Compt. Rend. B271, 165 (1970).

[47] C. Maples, G. W. Goth, and J. Cerny, Nucl. Data A2(Nos. 5, 6), 429 (1966).

[48] B. H. Armitage, A. T. G. Ferguson, G. C. Neilson, and W. D. N. Pritchard, Nucl. Phys. A133, 241 (1969).

[49] L. E. Samuelson, Ph.D. thesis, Michigan State University, 1972 (unpublished).

[50] J. Vervier, Nucl. Phys. 78, 497 (1966).

[51] H. J. Hausman, R. M. Humes, and R. G. Seyler, Phys. Rev. 164, 1407 (1967).

[52] L. L. Lee, Jr., and J. P. Schiffer, Phys. Letters 4, 104 (1963).

[53] J. R. Huizenga and A. A. Katsanos, Nucl. Phys. A98, 614 (1967).

[54] E. Sheldon and P. Gantenbein, J. Appl. Math. Phys. (ZAMP) 18, 397 (1967); E. Sheldon and R. M. Strang, Comp. Phys. Commun. 1, 35 (1969).

[55] E. H. Auerbach, ABACUS-II, Brookhaven National Laboratory Report No. BNL-6562 (to be published).

[56] F. Perey, *Direct Interactions and Nuclear Reaction Mechanism* (Gordon and Breach, New York, 1963).

[57] F. Perey and B. Buck, Nucl. Phys. 32, 353 (1962).

[58] E. Sheldon, Rev. Mod. Phys. 35, 795 (1963).

[59] K. M. Thompson and C. R. Gruhn, Nucl. Instr. Methods 74, 309 (1969).

[60] GADFIT, computer code written by R. A. Warner, Michigan State University Cyclotron Laboratory (unpublished).

[61] The absolute intensity standards were obtained from the Radiation Materials Corporation of Waltham, Massachusetts.

[62] P. A. Moldauer, Phys. Rev. 123, 968 (1961); 135, B642 (1964); Rev. Mod. Phys. 36, 1079 (1964).

[63] R. V. Jones, W. Dobrowolski, and C. D. Jeffries, Phys. Rev. 102, 738 (1956).

[64] R. L. Auble, Wm. C McHarris, and W. H. Kelly, Nucl. Phys. A91, 225 (1967), and references cited therein.

[65] W. Menti, Helv. Phys. Acta 40, 981 (1967).

[66] S. S. Hanna, J. Heberle, C. Littlejohn, G. J. Perlow, R. S. Preston, and D. H. Vincent, Phys. Rev. Letters 4, 177 (1960).

[67] M. N. Rao, Nucl. Data B3(Nos. 3,4), 43 (1970).

[68] M. R. Najam, W. F. Davidson, W. M. Zuk, L. E. Carlson, and M. A. Awal, Nucl. Phys. A173, 577 (1971).

[69] E. C. Halbert, J. B. McGrory, B. H. Wildenthal, and S. P. Pandya, in *Advances in Nuclear Physics*, edited by M. Baranger and E. Vogt (Plenum Press, New York, 1971), Vol. 4.

[70] S. A. Moszkowski, in *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland, Amsterdam, 1965), Vol. 2, Chap. XV.

PHYSICAL REVIEW C VOLUME 7, NUMBER 6 JUNE 1973

New Aluminum Isotope; Mass and β Decay of the $T_z = \frac{5}{2}$ Nuclide ^{31}Al and the Mass of ^{34}P[†]

David R. Goosman and David E. Alburger

Brookhaven National Laboratory, Upton, New York 11973

(Received 2 February 1973)

The first reported measurements of the β decay, half-life, and mass of ^{31}Al are presented. The new activity was produced by the ^{18}O(^{18}O,αp)^{31}Al reaction using 41-MeV incident ^{18}O ions, and was transferred pneumatically to a remotely located station where delayed γ rays and β rays were counted with Ge(Li) and NE 102 detectors, respectively. γ-ray energies (in keV) and relative intensities for the ^{31}Si daughter transitions are 621.81 ± 0.30 (9.94 ± 0.65), 752.23 ± 0.30 (18.5 ± 0.8), 1564.49 ± 0.30 (17.3 ± 1.6), 1694.73 ± 0.30 (58.9 ± 1.6), and 2316.64 ± 0.40 (72.8 ± 1.8). The ^{31}Si excitation energies (in keV) and relative β branching intensities are 752.24 ± 0.30 (<3.0), 1694.78 ± 0.30 (49.0 ± 1.7), and 2316.73 ± 0.40 (100 ± 2.5). A tentative β-ray transition to a state at $E_x = 2787.7 \pm 0.8$ keV is also observed. Upper limits on the strength of some possible γ-ray transitions following β decay to higher levels are given. ^{31}Al decays with a half-life of 644 ± 25 msec. By measuring the energy spectra of β rays populating the second and third excited states of ^{31}Si the mass excess of ^{31}Al has been measured to be $-15\,008 \pm 100$ keV. The mass excess of ^{34}P has been remeasured by a similar technique to be $-24\,550 \pm 90$ keV, and this value has been used to revise previous predictions for the masses of ^{33}Si and ^{35}P. The masses of several $T_z = \frac{5}{2}$ and $T_z = 3$ nuclides in the $2s$-$1d$ shell are compared with theoretical estimates. The β-decay measurements for ^{31}Al are shown to be in poor agreement with simple collective-model calculations, and in good agreement with recent detailed shell-model calculations.

I. INTRODUCTION

The study of light nuclei with large neutron excess is important for several reasons. Mass measurements of these nuclei provide tests for various extrapolation procedures used to estimate masses. The boundaries of the region of particle stability for neutron-rich nuclei as predicted by Garvey *et al.*[1] are surprisingly far from the valley of stability. The calculated location of these boundaries depends presently upon the measured masses of nuclei relatively close to β stability.

Thus measurements as far as possible from β stability provide more reliable estimates.

