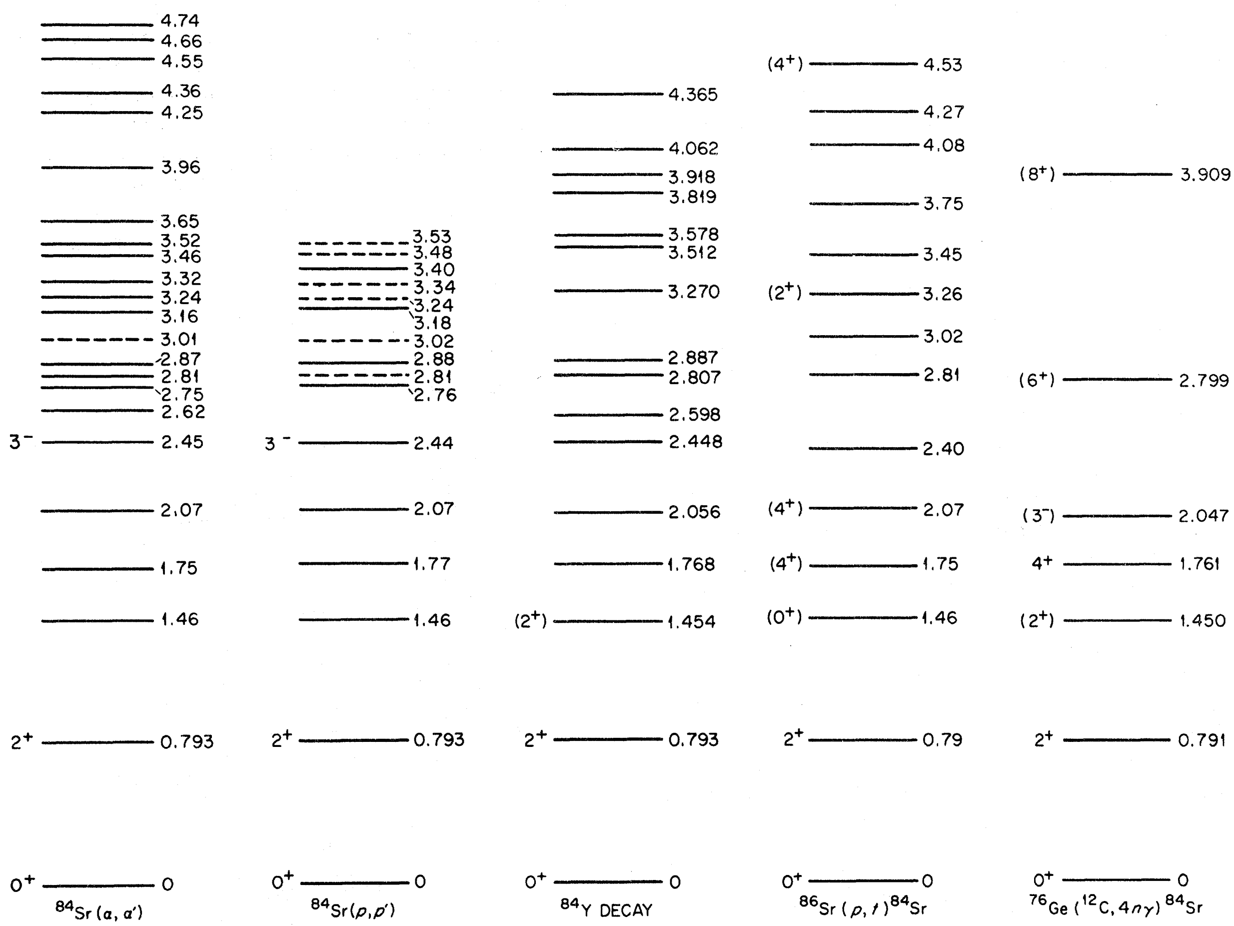

FIG. 2. The present results compared to those from measurements of Konijn *et al.* (Ref. 3), Davies *et al.* (Ref. 6), and Inamura *et al.* (Ref. 7), respectively.

