Energy Levels of Ne^{21} and Ne^{23}†

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The energies of twenty-seven excited states of Ne^{21} and seventeen of Ne^{23} have been established by a study of the (d,p) reactions in Ne^{20} and in Ne^{22}. Seven deuteron bombarding energies between 4.75 and 7.5 Mev were used, and the target was a cell with thin windows, containing either natural or Ne^{22}-enriched neon gas. The proton groups emitted at 90 degrees were analyzed with a broad-range magnetic spectrograph. The established calibration of the spectrograph, in terms of alpha particles from polonium, together with some well-known reactions, provided the data necessary for precise energy determinations. The Q values obtained for the ground-state reactions $Ne^{20}(d,p)Ne^{21}$ and $Ne^{22}(d,p)Ne^{23}$ were 4.534 ± 0.009 Mev and 2.791 ± 0.009 Mev, respectively. Deuteron groups inelastically scattered from Ne^{20} and Ne^{22} were also observed. The higher energy groups were used in the calibration procedure; the lower energy groups gave the results 4.250 ± 0.008 Mev and 3.356 ± 0.008 Mev for the second excited states of Ne^{20} and Ne^{22}, respectively. The interpretation of the level schemes of Ne^{21} and Ne^{23} in terms of the collective model has been considered and is discussed here briefly.

I. INTRODUCTION

MOST light nuclei which can be formed by (d,p) reactions on stable isotopes have received a fair amount of attention through these reactions, and many of their level positions and other properties are well known. Two notable exceptions are the neon isotopes, Ne^{21} and Ne^{23}, which result from (d,p) reactions on Ne^{20} and Ne^{22} (natural isotopic abundances 90.9 and 8.8%, respectively). A difficulty in the way of such studies has been that of making suitable thin neon targets. With natural and enriched gas targets, several experimenters[1–4] have found a number of excited states in Ne^{21} and two or possibly three in Ne^{23}. However, the over-all resolution that they were able to achieve was rather poor, largely because of the energy spread produced by the gas targets; and, as the present results will show, many levels in Ne^{21} were missed.

The use by Van Patter *et al.*[5] and by Ahnlund[6] of targets of electromagnetically separated Ne^{20} and Ne^{22} formed on silver backings, together with high-resolution magnetic analysis, has allowed precise measurements of the ground-state protons and, hence, the Q values for the $Ne^{20}(d,p)Ne^{21}$ and $Ne^{22}(d,p)Ne^{23}$ reactions. Two excited states of Ne^{21} have also been observed in this way.[6,7] However, with such targets, the low yields and the scattering from the backings have precluded the investigation of higher excited states. Levels of Ne^{21} can be reached through the $Na^{23}(d,\alpha)Ne^{21}$ reaction also, but only three excited states have been measured in this way.[8]

The experiments to be described here were undertaken with the object of determining, as precisely as possible, all the Ne^{21} and Ne^{23} levels up to a few Mev excitation by measuring the energies of the proton groups from (d,p) reactions in Ne^{20} and Ne^{22} with the aid of the MIT broad-range spectrograph. This entailed the development of a neon gas target which would produce a small enough energy spread in the emitted protons so that all the groups could be satisfactorily resolved. That this was in fact achieved (except for possible doublets separated by less than about 20 kilovolts) has been nicely confirmed in the case of Ne^{21} by the publication, since this work was completed, of measurements on the reaction $F^{19}(He^3,p)Ne^{21}$ by Hinds and Middleton.[9] The agreement between the Ne^{21} level scheme which they deduce and the results of our (d,p) work is quite satisfactory.

The levels of Ne^{21} and Ne^{23} are of some special interest insofar as these nuclei occur in a mass-number region where interpretations in terms of Nilsson's version of the collective model[10] have met with some successes. The relevance of the model to the two neon isotopes will be discussed in Sec. IV.