From another point of view, the study of β decay of nuclei with high T_z is rewarding because it provides nuclear structure information on both parent and daughter species. There have been several attempts to describe the structure of nuclei in the $2s$-$1d$ shell in terms of the collective model[2-5]; many rotational bands have been suggested by studies of electromagnetic transitions within s-d shell nuclides.[6,7] Another test of these assignments is provided by the ratios of ft values for the decay of the new parent isotope to the previously studied daughter, in which the rotational bands have been suggested. Recent extensive shell-model calculations[8,9] have been made for certain mass regions in the s-d shell, predicting β decays of presently unobserved nuclei as well as explaining previously studied decays.[10] New information on decays of high T_z nuclides tests the validity of these calculations. Having gained confidence in such predictions, the experimentalist can then use these calculations to *design* the optimum conditions for searching out nuclides with even higher T_z.

Masses of light nuclei with large neutron excess have been studied by a variety of methods. Early work using high-energy proton spallation reactions has been reported by Poskanzer *et al.*[11,12] and Thomas *et al.*[13] Extremely neutron-rich sodium isotopes have been studied using proton spallation in conjunction with a very chemically selective instrument by Klapisch *et al.*[14,15] The particle stability of 28 new isotopes in the region $Z = 6$–17 has been demonstrated by Artukh *et al.*,[16-18] who have also reported the first mass measurements for ^{21}O and ^{22}O using high-energy heavy-ion transfer reactions on heavy targets. The ^{12}Be mass has been measured via the ^{7}Li(^{7}Li, $2p$) reaction by Howard, Stokes, and Erkkila[19] and a preliminary mass for ^{29}Mg has been reported by Scott *et al.*[20] via the ^{26}Mg(^{11}B, ^{8}B) reaction. Preliminary masses for ^{27}Na and ^{28}Na have been obtained by Klapisch,[21] and several $T_z = 2$ nuclei in the s-d shell have been studied via (t, ^{3}He)[22,23] and (^{7}Li, ^{7}Be) reactions.[24]

Only a few measurements of the decay properties of very neutron-rich species ($T_z \geq \frac{5}{2}$) in the $2s$-$1d$ shell have been reported. The half-lives and β-ray singles spectra have been measured by Klapisch *et al.*[15] for ^{27}Na and ^{28}Na, and by Kabachenko *et al.*[25] for ^{25}Ne. The present authors have recently realized that another method of reaching and studying such nuclei is that of heavy-ion compound reactions at moderate energies. The masses and decay schemes of the $T_z = \frac{5}{2}$ species ^{33}Si, ^{35}P, and ^{25}Ne have been measured after forming these activities by the ^{18}O(^{18}O, $2pn$), ^{18}O(^{19}F, $2p$), and ^{9}Be(^{18}O, $2p$) reactions, respectively.[26-28] The decay scheme of ^{35}P was also studied independently by Grimm and Herzog[29] and Apt and Knight[30] by the ^{37}Cl(γ, $2p$) and the ^{37}Cl(t, αp) reactions, respectively, illustrating further the variety of methods that are used.

The present article reports the measurement of the mass and decay properties of ^{31}Al, a new $T_z = \frac{5}{2}$ nuclide, produced by the ^{18}O(^{18}O, αp) ^{31}Al reaction. This activity was not observed in previous ^{18}O + ^{18}O experiments[26] on 6.3-sec ^{33}Si, since the time delay after bombardment in that work was 3 sec by which time the ^{31}Al lines would have decayed to negligible proportions. A faster timing sequence was selected here in order to search both for ^{31}Al and for ^{34}Si which could be produced via the ^{18}O(^{18}O, $2p$)^{34}Si reaction. The only published information concerning ^{31}Al known to the authors is the demonstration of its particle stability by Artukh *et al.*[17] This is the fourth member of the $T_z = \frac{5}{2}$ series in the $2s$-$1d$ shell to be reached via heavy-ion compound reactions, and as has been pointed out already, there are several other species far from β stability that can probably be reached by this technique.

II. METHOD

Targets of ^{18}O were made by heating a strip of Ta to about 700°C in an atmosphere of oxygen enriched to 99% in ^{18}O, such that the weight increased by 3 mg/cm^2 on each side of the strip. The Brookhaven National Laboratory pneumatic

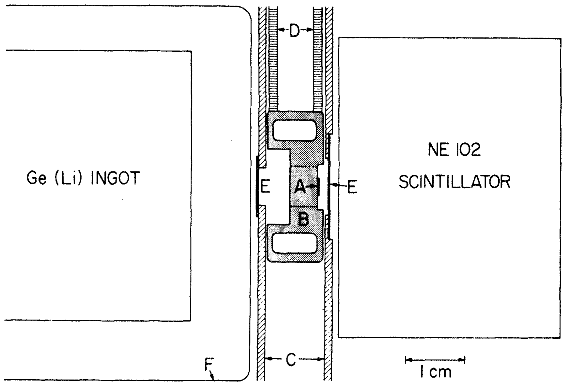

FIG. 1. The counting end of the rabbit facility. The ^{18}O target strip (A) mounted on the Delrin rabbit (B) slides inside the square stainless-steel tubing (C) and stops by contacting the polyvinylchloride tubing (D). γ and β radiations traverse the 47-mg/cm^2-thick Be windows (E) and are counted in Ge(Li) and NE 102 detectors, respectively. The front surface of the scintillator was covered with 19 mg/cm^2 of plastic and 7 mg/cm^2 of aluminum. The solid line (F) denotes the aluminum vacuum container for the Ge(Li) detector.

target transfer system was modified for high speed and used to shuttle the target between the irradiation room and the counting room. The target was irradiated in vacuum and transferred by a blast of helium to the counting location, which is shown in Fig. 1. After allowing 5 sec to pump away the helium used to transfer the rabbit to the irradiation station, the target was bombarded with about 150 nA (electrical) of 41-MeV ^{18}O ions of the +5 charge state for 1.5 sec and then transferred to the counting station. The counting period was divided into four sequential 0.6-sec time periods, starting 0.4 sec after the end of the irradiation. The rabbit maintained its position to well within 0.04 cm during the counting periods. An on-line computer stored γ-ray events for each of the four time periods separately, and simultaneously stored the spectra of β rays coincident with 12 digital windows set on various γ-ray photopeaks and backgrounds. The RCA-8575 photomultiplier coupled to the scintillator had a gain shift of less than 1% for ^{60}Co γ rays for counting rates between 2000 and 42 000 per second. Bipolar pulses 700 nsec wide were used for the linear β-ray pulse-height analysis, and pileup rejection circuitry vetoed events in the scintillator if two pulses larger than 200 keV occurred with a time difference between 30 and 1000 nsec.