first two energy-level diagrams in Fig. 2. The remaining diagrams in the figure show the results of the ^{84}Y decay measurements of Konijn *et al.*,[3] the $^{86}Sr(p, t)^{84}Sr$ measurements of Davies *et al.*,[6] and the $^{76}Ge(^{12}C, 4n\gamma)^{84}Sr$ measurements of Inamura *et al.*[7] None of the level schemes in Fig. 2 can be reconciled with that proposed by Doron and Blann.[4]

In Fig. 2, those levels from the present work which are represented by solid lines were clearly identified in at least four different spectra at four well-separated angles. Those levels represented by dotted lines were observed at less than four different angles. The level energies are mean values. From the average deviations of the energies and from comparison with the much more accurately known level energies obtained from the radioactive-decay[3] work, it was determined that the energies in the present work are accurate to within 0.03 MeV.

We attempted to analyze the angular distribution of the most prominent α-particle and proton groups with a distorted-wave Born approximation (DWBA), but we obtained inconclusive results. In the (α, α') experiment, the α-particle energy of 18 MeV was too low to provide more than rather featureless angular distributions. Oxygen, carbon, and nitrogen contaminants caused serious interference with the (p, p') angular distributions.

IV. $^{84}Sr(d, d')$ MEASUREMENTS

In order to obtain satisfactory angular distributions of particles scattered from the 0.793- and 2.447-MeV levels, we performed a $^{84}Sr(d, d')$ measurement with 12-MeV deuterons from the tandem Van de Graaff accelerator. This measurement was performed in an Enge spectrograph equipped with position-sensitive silicon detectors. The experimental resolution was better than 10 keV FWHM. A surface-barrier monitor detector was fixed at an angle of 45° with respect to the beam axis throughout the experiment. Its output was used for normalization.

The measured angular distributions are shown in Fig. 3. Error bars shown on the experimental points are twice the statistical error in each case. The theoretical curves were calculated with the DWBA computer program DWUCK,[9] using a Woods-Saxon potential. The optical-model parameters of Forster *et al.*[10] were used: $V = 90.35$ MeV, $r_0 = 1.226$ fm, $a = 0.684$ fm, $W = 0.0$, $W_D = 12.1$ MeV, $r_0' = 1.240$ fm, $a' = 0.841$ fm, $V_s = 7.5$ MeV, $r_s = 1.226$ fm, $a_s = 0.684$ fm, and $r_c = 1.25$ fm. Both the real and the imaginary parts of the optical-model potential were deformed in the calculations. Absolute cross sections were obtained by normalization of the elastic scattering angular distribution to the optical-model cross section at low angles.

The 0.793-MeV energy level is known from Coulomb excitation[5] to be a 2^+ state. Indeed the DWBA curve for an $L=2$ transfer fits the experimental angular distribution reasonably well. The value of the deformation parameter β_2 obtained from the normalization of the DWBA curve to the present results is 0.154 ± 0.015. This value is somewhat more precise than the value $\beta_2 = 0.21 \pm 0.07$, which one can calculate from the $B(E2)\uparrow$ value of 3.4 $\times 10^{-47}$ cm^4 for the first excited 2^+ state in ^{84}Sr measured by Alkhazov *et al.*[5] The present value $\beta_2 = 0.154$ seems to fit well into the systematics of β_2 values tabulated by Stelson and Grodzins[11] and is close to the value $\beta_2 = 0.130$ for the 1.076-MeV 2^+ state of ^{86}Sr obtained by Ramayya *et al.*[12] from inelastic scattering measurements with 12-MeV protons. It would appear that the early $B(E2)\uparrow$ measurement of Alkhazov *et al.*[5] is too large by a factor of 2.

