Gross Structure and 1d-Shell Nuclei

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The available high-resolution data for (1d,2s)-shell nuclei suggest that the requirements necessary for valid interpretation of gross-structure measurements are not met. As specific examples the data for Mg^{27}, Al^{28}, P^{32}, and S^{33} are discussed. There is also limited evidence of similar difficulties in the 1f shell.

THE interest in recent years in the measurement of gross-structure properties of nuclei[1] results from the success of the shell model in describing low-lying energy levels in terms of configurations of individual nucleons moving in a potential due to the rest of the nucleus. The "single-particle" states in the residual nucleus are those states well described as the target nucleus in its ground state plus a single excited nucleon and these states should be strongly excited in, for example, a deuteron stripping reaction. The probability of such excitation is measured by the "reduced width." It is well known, however, that because of nucleon interactions the single particle character[2] is spread over many levels. In the interpretation of gross structure measurements[1,2] it is assumed that while the single-particle reduced widths are spread over a band of levels, the spreading is not large compared to the spacing between the single-particle levels. Such measurements, therefore, are done with poor energy resolution in order to integrate over the many levels and thus pick out the single particle states. Since with poor resolution the measurements can be done in much less time than with high resolution, it in principle becomes possible to make a rapid systematic study of nuclei throughout the periodic table and determine energy differences between the single-particle states. Measurements of the angular distributions of the proton groups in a (d, p) reaction presumably permit assignment of the l values of the captured neutron, and it has also been suggested that measurements of the polarization of the protons, and angular correlations of the gamma-ray cascades from the gross structure peaks would permit the unambiguous determination of the j value associated with a given group.

It has been pointed out[1] that complications would arise in the interpretation of the gross structure measurements when the nuclei are strongly deformed and that an unambiguous interpretation can be made only for those nuclei possessing nearly spherical symmetry. Even for spherical nuclei, however, the short-range nucleon-nucleon interactions may spread the single-particle reduced widths over an energy interval large compared to the single-particle spacing. The interpretation of the measurements is further complicated, as French and Macfarlane have recently emphasized,[3] by the fact that the angular distributions obtained for gross structure groups and in fact for some single levels do not always provide clear cut assignments of the l value. The difficulty in the interpretation of single-level angular distributions has been essentially removed as a result of the improved understanding of distorted wave effects in stripping reactions.[4]

There is considerable evidence now at hand that many nuclei in the first d shell are significantly deformed. In a deformed nucleus the single-particle $(2j+1)$-fold degeneracy is reduced to a twofold degeneracy in proton and neutron occupation, and results in an energy level sequence such as that given by Nilsson.[5] In the Nilsson sequence certain levels which grow out of different intrinsic or single-particle configurations merge as the deformation increases, and in fact can cross when the deformation becomes sufficiently large. As specific examples in the (1d,2s) shell the $\Omega=5/2^+$ level from the $d_{5/2}$ configuration approaches and crosses the $\Omega=1/2^+$ level of the $s_{1/2}$ configuration for deformations of $\eta\simeq+3$, and the $\Omega=1/2^-$ level of the $f_{7/2}$ configuration crosses the $\Omega=3/2^+$ level of the $d_{3/2}$ configuration for values $\eta\simeq+5$. Further, examination of the c_j (the coefficients which give the single-particle wave function for the deformed nucleus in terms of spherical shell-model wave functions) indicates that as the deformation increases the coefficients for values of j other than that of the parent orbit increase while the c_j for the parent orbit decreases. As a result members of a rotational band of given $K=\Omega$ occasionally have a larger reduced width than the state with $I=j$ of the parent. In addition, because of rotation-particle coupling, there is an interaction between levels of the same total spin I belonging to bands for which K differs by unity. This interaction can shift levels by as much as one to two Mev. All of these factors taken together indicate that it should not be surprising to find strong even-parity levels lying close to strong odd-parity levels, and to

[1] G. R. Satchler, *Comptes Rendus du Congrès International de Physique Nucléaire; Interactions Nucléaires aux Basses Energies et Structure des Noyaux, Paris, 1958* (Dunod, Paris, 1959), p. 101, and references therein. J. P. Schiffer, L. L. Lee, Jr., and B. Zeidman, Phys. Rev. **115**, 427 (1959); J. P. Schiffer, *Proceedings of the International Congress on Nuclear Structure, Kingston* (University of Toronto Press, Toronto, 1960), Sec. 7.2.