The delayed γ-ray spectrum from the ^{18}O + ^{18}O reaction is rich with lines from many *s-d* shell nuclei, providing internal energy calibrations and measures of the relative dead time in each time period. The β spectra coincident with some of these γ rays provide calibration spectra for the β counter.

Several delayed γ-ray transitions in ^{31}Si were seen in the course of this work. Data were taken in three separate runs at different gains and the lines seen in one of these runs are shown in Fig. 2. The half-life of each line is shown also in Fig. 2.

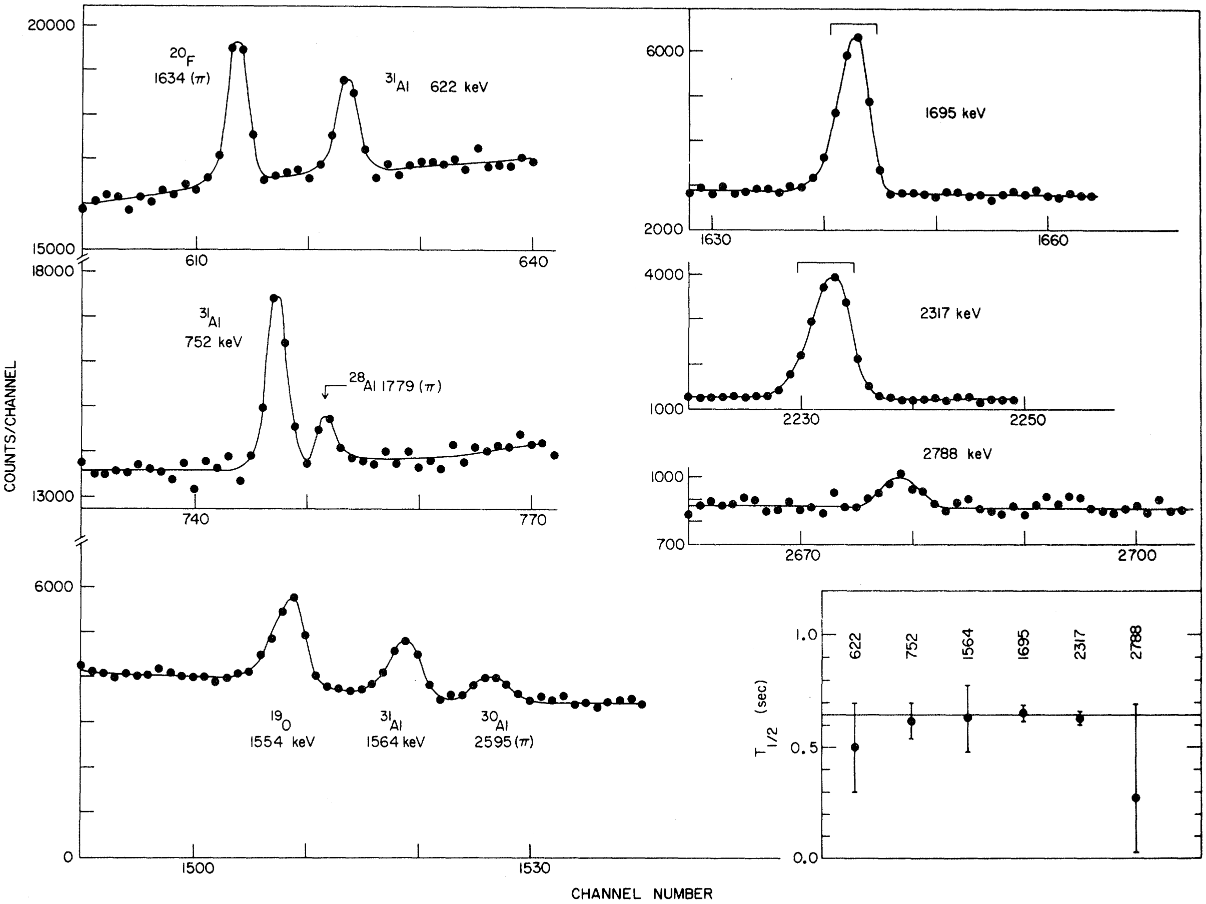

FIG. 2. Selected regions of the delayed γ-ray spectrum from ^{18}O + ^{18}O, showing lines from the decay of ^{31}Al observed in the first 0.6-sec time bin. The dispersion is 1.05 keV per channel. The half-lives observed for these transitions are shown in the inset. Horizontal brackets over the 1695- and 2317-keV peaks show the locations of digital windows used in the coincidence work. The 2787-keV line is not definitely established as being due to the decay of ^{31}Al.

The combined data for the 1695- and 2317-keV lines for all runs was summed to provide the best measure of the ^{31}Al half-life, as shown in Fig. 3. A half-life of 644 ± 25 msec is adopted for ^{31}Al. The assigned uncertainty is larger than the 15-msec uncertainty deduced from a least-squares fit to the data in order to include uncertainties in some possible systematic effects.

γ-ray intensities were extracted from the data by using an absolute efficiency curve for this detector which was determined by counting calibrated sources in a geometry nearly identical to that shown in Fig. 2. Summing effects were considered in constructing this efficiency curve. The ^{31}Al raw data were corrected for summing effects (about 5%) using the measured efficiencies and photofractions for various γ rays. Relative β-ray branching intensities were then calculated, and the results are shown in Table I. Limits on several other γ-ray intensities are also given. Tables II and III compare our results regarding ^{31}Si with those of previous publications. Figure 4 shows our results for the ^{31}Al β decay.

We have deduced a cross section for making the 2317-keV γ ray of 340 ± 150 μb, averaged over bombarding energies between 22 and 41 MeV in the lab.

III. β-RAY SPECTRA AND THE MASS OF ^{31}Al

The spectrum of β rays coincident with the 2317-keV γ ray provides a measure of the mass of ^{31}Al. Since there are no γ rays feeding the 2317-keV level from the β decay of ^{31}Al, the coincidence spectrum of pulses in the scintillator consists only of β rays. However, the spectrum coincident with the 1695-keV photopeak contains β rays feeding the 1695-keV level directly as well as β rays feeding the 2317-keV level and 622-keV γ rays, some of which sum with β-ray pulses. After the appropriate corrections are made the spectrum of β rays feeding the 1695-keV level, denoted β(1695), can be used to provide a second measure of the ^{31}Al mass.