Theoretical curves for L transfers from 1–5 were compared to the angular distribution of deuterons scattered from the 2.447-MeV excited state, the $L=3$ transfer giving the best fit. As such an easily excited level must be a natural-parity state, one concludes that it has a spin and parity of 3^-. Such an assignment fits well into the energy systematics of 3^- states of even-even nuclei in this region. The value $\beta_3 = 0.129 \pm 0.013$ was deduced from the present measurements. In comparison,

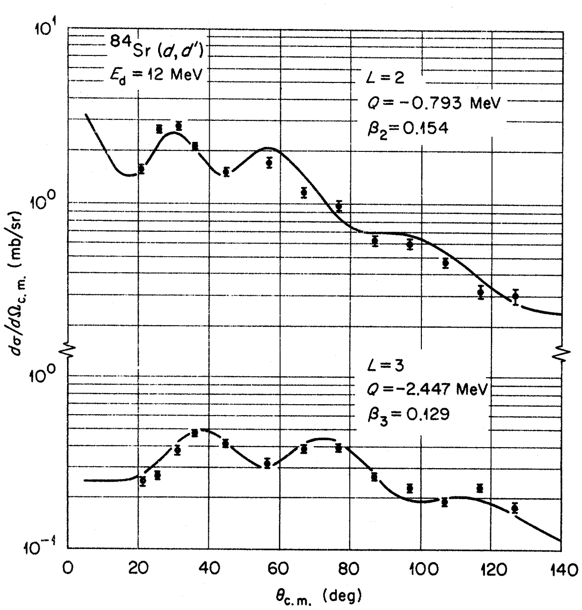

FIG. 3. The differential cross sections for inelastic scattering of 12-MeV deuterons from the 0.793- and 2.447-MeV states in ^{84}Sr. The solid lines are theoretical DWBA curves.

Ramayya *et al.*[12] obtained the value $\beta_3=0.153$ for the 2.482-MeV 3^- state in ^{86}Sr.

V. ^{84}Sr($\alpha,\alpha'\gamma$) AND ^{84}Sr($p,p'\gamma$) MEASUREMENTS

A. Experimental Procedure

The α'-γ and p'-γ coincidence experiments were also performed with the particle beams described in in Sec. III A. These measurements were made in the scattering chamber described in Ref. 13. For the ($p,p'\gamma$) experiment, two 2000-μm surface-barrier detectors were placed at 120 and 135° with respect to the beam axis and 3.5 cm from the target. Rectangular 5- by 10-mm² collimators in front of the detectors limited the horizontal opening angle to 8.5° and the vertical opening angle to 17°. The target was oriented in a plane perpendicular to the beam axis. A 40-cm³ Ge(Li) detector was placed at 120° and 5 cm from the target. A similar arrangement was employed in the ($\alpha,\alpha'\gamma$) experiment, the only changes being the use of 1000-μm detectors at 80 and 100° for α-particle detection instead of the 2000-μm detectors, and reorientation of the target to an angle of 60° with respect to the beam axis. The Ge(Li) detector had a resolution of 4 keV FWHM for 1.33-MeV γ rays. The total system resolution for the 2000-μm detectors was 150 keV FWHM for 12.66-MeV protons, and that for the 1000-μm detectors was 380 keV FWHM for 16.96-MeV α particles. During the course of the ($\alpha,\alpha'\gamma$) measurements the 100° detector had to be taken out of operation.

Coincidence timing signals between the Ge(Li) detector and each of the particle detectors were obtained by means of crossover timing networks and time-to-amplitude converters. The timing spectra from each of the two time-to-amplitude converters were digitized by a 7-bit analog-to-digital converter. The energy spectra were digitized with a 12-bit analog-to-digital converter. Thus each coincidence event between the Ge(Li) detector and a particle detector was labeled with a γ-ray energy address, a particle-energy address, a particle-detector address, and a time address. These sets of coincidence addresses were stored in the buffer memory of a CDC-1700 computer and periodically dumped onto magnetic tape. Engmann[14] has described the data-handling system in more detail.

At the end of the experiments, gates of interest were selected along the two-particle energy axes, the γ-ray energy axis, and the two time axes corresponding to the two γ-ray particle detector coincidence timing spectra. By the selection of appropriate time gates, spectra of random events could be obtained. For each experiment, all gates were read simultaneously from the magnetic tapes, stored on a disk, and then punched onto paper tape for further processing.

TABLE I. ^{84}Sr($\alpha,\alpha'\gamma$) results, α'(80°)-γ(120°).