[2] A. M. Lane, R. G. Thomas, and E. P. Wigner, Phys. Rev. **98**, 693 (1955).

[3] J. B. French and M. H. Macfarlane, Bull. Am. Phys. Soc. **6**, 314 (1961).

[4] W. Tobocman and M. H. Kalos, Phys. Rev. **97**, 132 (1955); R. Huby, M. Y. Refai, and G. R. Satchler, Nuclear Phys. **9**, 94 (1958); G. R. Satchler (private communication).

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

find the spacing between such levels to be quite different from the spacing of the intrinsic levels. In certain cases, therefore, the characteristics of gross structure remain, but the interpretation would be erroneous.

High-resolution data are now available for a number of $(1d,2s)$-shell nuclei,[6,7] the individual levels having been examined up to 5 Mev or more excitation and reduced widths obtained for those levels which show characteristic stripping patterns. It is of interest therefore to compare the results obtained from the high and the low resolution data.[8] Several high-resolution spectra have been integrated to produce "poor" resolution spectra; in all cases the characteristic gross-structure features become evident. The results obtained for Mg^{27}, Al^{28}, P^{32}, and S^{33} are shown in Fig. 1. The integrated spectra were obtained from the high resolution data by converting each individual level to a Gaussian of 400-kev half-width and of area proportional to the intensity, and then summing the contributions of all individual levels. The levels which contribute significantly to the gross peaks are indicated by vertical lines in Fig. 1, the heights of which are proportional to the intensities of the levels. The l value for each is indicated along the abscissa. In obtaining these spectra the contributions due to the target contaminants, primarily oxygen and carbon, have been removed. It should be noted that in actual gross structure measurements with isotopically enriched targets the contribution of con-