Using a 100-nA beam of the 5$^+$ charge state of ^{18}O the counting rates in the Ge(Li) and NE 102 detectors were 4000 and 30 000 per second, and with a 23-nsec resolving time the real-to-random ratio exceeded 500. The spectra of pulses in the scintillator coincident with the 1057-keV γ ray from ^{20}O decay, denoted as the ^{20}O(1057) line, as well as the ^{34}P(2127), ^{20}F(1633), ^{31}Al(1695), and ^{31}Al(2317) lines, were recorded simultaneously. The ^{20}O and ^{20}F spectra provided calibration data.

TABLE I. β decay of ^{31}Al to levels of ^{31}Si. All information concerning the levels below 3 MeV is from the present work.

^{31}Si level E_x (keV)	I_β (rel)	E_γ (keV)	I_γ (rel)	E_β(max) (MeV)
0				7.94 ± 0.10
752.24 ± 0.30	<3.0	752.23 ± 0.30	18.5 ± 0.8	7.19 ± 0.10
1694.78 ± 0.30	49.0 ± 1.7	1694.73 ± 0.30	58.9 ± 1.6	6.25 ± 0.10
		621.81 ± 0.30	9.94 ± 0.65	
		1564.49 ± 0.30	17.3 ± 1.6	
2316.73 ± 0.40	100.0 ± 2.5	2316.64 ± 0.40	72.8 ± 1.8	5.62 ± 0.10
(2787.7 ± 0.8) [a]	(3.8 ± 1.5) [a]	(2787.6 ± 0.8) [a]	(3.6 ± 1.5) [a]	5.15 ± 0.10
3133.5 ± 0.5 [b]	<3.9	1438.7 ± 0.5	<3.9	4.81 ± 0.10
3534 ± 1 [c]	<1.6	2782 ± 1	<1.5	4.41 ± 0.10
3870 ± 6 [d]		3870 ± 6	<0.83	4.07 ± 0.10
4260 ± 6 [d]		4260 ± 6	<1.1	3.68 ± 0.10
4382.3 ± 0.8 [e]	<1.6	3630 ± 1	<1.2	3.56 ± 0.10
4687 ± 6 [d]		4687 ± 6	<2.2	3.25 ± 0.10
4720 ± 4 [d]		4720 ± 4	<1.5	3.22 ± 0.10
4936 ± 6 [d]		4936 ± 6	<1.8	3.00 ± 0.10
4962 ± 6 [d]		4962 ± 6	<1.8	2.98 ± 0.10
5263 ± 7 [d]		5263 ± 7	<1.4	2.68 ± 0.10

[a] The 2787.6-keV γ ray upon which this information is based is not definitely established as arising from the decay of ^{31}Al.

[b] H. D. Graber, P. W. M. Glaudemans, and P. M. Endt, Nucl. Phys. A149, 1 (1970).

[c] Our average of values quoted in Ref. b and A. M. J. Spits, A. M. F. Op Den Kamp, and H. Gruppelaar, Nucl. Phys. A145, 449 (1970) (see Table II).

[d] P. M. Endt and C. Van Der Leun, Nucl. Phys. A105, 1 (1967).

[e] Spits, Op Den Kamp, and Gruppelaar (see Ref. c).

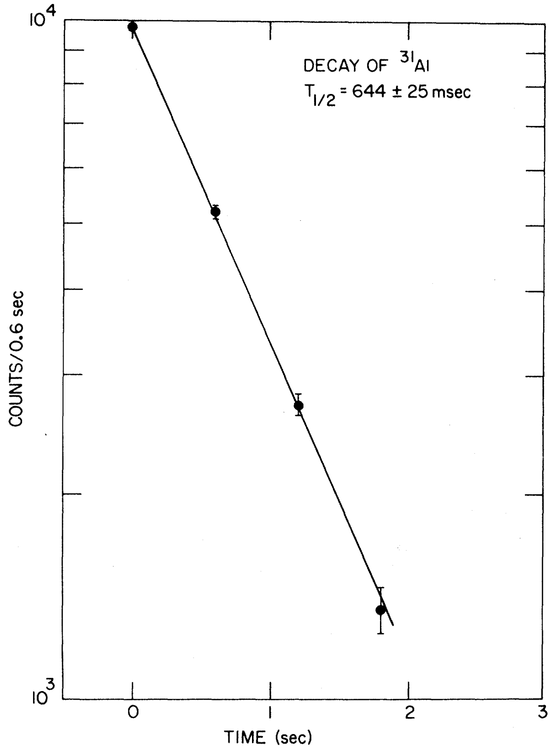

FIG. 3. The decay curve of ^{31}Al, as determined by the sum of the 1695- and 2317-keV photopeak yields, summed over three separate runs.

TABLE II. Comparison of excitation energies in ^{31}Si.

Ref. a E_x (keV)	Ref. b E_x (keV)	Ref. c E_x (keV)	Present work E_x (keV)
752.6 ± 0.2	752.4 ± 0.2		752.24 ± 0.30
1694.9 ± 0.3	(1695.2 ± 0.5)		1694.78 ± 0.30
2317.4 ± 1.0			2316.73 ± 0.40
2790.1 ± 0.8			(2787.7 ± 0.8)
3133.5 ± 0.5			
3534.6 ± 0.8	3533.2 ± 0.5		
		3870 ± 6	
		4260 ± 6	
	(4382.3 ± 0.8)	4383 ± 4	
		4687 ± 6	
		4720 ± 4	
		4936 ± 6	
		4962 ± 6	
		5263 ± 7	

[a] H. D. Graber, P. W. M. Glaudemans, and P. M. Endt, Nucl. Phys. A149, 1 (1970).

[b] A. M. J. Spits, A. M. F. Op Den Kamp, and H. Gruppelaar, Nucl. Phys. A145, 449 (1970).

[c] P. M. Endt and C. Van Der Leun, Nucl. Phys. A105, 1 (1967).