^{84}Sr levels excited (MeV)	Coincident γ rays (MeV)[a,b]
0.793	0.793(VS)
1.454	0.427(W), 0.661(S), 0.793(S)
1.767	0.661(W), 0.793(S), 0.974(S)
2.07	0.661(S), 0.793(S)
2.447, 2.62	0.661(VS), 0.687(VW), 0.793(VS), 0.974(W), 0.993(S), 1.454(VW), 1.657(VW)
2.75, 2.81, 2.87	0.661(W), 0.710(VW), 0.793(S), 0.974(S)
3.46, 3.52, 3.65	0.467(VW), 0.793(S), 0.974(W)

[a] VW = very weak, W = weak, S = strong, VS = very strong.

[b] Energies of strong and very strong transitions are accurate to better than ±0.001 MeV.

B. ^{84}Sr($\alpha,\alpha'\gamma$) and ^{84}Sr($p,p'\gamma$) Results

Table I lists the results of the ($\alpha,\alpha'\gamma$) experiment. Except for one rather surprising difference (see Fig. 4), these results are compatible with the decay schemes of Konijn *et al.*[3] and Zaitseva *et al.*[2] Konijn *et al.*[3] report an energy level at 2.447 MeV which is depopulated by γ rays with energies 0.6804, 0.9942, and 1.6546 MeV and branching ratios 40%, 36%, and 24%, respectively. In the

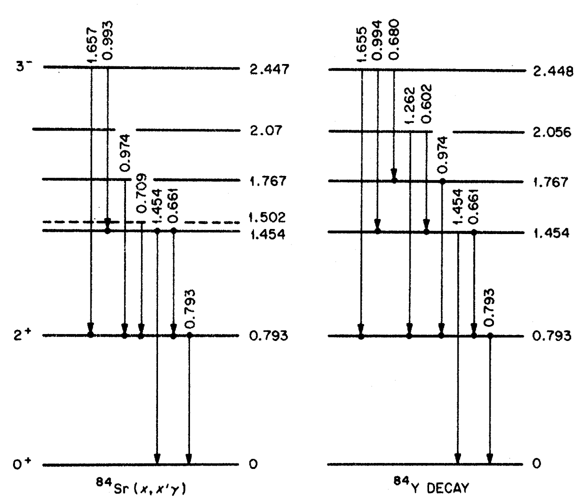

FIG. 4. The composite decay scheme of the lower excited states of ^{84}Sr from the ($\alpha,\alpha'\gamma$) and ($p,p'\gamma$) measurements compared to the scheme of Konijn *et al.* (Ref. 3) from the decay of ^{84}Y.

TABLE II. $^{84}Sr(p, p'\gamma)$ results, $p'(135°)-\gamma(120°)$.

^{84}Sr levels excited (MeV)	Coincident γ rays (MeV) [a,b]
0.793	0.793(VS)
1.454, (1.502)	0.661(W), 0.709(W), 0.793(S)
1.767	0.793(W), 0.974(W)
2.448, 2.62	0.661(S), 0.793(S), 0.905(VW), 0.994(S)

[a] VW = very weak, W = weak, S = strong, VS = very strong.

[b] Energies of strong and very strong transitions are accurate to better than ±0.001 MeV.

present work, a level at 2.447 ± 0.001 MeV was strongly excited by α particles. Transitions with energies 0.994 and 1.654 MeV appear in the coincident γ-ray spectrum, but a transition at 0.680 MeV evidently does not appear in the spectrum at all. The ratio of the intensity of the 0.994 γ ray to that of the 1.654-MeV γ ray is 1.5 ± 0.2 from the β-decay work[3] and 2.8 ± 1.3 from the present work.

The $(p, p'\gamma)$ results shown in Table II reveal the same discrepancy between the β-decay results[2,3] and nuclear scattering results with respect to which transitions depopulate the 2.447-MeV level. A 0.680-MeV γ ray is evidently absent from the 2.447-MeV proton gates as well. One concludes that either the 0.680-MeV γ ray is misplaced in the decay scheme from the β-decay work or an entirely different state of the same energy was excited in the present work.