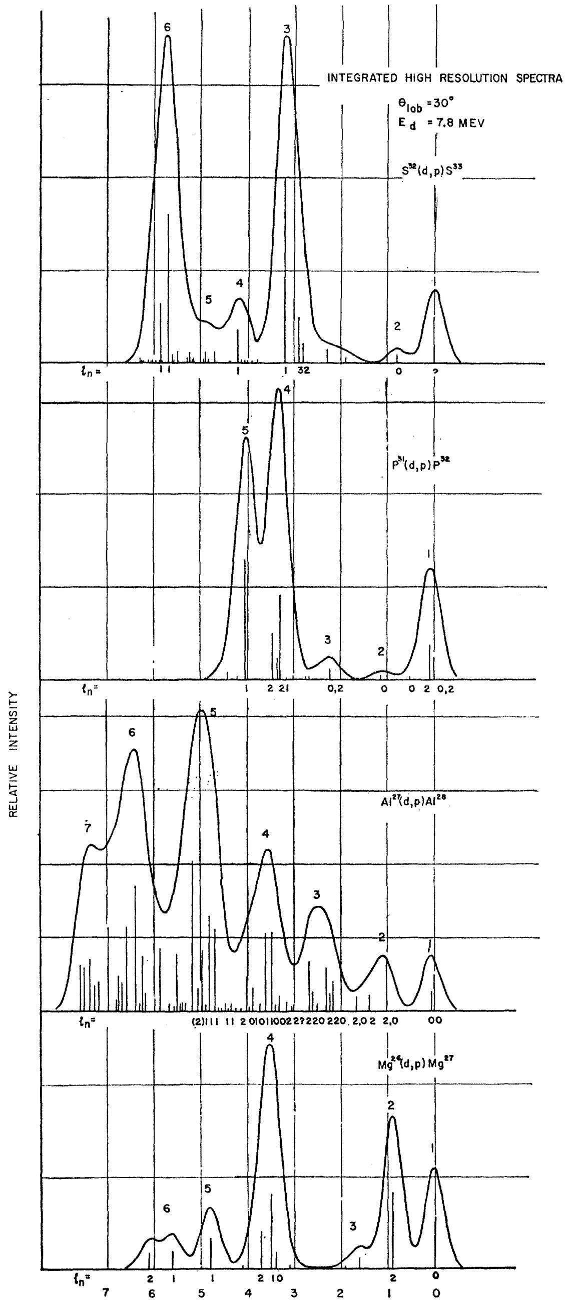

FIG. 1. Gross-structure spectra obtained by integration of high-resolution data. Those levels which contribute significantly to the gross peaks are indicated by vertical lines, the heights of which are proportional to the intensities of the levels. The l_n values, when known, are indicated along the abscissa.

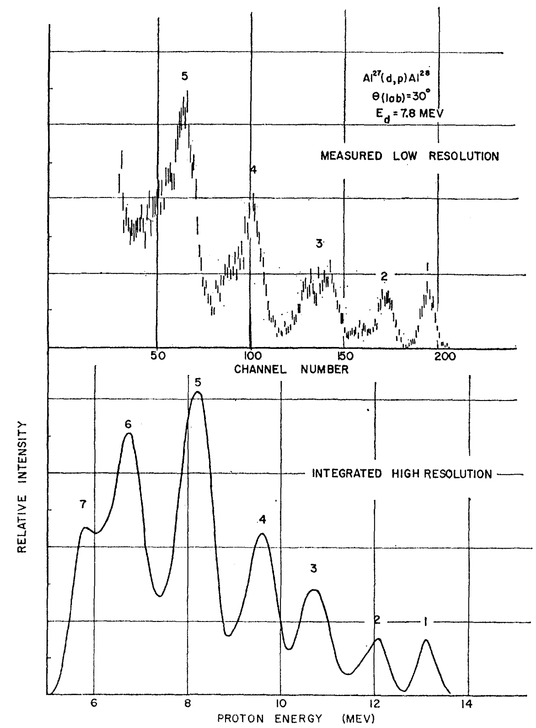

FIG. 2. Comparison of the measured low-resolution and integrated high-resolution spectra. The abscissa "channel number" is not linear in energy.

[6] M. H. Macfarlane and J. B. French, Revs. Modern Phys. **32**, 567 (1960).

[7] Papers KA1 through KA6, Bull. Am. Phys. Soc. **6**, 259 (1961).

[8] A preliminary report of this work is given in the Proceedings of the Manchester Conference, 1961, paper C5/39. Proceedings of the Rutherford Jubilee International Conference. Edited by J. B. Birks (Heywood and Company, London, 1962).

