found to follow the formula $(\Delta H_2^2)_{\text{exp}} = (\Delta H_2^2)_{\text{true}} + \frac{1}{3}Hm^2$, exactly as determined above. Thus, the experimentally measured value of the second moment is always larger than the true value.

In the Van Vleck[2] formula for the second moment the internuclear distances appear to the inverse sixth power. Thus, an error of 10–20 percent in the determination of the second moment results in an error of only 1–3 percent in the evaluation of the internuclear parameters. A further check on Eq. (7), however, is provided by an analysis of the compound KH_2PO_4, where the calculated second moment (assuming that the hydrogens lay midway along the O–H–O bond, and taking an O–H–O bond distance of 2.54A as determined from Raman spectra experiments) of the proton resonance is 3.3 gauss.[2] The average uncorrected experimental second moment on the basis of 6 runs at $-183°$C was found to be 4.8 ± 0.4 gauss^2 (an error of $\sim$45 percent). A modulation amplitude of 2 gauss was used, thus yielding a corrected second moment of 3.5 ± 0.4 gauss^2 in agreement with the calculated result.

[2] J. H. Van Vleck, Phys. Rev. 74, 1168 (1948).

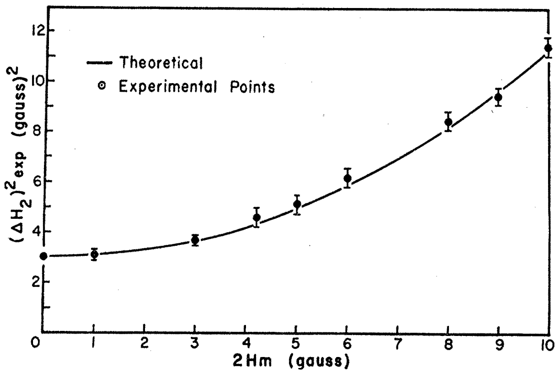

FIG. 1. The experimental modulation correction.

The experimentally observed line is the derivative of the true absorption line. When the modulation amplitude becomes nearly equal to the line width, small amounts of higher odd order derivatives are admixed. However, these effects are small, and a reasonably faithful first derivative may be obtained even in this region. In any case, the correction has been found to hold when the amplitude approaches the line width.

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Energy Levels in Light Nuclei*

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Targets of beryllium, Nylon, lead fluoride, sulfur, and lead sulfide were bombarded with 8-Mev protons from the University of Pittsburgh cyclotron. Energy levels were observed in Be^9, C^{12}, N^{14}, O^{16}, F^{19}, and S^{32} by inelastic scattering at 150° from thin targets. Single levels were assigned in Be^9 and C^{12}; two levels were assigned in N^{14}; nine levels were assigned in F^{19}; and seven levels were assigned in S^{32}.

I. INTRODUCTION

THE present investigation was undertaken to look for additional low-lying levels in some light nuclei. Similar work has been done at this laboratory by Ely *et al.*,[1] Reilley *et al.*,[2] and Hausman *et al.*[3] The 8-Mev proton beam from the University of Pittsburgh cyclotron was used to bombard targets of beryllium, Nylon, fluorine, and sulfur. The incident and reaction particle momenta were analyzed magnetically. Inelastic scattering was used to determine energy levels in Be^9, C^{12}, N^{14}, O^{16}, F^{19}, and S^{32}.

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[1] Ely, Allen, Arthur, Bender, Hausman, and Reilley, Phys. Rev. 86, 859 (1952).
[2] Reilley, Allen, Arthur, Bender, Ely, and Hausman, Phys. Rev. 86, 857 (1952).
[3] Hausman, Allen, Arthur, Bender, and McDole, following paper [Phys. Rev. 88, 1296 (1952)].

II. APPARATUS

The apparatus used is essentially the same as that described previously.[4,5] It was modified by placing the detector inside the vacuum system to permit the observation of lower energy scattered particles. The target holder was remodeled to provide a means for calibration of the reaction particle analyzer without losing the vacuum.