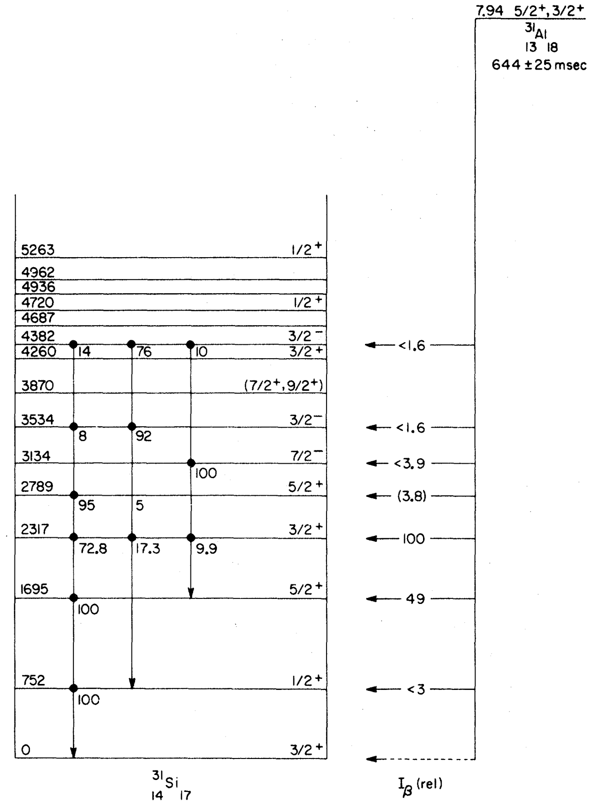

FIG. 4. The decay scheme for ^{31}Al to levels of ^{31}Si. The ground-state β branch has not been measured, but is expected from shell-model calculations to be of comparable strength with the branch to the 2317-keV level. The transition in parentheses to the 2789-keV level has not been definitely established. References for the information presented here may be obtained by comparison with Tables I, II, and III.

TABLE III. Comparison of γ-ray branching ratios in ^{31}Si.

^{31}Si transition (keV)	Ref. a (%)	Ref. b (%)	Ref. c (%)	Present work (%)
752-0	100	100	100	
1695-0	100	96 ± 2	100	
1695-752	<3	4 ± 2	<5	
2317-0	66 ± 3	72 ± 6	80	72.8 ± 1.8
2317-752	20 ± 3	18 ± 6	20	17.3 ± 1.6
2317-1695	14 ± 2	10^{+2}_{-6}	<10	9.94 ± 0.65
2790-0	100	86 ± 5	95 ± 2	
2790-752	<10	<3	5 ± 2	
2790-1695	<10	<3	<4	
2790-2317	<3	14 ± 5	<4	

[a] H. D. Graber, P. W. M. Glaudemans, and P. M. Endt, Nucl. Phys. A149, 1 (1970).

[b] Reference 33.

[c] R. D. Gill, G. P. Littlewood, J. S. Lopes, and H. J. Rose, Nucl. Phys. A114, 416 (1968).

The spectrum of pulses coincident with the 2317-keV photopeak corrected for background is shown in Fig. 5. The solid curve is the experimentally determined shape of the ^{20}F β spectrum, stretched by a factor of 1.040. The fit was effected by a least-squares program, using a height normalization and a stretching factor as free parameters. This shape-fitting procedure is more suitable than fitting spectra to an allowed shape function folded into a resolution function, because firstly there is an excess of low-energy pulses due to scattering and secondly the shape fit uses all the data. The very fortunate proximity between the endpoint energies of the ^{20}F and ^{31}Al(2317) β spectra removes, for all practical purposes, all systematic uncertainties in the determination of the ^{31}Al end-point energy.

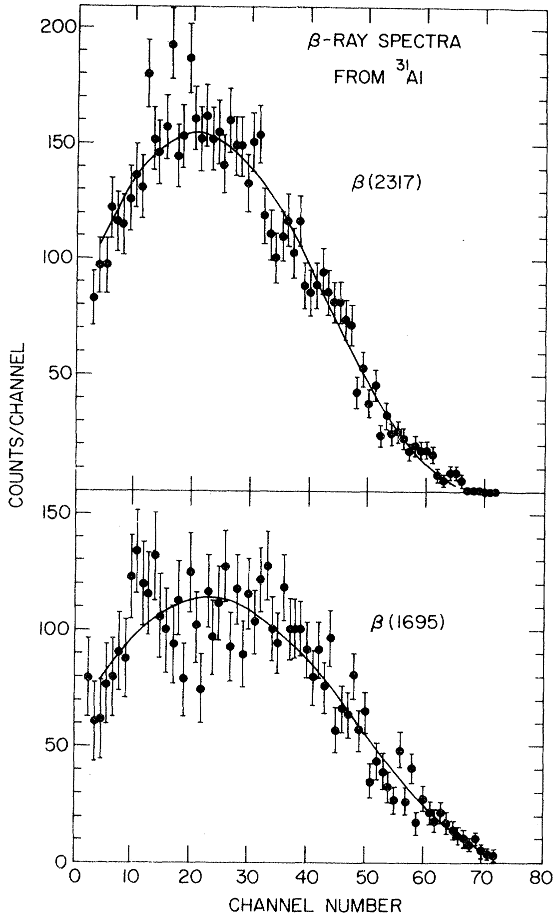

FIG. 5. Spectra of β rays populating the 2317- and 1695-keV levels of ^{31}Si. The solid curves are least-squares fits of the data to a shape determined experimentally from the 5393-keV β spectrum from the decay of ^{20}F. The upper and lower curves represent the ^{20}F β-ray shape stretched horizontally by factors of 1.04 and 1.177, respectively. The normalized χ^2 for these fits are 1.2 and 1.1, respectively. The lower curve has been corrected for summing and other effects as described in the text. The dispersion is about 82 keV/channel. 10 000 cycles of irradiation and counting over a total period of 26 h were used to obtain these spectra.