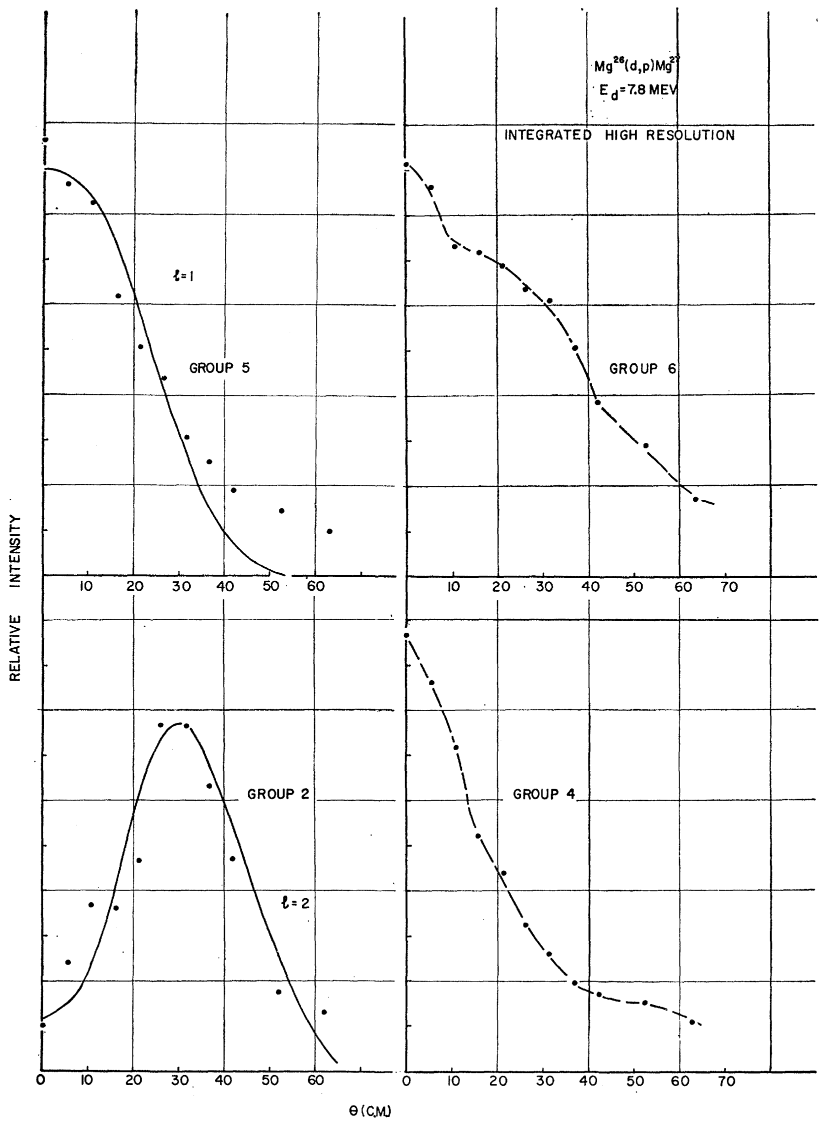

FIG. 3. Angular distributions obtained from the integrated high resolution spectra of Mg^{27}.

taminants cannot be easily removed and this fact complicates the reduction of the data. The problem does not arise for Al^{28} however since Al^{27} has 100% natural abundance and can be obtained with high purity. The results obtained for Al^{28} by integration and by actual measurement are compared in Fig. 2. The measurements were made using as a detector a single crystal of gold-doped silicon, the characteristics of which are described elsewhere.[9] The "poor" resolution of approximately 350 kev was obtained by using a thick aluminum target and by placing lead foils in front of the detector to remove from the scattered beam all particles other than protons. For this reason the abscissa for the measured data in Fig. 2 is not linear in energy.

[9] W. C. Parkinson and O. M. Bilaniuk, Rev. Sci. Instr. 32, 1136 (1961).

The angular distributions obtained for a number of the gross structure peaks are shown in Figs. 3 through 6 for Mg^{27}, Al^{28}, P^{32}, and S^{33}, respectively, and are identified by the numbers 1, 2, 3, $\cdots$, at the top of each peak in Fig. 1. For Mg^{27} the angular distributions of groups 1, 2, 3, would be expected to be, and are, fit by single Butler distributions. Groups 4 and 6, however, as indicated by the high-resolution data, are composites of $l=0$, 1, 2, and $l=1$, 2, respectively. The angular distributions obtained for groups 2, 4, 5, and 6 are shown in Fig. 3. The solid lines (groups 2 and 5) are the calculated Butler curves for the l values shown. It is probable that group 4 in a gross structure measurement would be interpreted as either $l=0$ or $l=1$ and group 6 as $l=1$. Table I gives the l values determined for each level in Mg^{27} together with their relative reduced widths. The ground and first excited states

TABLE I. Energy levels, l values, and relative reduced widths in the reaction $Mg^{26}(d,p)Mg^{27}$.