A beam of 8-Mev protons from the cyclotron was focused by a sector magnet into a shielded scattering room. Within the scattering room the incident beam was analyzed magnetically by a 40° sector magnet and the spread in energy adjusted by appropriate slits. Charged reaction particles were momentum analyzed by a 60° sector magnet and detected by a scintillation counter using a ZnS crystal. Both analyzing magnets were calibrated with polonium alpha-particles using

[4] Bender, Reilley, Allen, Ely, Arthur, and Hausman, Rev. Sci. Instr. 23, 542 (1952).
[5] University of Pittsburgh Radiation Laboratory Precision Scattering Report No. 2, May (1952) (unpublished).

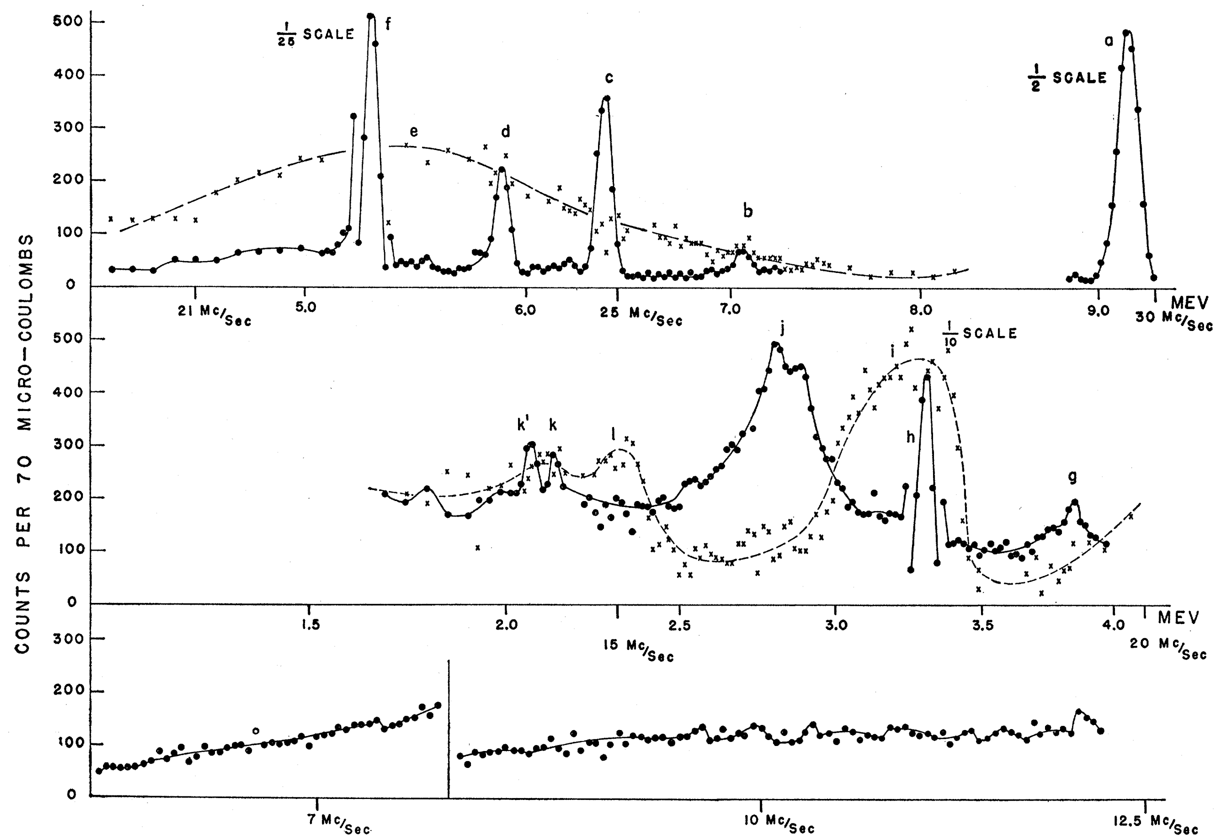

FIG. 1. Spectrum of charged particles scattered from beryllium at 150°.

$H\rho = 3.3159\times 10^5$ gauss-cm[6]. Magnetic field strength measurements were made with proton resonance detectors. The analyzing magnets were carefully demagnetized before each run. The incident beam current was integrated to 70 microcoulombs (30 microcoulombs for one S^{32} bombardment) for each setting of the magnet which analyzed the scattered particles. The spread in incident energy was 0.04 Mev during the experiment with the beam incident perpendicularly on the target. At least two bombardments of each element were made using different targets where possible.