In order to derive the shape of the β spectrum feeding the 1695-keV level, the β(2317) spectrum shown in Fig. 5 was summed with the Compton-response function for a 622-keV γ ray. The result was multiplied by the appropriate fraction (0.179 ± 0.014) and subtracted from the raw spectrum coincident with the 1695-keV photopeak. From this result was subtracted the small number of events corresponding to the 622-keV γ ray interacting in the scintillator with the coincident β ray missing the scintillator. The resultant spectrum is shown at the bottom of Fig. 5. The solid curve is a shape fit with a stretching factor of 1.177 applied to the ^{20}F β spectrum. The mass excess for ^{31}Al derived from the lower spectrum is more uncertain than that value derived from the upper spectrum, since systematic effects are essentially absent in the latter. The two results agreed well within uncertainties and correspond to a β-ray end-point energy to the ground state of ^{31}Al of 7.94 ± 0.10 MeV. This corresponds to a mass excess for ^{31}Al of −15 008 ± 100 keV.

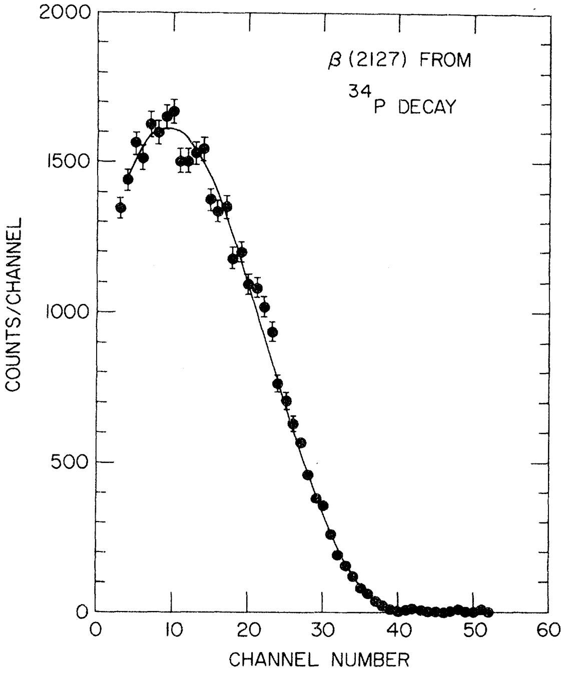

FIG. 6. The spectrum of β rays coincident with the 2127-keV γ ray from the decay of ^{34}P. The solid curve is the experimentally determined shape of the β spectrum from ^{20}O decay, stretched horizontally by a factor of 1.198. χ^2 for this fit is 1.7.

IV. MASS OF ^{34}P

The spectrum of β rays coincident with the 2127-keV γ ray of ^{34}P, corrected for a small background, is shown in Fig. 6. The solid curve is the ^{20}O shape stretched by a factor of 1.198. This result is subject to less statistical uncertainty than the ^{31}Al β(2317) spectrum, but contains more systematic uncertainties. Small uncertainties in electron energy losses in the Be window of the rabbit tubing and zero offset effects have been considered, and we deduce a β-ray end point to the 2127-keV level of ^{34}S of 3252 ± 90 keV. This result using the ^{20}O shape is consistent with the value deduced by compressing the ^{20}F shape to fit the data shown in Fig. 6. The uncertainty in this value due to the possibility of some ^{34}Cl being produced by the irradiation is negligible, since we saw no evidence for several well-known γ rays from the ^{34}Cl decay. There is also no way to make ^{34}Cl with an ^{18}O beam irradiating targets with $Z \leqslant 8$. Our result of 3252 ± 90 keV is to be compared with the values 3200 ± 200 keV reported by Bleuler and Zünti[31] and 2900 ± 200 keV reported by Ward and Kuroda.[32] These authors also reported β-ray end-point energies to the ground state of ^{34}S of 5100 ± 200 keV and 5000 ± 200 keV, respectively. Using our result we calculate a ground-state β-ray end-point energy of 5379 ± 90 keV, and a mass excess for ^{34}P of −24 550 ± 90 keV. This result is 280 keV different from the mass used by Garvey *et al.*,[1] which was determined from the 5100 ± 200 keV ground-state β ray of Ref. 31.

V. DISCUSSION

Webb *et al.*[6,33] have extensively studied electromagnetic transitions in ^{31}Si and have deduced that using a deformation of −2, simple unmixed Nilsson wave functions are able to provide good agreement with excitation energies as well as multipole-mixing ratios and γ-ray branching ratios for states below 3 MeV. The results of Wosniak and Donahue[7] on the lifetimes of these states indicate support for this interpretation. The configurations used by Webb *et al.*[6] are shown in Fig. 7. If ^{31}Al has the same deformation, then this model predicts a spin of $\frac{3}{2}^+$ as shown in Fig. 7. Our results for the β decay necessitate that the spin be $\frac{3}{2}^+$ or $\frac{5}{2}^+$. The unmixed Nilsson model[34] can produce a $\frac{5}{2}^+$ state for ^{31}Al if the deformation is between zero and three, as shown in the dashed inset in Fig. 7. However, this $\frac{5}{2}^+$ state cannot β decay to the assumed ^{31}Si configurations, due to the impossibility of emptying orbit No. 11 and due to the $\Delta K = 2$ change required to populate the ^{31}Si $K = \frac{1}{2}$ members. The decoupling parameters for orbits 6 and 9 are such as to make their band heads have $J = \frac{1}{2}$, and thus there is no way to construct another $J = \frac{5}{2}$ ground state for ^{31}Al in this simple model.

Using the $J = K = \frac{3}{2}$ configuration for ^{31}Al and the ^{31}Si wave functions shown in Fig. 7, we have calculated the relative values of *ft* as predicted by this model.