Level (excitation in Mev)	l_n	$[J]\theta^2$
0	0	10.7
0.982	2	9.8
1.692	2	6.0
1.936	...	...
3.109	...	...
3.423	...	...
3.470 3.485	0	10.0
3.556	1	14.4
3.757 3.782	2(0)	13.0
3.880	...	...
4.146	2(?)	1.3
4.394	...	...
4.549	...	...
4.763	...	...
4.816	1	4.7
4.982	...	...
5.016	1	0.3
5.292	...	...
5.365	...	...
5.405	...	...
5.618	3?	27
5.742 5.762	...	...
5.817	...	...
5.922	...	...
6.005	...	...
6.074	2	6
6.122	...	...
6.152	...	...
6.306	...	...

characterized by $l_n=0$ and $l_n=2$, respectively, and the second excited state characterized by $l_n=2$ have relative reduced widths in the ratios of 2.0, 1.8, and 1.1. These would be difficult to interpret in gross-structure studies and are in fact more probably the $1/2^+$, $3/2^+$, and $5/2^+$ levels of the $K=1/2$ band (orbit 9 of Nilsson) which have been pushed down by the three way interaction

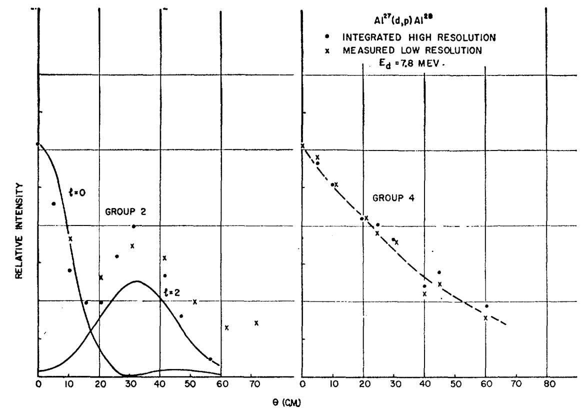

FIG. 4. Comparison of angular distributions obtained for Al^{28} from the measured low-resolution spectra and the integrated high-resolution spectra.

between $K=1/2$ (orbit 9), $K=1/2$ (orbit 11), and $K=3/2$ (orbit 8) bands.

The situation in Al^{28} is shown in Figs. 2 and 4. The angular distribution for group 1 (not shown) is a "good" $l=0$ with very little admixture of $l=2$, while those for groups 2 and 3 indicate an admixture of $l=0$ and 2. The angular distributions for groups 2 and 4 are shown in Fig. 4. The "dots" are points obtained by integration; the crosses are values obtained from the low-resolution measurements. The solid lines are the calculated Butler curves for $l=0$ and $l=2$. The high-resolution data indicate that group 4 is made up of four weak $l_n=0$ levels, two $l_n=2$ levels, and three $l_n=1$ levels. Group 5 is nearly pure $l=1$ and is made up mainly of three strong $l=1$ levels plus a weak $l=2$. Again these groups would be difficult to understand in terms of single-particle configurations since the $d_{5/2}$ neutron levels are filled for Al^{27}.