III. EXPERIMENTAL PROCEDURE AND DISCUSSION

A. Be^9+Proton

Beryllium targets of 0.2 mg/cm² and 0.3 mg/cm² were bombarded with protons and the reaction particles studied at 150° with respect to the incident beam. Figure 1 shows a plot of the number of counts per 70 microcoulombs of charge collected *vs* proton resonance frequency in Mc/sec at which reaction particles were detected. Peaks *b*, *c*, *d*, and *f* are due to elastic scattering from Al^{27}, O^{16}, C^{12}, and Be^9. Peak *h* is from the known excited level in Be^9 at 2.4 Mev. The average value of excitation energy obtained for this level from two runs is 2.44 Mev, which is to be compared with the values of 2.422±0.005 Mev determined by Van Patter *et al.*[6] and 2.433±0.005 Mev determined by Browne *et al.*[7] No new levels were found in Be^9 for an excitation energy of 6 Mev.

Peaks *a*, *e*, *g*, and *j* have been identified as deuterons from the reaction $Be^9(p,d)Be^8$ corresponding to the ground state and energy levels in Be^8 at 2.8, 4.0, and 5.1 Mev, respectively.

Peaks *i* and *l* are alpha-groups from the $Be^9(p,\alpha)Li^6$ reaction corresponding to the ground state and excited levels in Li^6 at 2.1 Mev (for a bibliography see Hornyak *et al.*,[8] hereafter referred to as HFML). The peaks *k* and k^1 are attributed to inelastic protons from the 4.4-Mev level in C^{12} which appears as a surface contaminant on the front and back of the target.

Peaks *e*, *i*, and *l* were obtained by subtraction of the readings taken with a foil in front of the detector from readings taken without a foil.

B. Nylon+Proton

Nylon targets of surface density 0.50 mg/cm² were bombarded by 8-Mev protons. The reaction particles

[6] Van Patter, Sperduto, Huang, Strait, and Buechner, Phys. Rev. **81**, 233 (1951).
[7] Browne, Williamson, Craig, and Donahue, Phys. Rev. **83**, 179 (1951).
[8] Hornyak, Lauritsen, Morrison, and Fowler, Revs. Modern Phys. **22**, 309 (1950).

were analyzed at 90° and 150°. Peaks a, b, c_1, and c of Fig. 2 are elastically scattered protons from O^{16}, N^{14}, C^{13}, and C^{12}, respectively. Peak f is the only excited state obtained in C^{12} for an excitation energy of 6.5 Mev. An excitation energy of 4.45 Mev was determined for this level. This is an average value obtained from four Nylon bombardments and nine other bombardments where carbon was a surface contaminant. The width of the peak is thought to be caused mainly by target thickness. A fresh target was used for the data yielding peak f Fig. 2 in an attempt to reduce the probability of target deterioration causing a widening of the peak. Many previous investigations of C^{12} have been made (see HFML, p. 325). The most accurately known value for this energy level is 4.438±0.014 Mev obtained by magnetic analysis.[8]

Three levels and possibly a fourth were found in N^{14} from the reaction $N^{14}(p,p')N^{14*}$. Peaks d, e, and g of Fig. 2 correspond to energy levels of 2.32, 3.96, 5.09 Mev. If e_1 were a peak in N^{14} the value of the energy level would be 3.76 Mev. Since a C^{13} elastic peak was observed it is possible that it is an energy level of this isotope.|| Its excitation energy in C^{13} would be 3.69 Mev. A level in C^{13} is known to exist at 3.677±0.005 Mev.[8] Previous investigations on N^{14} energy levels were made by Thomas and Lauritsen[9] giving values of 1.643±0.004, 2.318±0.008, 3.390±0.010, 3.9?, 5.056±0.025 Mev; by Burrows *et al.*[10] giving values of 3.95 and 5.06 Mev; and by Heydenburg *et al.*[11] giving levels at 2.35 and 3.95 Mev. Thomas and Lauritsen observed gamma-rays resulting from bombarding an enriched C^{13} target with deuterons. The gamma-ray energies which they assigned as energy levels in N^{14} at 1.6 Mev and 3.4 Mev have since beeen attributed to cascading gamma-rays (private communication with T. Lauritsen).