In addition to the expected 0.661- and 0.793-MeV γ rays, a 0.709-MeV γ ray appears in coincidence with the 1.45-MeV proton group in both the 120 and the 135° detectors (Fig. 5). This fact suggests that, as well as the 1.454-MeV (2^+) level known from the β-decay work,[2,3] there is also a 1.502 ± 0.002-MeV state depopulated by the 0.709-MeV transition. This interpretation has just been confirmed by preliminary $^{86}Sr(p, t)^{84}Sr$ measurements[15] which have tentatively revealed 0^+ excited states in ^{84}Sr at 1.504, 2.076, and 2.524 MeV.

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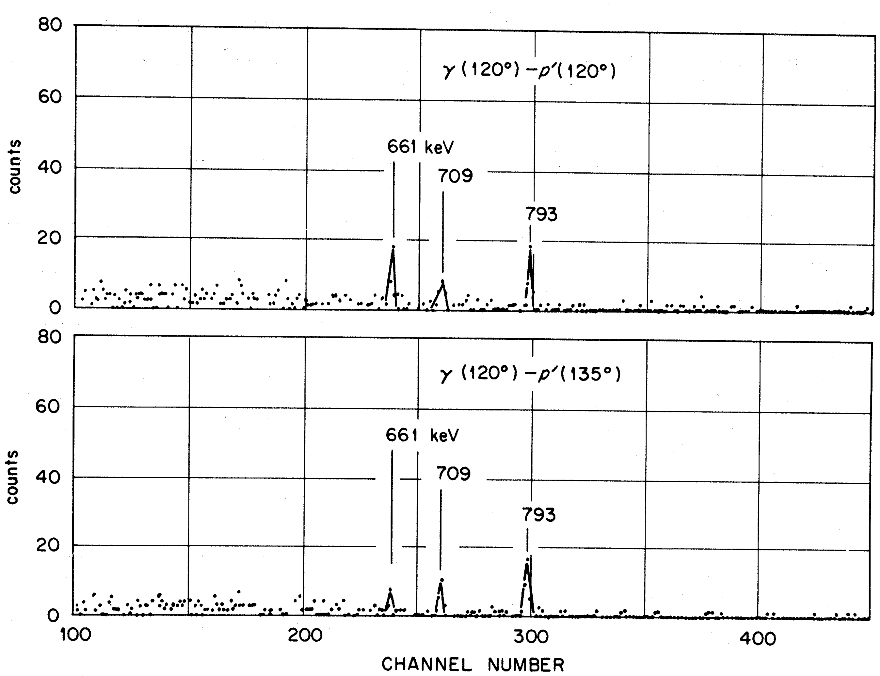

FIG. 5. The γ-ray gates on the 1.45-MeV proton groups.

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Nuclear Structure Calculations in ^{21}Ne and ^{23}Na

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The energy levels, static moments, and electromagnetic transition probabilities in ^{21}Ne and ^{23}Na are calculated from the projected multishell Hartree-Fock wave functions obtained with a realistic *NN* interaction. The modified Elliott interaction is employed as the realistic *NN* interaction. The results of these calculations are in good agreement with the experimental data. In particular, the magnetic moment of the ground state and the excitation energy of the first $\frac{1}{2}^+$ state in both the nuclei are predicted accurately. The computed *ft* values of the β transitions to the states in the two nuclei are in semiquantitative agreement with the experimental data.

1. INTRODUCTION

The extensive experimental investigations[1] carried out recently on the nuclear reactions ^{18}O-$(\alpha, n\gamma)$, ^{23}Na$(\alpha, \alpha'\gamma)$, ^{23}Na(p, p'), and ^{24}Mg$(t, \alpha\gamma)$ have established the sequence of positive-parity nuclear states in ^{21}Ne and ^{23}Na. The energy-level spectra of these two odd-*A* nuclei are expected to be basically characteristic of the eleventh odd nucleon in the *sd* shell and this expectation is borne out by the striking similarity in the two experimental spectra. The static electromagnetic moments for the $J=\frac{3}{2}^+$ ground state in both the nuclei are accurately measured. The $B(E2)$ and $B(M1)$ values for the electromagnetic transitions and *ft* values for the β transitions to the states in ^{21}Ne and ^{23}Na are also available. The shell-model (SM) calculations carried out recently by considering