Recent extensive shell-model calculations by Wildenthal *et al.*[8,9] have had success in describing the β decays of high T_z nuclei. Lanford and Wildenthal[35] have provided us with their unpublished predictions for the ^{31}Al decay. In particular they predict a spin of $\frac{5}{2}^+$ for ^{31}Al, as would the simple shell model. We have taken their predictions combined with our mass and tabulated relative *ft* values, as shown in Table IV. Since we have no measure of the ground-state β branch, we can compare only relative *ft* values. However, with

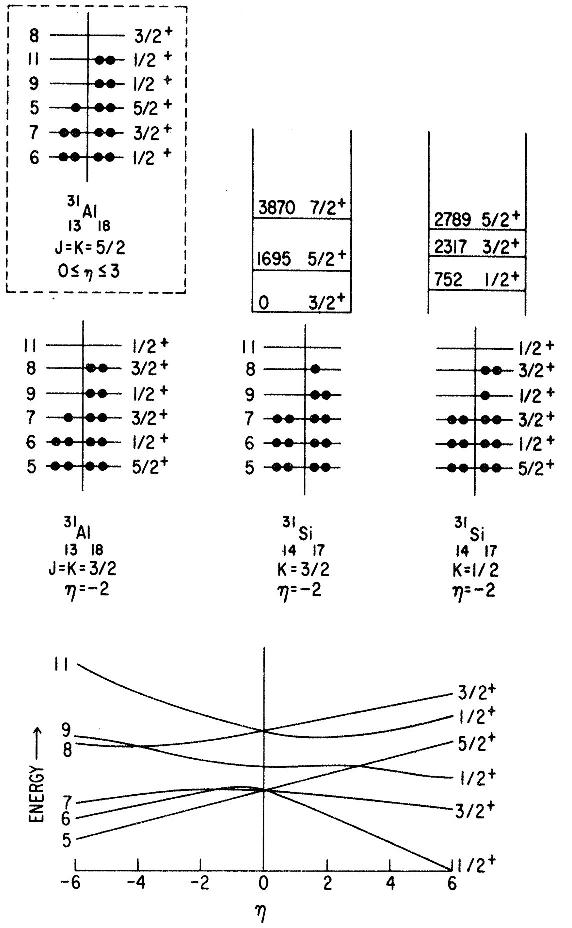

FIG. 7. The collective-model configurations for ^{31}Si levels suggested by Ref. 6, and two hypothetical configurations for the ^{31}Al ground state. The lower curves are labeled with the Nilsson orbit number and $K = \Omega$ quantum numbers as a function of the deformation η. The ^{31}Al configuration in the dashed box cannot decay to the ^{31}Si configurations shown here.

TABLE IV. Comparison of the ^{31}Al β decay with detailed shell-model and simple Nilsson-model calculations.

^{31}Si level (keV)	J^π	K[a]	$ft(2317)/ft$ Collective model ^{31}Al ($J=K=\frac{3}{2}$)	Shell model[b] ^{31}Al ($J^\pi=\frac{5}{2}^+$)	Expt.
0	$\frac{3}{2}^+$	$\frac{3}{2}$	2.84	0.219	...
752	$\frac{1}{2}^+$	$\frac{1}{2}$	1.25	0	<0.01
1695	$\frac{5}{2}^+$	$\frac{3}{2}$	1.90	0.186	0.30 ± 0.013
2317	$\frac{3}{2}^+$	$\frac{1}{2}$	1.00	1.00	1.00
2790	$\frac{5}{2}^+$	$\frac{1}{2}$	0.25	0.144	(0.057 ± 0.024)[c]

[a] Reference 6.
[b] Reference 35.
[c] This value is not definitely established.

our mass and the shell-model predictions for the absolute ft values, we calculate a predicted half-life for ^{31}Al of 0.44 ± 0.05 sec, in reasonable agreement with the measured value of 0.644 ± 0.025 sec. From Table IV we see that the shell-model calculations are in respectable agreement with the measured values, while the simple unmixed collective model bears little resemblance to fact. The collective model ft values to the presumed $K=\frac{1}{2}$ band[6] in ^{31}Si are independent of deformation and depend only upon Clebsch-Gordan coefficients. It may, of course, be possible to obtain agreement with experiment if Coriolis band mixing is employed for ^{31}Al.

VI. PREDICTED AND MEASURED MASSES OF $T_z \geq \frac{5}{2}$ NUCLEI IN THE 2s-1d SHELL

Garvey *et al.*[1] have used simple fundamental assumptions to derive extrapolation formulas for predicting masses of nuclei away from stability. Using recently available masses for some $T_z=2$ nuclei which differed significantly from previous measurements, Thibault and Klapisch[36] have revised some of the original estimates, using the same formalism. Their revision did not include values for masses of nuclei with $Z>13$. Therefore, using our ^{34}P mass as presented in this article and the transverse propagation relation of Garvey

TABLE V. Atomic mass excess $M-A$ of $T_z=\frac{5}{2}$ and $T_z=3$ nuclides in the $2s$-$1d$ shell.

Nucleus	T_z	$M-A$ (MeV) Experiment	Prediction	Difference
^{21}O	$\frac{5}{2}$	$9.3^{+0.3}_{-0.7}$ [a]	8.91 [b]	$+0.4^{+0.3}_{-0.7}$
^{23}F	$\frac{5}{2}$	...	4.00 [b]	...
^{25}Ne	$\frac{5}{2}$	−1.96 ± 0.30 [c]	−1.28 [b]	−0.68 ± 0.30
^{27}Na	$\frac{5}{2}$	(−5.88 ± 0.20) [d]	−5.98 [b]	(+0.1 ± 0.2)
^{29}Mg	$\frac{5}{2}$	(−12.33 ± 0.16) [e]	−11.39 [b]	(−0.94 ± 0.16)
^{31}Al	$\frac{5}{2}$	−15.01 ± 0.10 [f]	−15.56 [b]	+0.55 ± 0.10
^{33}Si	$\frac{5}{2}$	$-20.51^{+0.25}_{-0.20}$ [g]	−20.99 [h]	$+0.48^{+0.25}_{-0.20}$
^{35}P	$\frac{5}{2}$	−24.936 ± 0.075 [i]	−24.78 [h]	−0.156 ± 0.075
^{22}O	3	$11.5^{+0.2}_{-0.5}$ [a]	10.14 [b]	$+1.4^{+0.2}_{-0.5}$
^{28}Na	3	(−1.22 ± 0.30) [d]	−1.55 [b]	(+0.33 ± 0.30)

[a] Reference 18.
[b] Reference 36.
[c] Reference 28.
[d] Reference 21.
[e] Reference 20.
[f] Present work.
[g] Reference 26.
[h] Our predictions, based the t relation of Ref. 1 and our present value for the mass of ^{34}P.
[i] Reference 27.

et al.,[1] we have made revised predictions for the masses of ^{33}Si and ^{35}P. Since the new ^{34}P mass differs from the previous measurements,[31,32] our new estimates for ^{33}Si and ^{35}P differ somewhat from those of Garvey *et al.*[1]

With the exception of ^{23}F there are now measurements, or at least preliminary values, for the masses of all the $T_z = \frac{5}{2}$ nuclides in the $2s$-$1d$ shell, as well as two $T_z = 3$ masses, as is shown in Table V. It is to be emphasized that the masses given for ^{27}Na, ^{28}Na, and ^{29}Mg are only preliminary values. Nevertheless, it is interesting to note that for the $T_z = \frac{5}{2}$ series, the rms value of the difference column is about 0.5 MeV, while the average deviation is nearly zero.