Peaks h and i are assigned to the oxygen doublet at 6.0 and 6.1 Mev. The best information about the doublet which can be calculated from the Nylon, PbS, and PbF_2 data (oxygen appeared as a contaminant on the last two targets) is a value of 0.087±0.010 Mev for the doublet separation. Previous measurements of these levels and their separation have been made by Chao *et al.*[12] They give values of 6.052, 6.136, and 0.084±0.006 Mev for the energy levels of the two peaks and their separation, respectively. Several other measurements of these levels have been made (see HFML, p. 343).

C. F^{19}+Proton

A target of PbF_2(1.20 mg/cm²) was evaporated on a gold backing. With 8-Mev protons incident on the

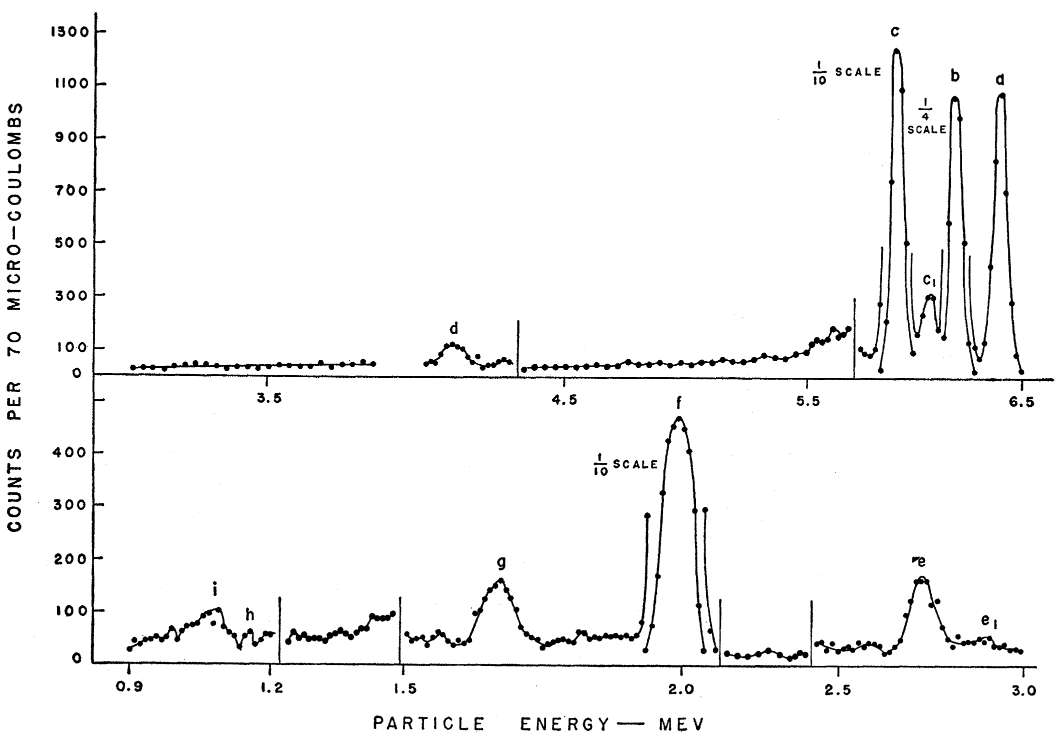

FIG. 2. Spectrum of charged particles scattered from Nylon at 150°.

|| *Note added in proof:* Further work indicates that this level is from C^{13}.
[9] R. G. Thomas and T. Lauritsen, Phys. Rev. **78**, 88 (1950).
[10] Burrows, Powell, and Rotblat, Proc. Roy. Soc. **A209**, 478 (1951).
[11] Heydenburg, Phillips, and Cowie, Phys. Rev. **85**, 742 (1952).
[12] Chao, Tollestrup, Fowler, and Lauritsen, Phys. Rev. **79**, 108 1950).