Comparison of the high- and low-resolution data for

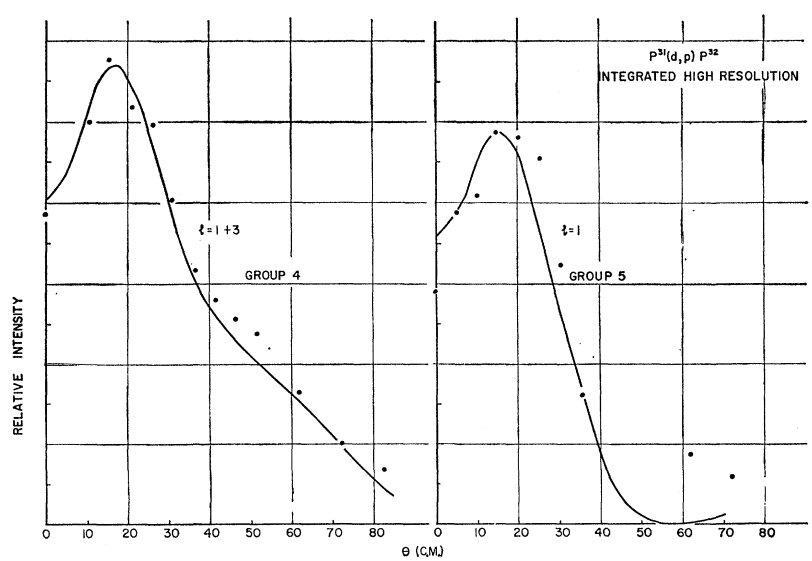

FIG. 5. Angular distributions obtained for groups 4 and 5 in P^{32}. The solid lines are Butler curves calculated for the l_n values indicated.

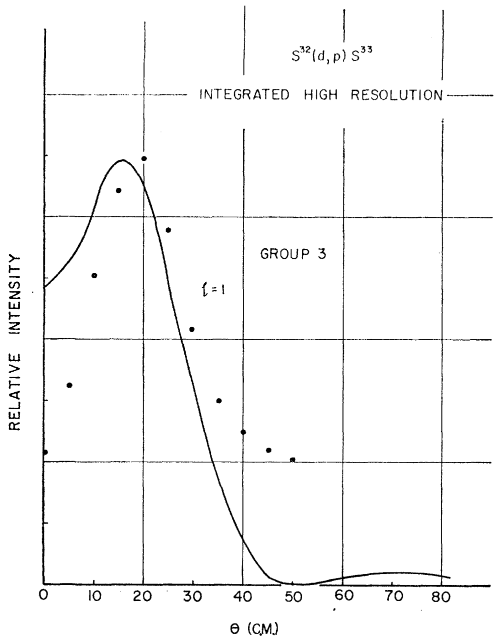

FIG. 6. Angular distribution obtained for group 3 in S^{33}. The solid line is the Butler curve calculated for $l=1$.

P^{32} would lead one to expect the angular distributions for all but group 4 to be fitted by normal Butler curves, and in fact they are. Group 4 contains two $l=2$ and one $l=1$ level. It is, however, well-fitted by the sum of $l=1$ and $l=3$ Butler curves as shown in Fig. 5.

In S^{33} only group 3 has any significant admixture of l values, and of these $l=1$ is dominant. The angular distribution is a "reasonable" $l=1$ fit as shown in Fig. 6.

In the spins of the individual levels were known, the center of gravity of those levels of the same j formed by the same l capture could be determined, and an estimate of the single-particle level spacings made. It is clear, however, from the limited data on Mg^{27} given in Table I that these would not coincide with the gross-structure peaks.

While there is considerable evidence of significant deformations in the $(1d,2s)$ shell nuclei, the $1f$ and higher shells are relatively unexplored with high resolution. The available evidence does not support large deformations in the $1f$ region, but there is evidence[10,11] that the single-particle character is spread over a band of levels large compared to the intrinsic spacing of the single-particle levels. This presumably means that the spreading is due to short-range nucleon-nucleon interactions (of which "pairing correlations" would be one manifestation), rather than a quadrupole deformation. In $Mn^{55}(d,p)Mn^{56}$, for example,[10] a series of $l=1$ transitions is spread over some 3-Mev excitation, and cannot be fitted with previous interpretations[1] of gross-structure data. Additional evidence comes from the measured level schemes[11] for Ni^{59}, Ni^{61}, Fe^{57}, and Ti^{49}, although in these cases the spin assignments are made to fit the energy gap or pairing theory, and can hardly be considered convincing experimental evidence against the gross-structure idea.

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[10] A. W. Dalton, G. Parry, H. D. Scott, and S. Swierszczewski, Proc. Phys. Soc. (London) **78**, 404 (1961).
[11] B. L. Cohen, R. H. Fulmer, and A. L. McCarthy, Phys. Rev. **126**, 698 (1962).