Note added in proof: We have also produced ^{31}Al in the ^{15}N(^{18}O, $2p$)^{31}Al reaction by bombarding a thick Zr^{15}N target with 41-MeV ^{18}O ions. However, the yield was low and only the strongest ^{31}Al γ-ray line at 2317 keV could be observed in the Ge(Li) spectrum above the background of other activities. Further studies of ^{31}Al using this reaction were discontinued. C. N. Davids participated in these experiments including the preparation of targets.

---

†Work performed under the auspices of the U. S. Atomic Energy Commisssion.

[1] G. T. Garvey, W. J. Gerace, R. L. Jaffe, I. Talmi, and I. Kelson, Rev. Mod. Phys. Suppl. 41, S1 (1969).

[2] A. E. Litherland, H. McManus, E. B. Paul, D. A. Bromley, and H. E. Gove, Can. J. Phys. 36, 378 (1958).

[3] G. R. Bishop, Nucl. Phys. 14, 376 (1959).

[4] K. H. Bhatt, Nucl. Phys. 39, 375 (1962).

[5] G. C. Morrison, D. H. Youngblood, R. C. Bearse, and R. E. Segel, Phys. Rev. 174, 1366 (1968).

[6] V. H. Webb, N. R. Robertson, and D. R. Tilley, Phys. Rev. 170, 989 (1968).

[7] M. J. Wosniak, Jr., and D. J. Donahue, Phys. Rev. C 1, 601 (1970).

[8] B. H. Wildenthal, E. C. Halbert, J. B. McGrory, and T. T. S. Kuo, Phys. Rev. C 4, 1266 (1971).

[9] B. H. Wildenthal, J. B. McGrory, E. C. Halbert, and H. D. Graber, Phys. Rev. C 4, 1708 (1971).

[10] W. A. Lanford and B. H. Wildenthal, Phys. Rev. C 7, 668 (1973).

[11] A. M. Poskanzer, S. W. Cosper, E. K. Hyde, and J. Cerny, Phys. Rev. Letters 17, 1271 (1966).

[12] A. M. Poskanzer, G. W. Butler, E. K. Hyde, J. Cerny, D. A. Landis, and F. S. Goulding, Phys. Letters 27B, 414 (1968).

[13] T. D. Thomas, G. M. Raisbeck, P. Boerstling, G. T. Garvey, and R. P. Lynch, Phys. Letters 27B, 504 (1968).

[14] R. Klapisch, C. Thibault-Philippe, C. Détraz, J. Chaumont, R. Bernas, and E. Beck, Phys. Rev. Letters 23, 652 (1969).

[15] R. Klapisch, C. Thibault, A. M. Poskanzer, R. Prieels, C. Rigaud, and E. Roeckl, Phys. Rev. Letters 29, 1254 (1972).

[16] A. G. Artukh, V. V. Avdeichikov, L. P. Chelnokov, G. F. Gridnev, V. L. Mikheev, V. I. Vakatov, V. V. Volkov, and J. Wilczynski, Phys. Letters 32B, 43 (1970).

[17] A. G. Artukh, V. V. Avdeichikov, G. F. Gridnev, V. L. Mikheev, V. V. Volkov, and J. Wilczynski, Nucl. Phys. A176, 284 (1971).

[18] A. G. Artukh, G. F. Gridnev, V. L. Mikheev, V. V. Volkov, and J. Wilczynski, Nucl. Phys. A192, 170 (1972).

[19] H. H. Howard, R. H. Stokes, and B. H. Erkkila, Phys. Rev. Letters 27, 1086 (1971).

[20] D. K. Scott, C. U. Cardinal, P. S. Fisher, P. Hudson, and N. Anyas-Weiss, in Proceedings of the Fourth International Conference on Atomic Masses and Fundamental Constants, 1971 (to be published).

[21] R. Klapisch, private communication to J. Cerny.

[22] F. Ajzenberg-Selove and G. Igo, Phys. Rev. 188, 1813 (1969).

[23] R. H. Stokes and P. G. Young, Phys. Rev. 178, 1789 (1969).

[24] G. C. Ball, W. G. Davies, J. S. Forester, and J. C. Hardy, Phys. Rev. Letters 28, 1069 (1972).

[25] A. P. Kabachenko, I. V. Kuznetsov, K. Sivek-Vilchinka, E. A. Skakun, and N. I. Tarantin, Joint Institute for Nuclear Science, Dubna Report No. D7-5769, 1971 (unpublished), p. 204.

[26] D. R. Goosman and D. E. Alburger, Phys. Rev. C 6, 825 (1972); 5, 1252 (1972).

[27] D. R. Goosman and D. E. Alburger, Phys. Rev. C 6, 820 (1972).

[28] D. R. Goosman, D. E. Alburger, and J. C. Hardy, Phys. Rev. C 7, 1133 (1973).

[29] W. Grimm and W. Herzog, Z. Naturforsch. 26a, 1933 (1971).

[30] K. W. Apt and J. D. Knight, Phys. Rev. C 6, 842 (1972).

[31] E. Bleuler and W. Zünti, Helv. Phys. Acta 19, 137 (1946).

[32] T. Ward and P. Kuroda, J. Inorg. Nucl. Chem. 33, 609 (1971).

[33] V. H. Webb, N. R. Roberson, R. V. Poore, and D. R. Tilley, Phys. Rev. 170, 979 (1968).

[34] S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. 29, No. 16 (1955).

[35] W. A. Lanford and B. H. Wildenthal, private communication.

[36] C. Thibault and R. Klapisch, Phys. Rev. C 6, 1509 (1972).