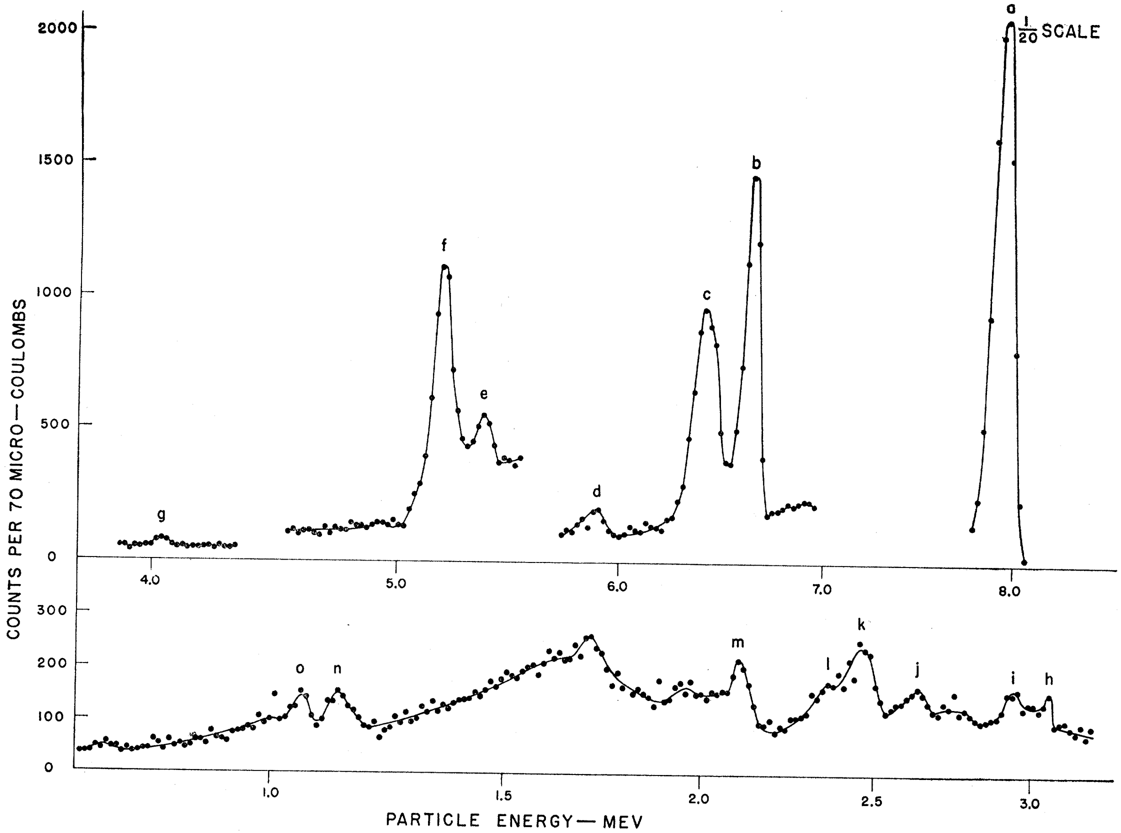

FIG. 3. Spectrum of charged particles scattered from fluorine at 150°.

target protons from the reaction $F^{19}(p,p')F^{19*}$ were observed at 150°. Figure 3 shows sections of each of two bombardments. Peak a is a group of protons elastically scattered from lead and gold. Peaks b, c, and d are the elastic peaks of F^{19}, O^{16}, and C^{12}, respectively. Peaks e, f, g, h, i, j, j_1, k, and l correspond to energy levels in F^{19} at 1.37, 1.59, 2.82, 3.94, 4.06, 4.41, 4.48, 4.59, and 4.76. Peak j_1 is not shown as a peak in Fig. 3. Peak m is the excited state in C^{12} at 4.4 Mev. Peaks n and o are the 6.0- and 6.1-Mev levels in O^{16}. No other levels of comparable intensity were observed for an excitation energy of 6.7 Mev. There were indications of seven other possible energy levels: one each at 4 and 4.3, three near 4.6, and two near 4.8 Mev, each of which reproduced on the two bombardments. A bibliography of previous investigations of energy levels of F^{19} is given by HFML, p. 353. Recently, Bullock and Sampson[13] found energy levels at 1.36±0.05, 2.76 ±0.05, 3.92±0.05 Mev; Heydenburg, Phillips, and Cowie[12] found levels at 1.53, 3.83 Mev, and Shull[14] found a level at 1.52 Mev. No attempt was made to study the reaction $F^{19}(p,\alpha)O^{16*}$. The spectrum shown in Fig. 3 is taken with the alpha-groups removed by placing aluminum foils in front of the detector. A broad peak appears between 1 and 2 Mev. This is a proton group which appeared on a bombardment of the gold backing made under similar conditions. It is thought to be due to (p,p') reactions in copper or silver known to exist in the gold in quantities less than 0.2 percent. All peaks shown in Fig. 3 were observed on two bombardments of the same target; however, the values above were calculated from the second run only.

D. S^{32}+Proton

The $S^{32}(p,p')S^{32}$ reaction was studied by bombarding targets of lead sulfide and sulfur on gold. A spectrum of the reaction particles in the 150° direction obtained by bombarding S^{32} with 8-Mev protons is shown in Fig. 4. a, b, and c are the elastic peaks of Au^{197}, S^{32}, and O^{16}, respectively. Peaks e, f, g, h, i, j, and n are assigned to excited levels in S^{32} at 2.25, 3.81, 4.32, 4.50, 4.74, 5.04, and 5.83 Mev, respectively. Peaks k and l are attributed to the 4.4-Mev level in C^{12} and result from carbon contaminants on the target surfaces. Four peaks (d, d_1, m, and o) were not used for calculations. In previous studies of S^{32} (see Alburger and Hafner[15]) excited levels were observed at 2.25 and 4.34 Mev.

[13] M. L. Bullock and M. B. Sampson, Phys. Rev. 84, 967 (1951).
[14] F. B. Shull, Phys. Rev. 83, 875 (1951).
[15] D. E. Alburger and E. M. Hafner, Revs. Modern Phys. 22, 379 (1950).

IV. RESULTS AND ERRORS

Table I is a list of the elements studied and the energy levels obtained. In all (p,p') reactions, except F^{19}, where three figures are quoted an estimate of the probable error is 0.02 Mev (for F^{19} the estimated probable error is 0.03 Mev). The primary contribution to this probable error is due to an uncertianty in the calibration of the magnetic field strength of the reaction particle analyzer. This uncertainty arises from a nonlinearity between the ratio of the measured field strength to the fringing field strength and the measured field strength and also from hysteresis effects. There are indications, in general, that the levels are higher than previously published values of the same levels where the accuracy quoted is of the order of 0.01 Mev.

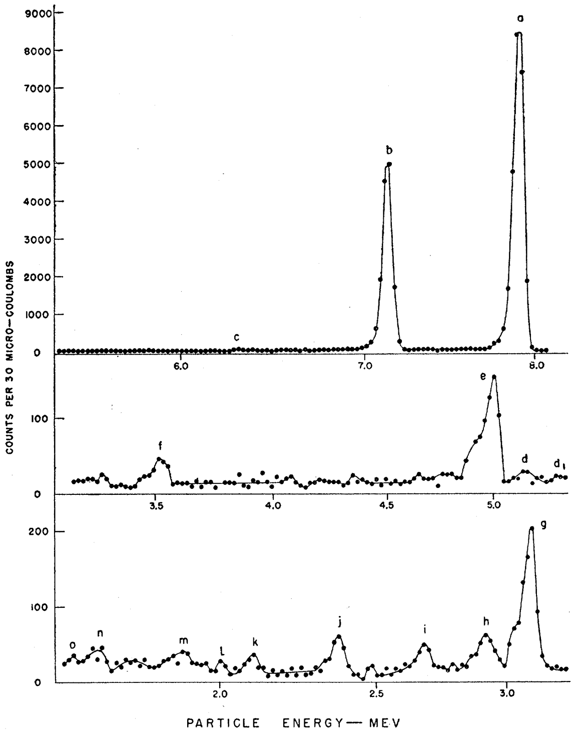

FIG. 4. Spectrum of charged particles scattered from sulfur at 150°.

TABLE I. Energy levels in Be^9, N^{14}, O^{16}, F^{19}, and S^{32}.

Element	Energy level (Mev)	Doublet separation (Mev)
Be^9	2.44	
C^{12}	4.45	
N^{14}	2.32	
	3.76?	
	3.96	
	5.09	
O^{16}	6.0	0.087
	6.1	
F^{19}	1.37	
	1.59	
	2.82	
	3.94	
	4.06	
	4.41	
	4.48	
	4.59	
	4.76	
S^{32}	2.25	
	3.81	
	4.32	
	4.50	
	4.74	
	5.04	
	5.83	

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