II. EXPERIMENTAL METHOD

The source of deuterons for these experiments was the MIT-ONR electrostatic accelerator. Bombarding energies from 4.75 to 7.5 Mev were used. The general experimental technique, which employed a broad-range magnetic spectrograph for analysis of the reaction products, has already been described in some detail.[11,12]

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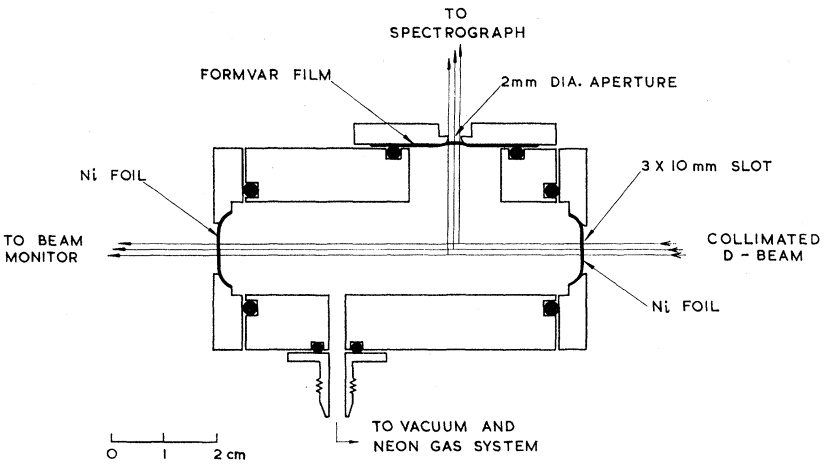

FIG. 1. Diagram showing a horizontal section of the gas cell.

The main departure from previous procedures was the replacement within the target chamber of the normal thin solid target with a gas cell. This cell is illustrated in Fig. 1. It was made from a stainless steel block, the apertures being sealed with thin windows, and was suspended inside the target chamber by an adjustable shaft. The cell could be evacuated simultaneously with the target chamber and could then be isolated to allow neon gas at the required pressure to be introduced. Pressures of 11 to 13 cm Hg were normally used. The deuteron beam, collimated by slits to the dimensions 0.75 mm in height and 2.25 mm in width, entered the gas cell through a nickel foil (nominal thickness about 1 mg/cm^2) cemented over an aperture 3 mm wide and 1 cm long. After irradiating a thin strip of gas as it traversed the cell, the beam passed through a second nickel window to a collector. Reaction products emitted at 90 degrees to the deuteron-beam direction from a short section of the irradiated gas were able to pass through a Formvar window so as to enter the magnetic spectrograph. The Formvar window was made up of a series of very thin films formed on a clean-water surface. These were laid successively on a flat metal plate with a 2.5-mm diameter central aperture, the boundary of which was rounded and polished. The plate with its Formvar film was then sealed to the gas cell with an O-ring. Windows with thicknesses equivalent to about 0.1 cm of air proved to be quite robust and durable under the experimental conditions.

At each deuteron bombarding energy, the spectrograph field was adjusted so that the deuteron groups corresponding to elastic scattering from Ne^{20} and Ne^{22} nuclei appeared near the upper (high-energy) end of the photographic plates used for detection. The ground-state proton groups from the (d,p) reactions in the two neon isotopes then also appeared at about the same region of the plates. Proton, deuteron, and alpha-particle tracks were distinguished by their lengths in the photographic emulsions, which were 50 microns thick. About twenty-four proton groups were observed in a single exposure, and adequate yields were obtained for a total deuteron charge collection of 500 to 1000 microcoulombs. Average beam currents were one- or two-tenths of a microampere. At most of the bombarding energies chosen, a second exposure was made at a lower spectrograph field setting so that proton groups corresponding to higher excited states in Ne^{21} and Ne^{23} could be observed. Some comparison runs were also made with air replacing the neon in the target cell.

III. EXPERIMENTAL RESULTS

A typical spectrum obtained with natural neon at a deuteron bombarding energy of 7.19 Mev is shown in the upper diagram of Fig. 2. The number of tracks per strip of emulsion one-half mm wide is plotted against distance along the photographic plate relative to a zero fixed at the low-energy end. Deuteron groups are represented by broken curves and proton groups, by full curves. These groups have greater widths than are usually encountered in experiments using the broad-range spectrograph,[12] because of the energy spread introduced by the windows and gas of the target cell. Most of this energy spread is attributed to nonuniformity in the nickel input window, since the widths (measured in terms of energy) of all the proton and deuteron groups are closely the same. However, even with this additional broadening of the peaks, the resolution (full width at half height divided by the particle energy) was 0.3% for 10-Mev protons varying to 0.6% for 5-Mev protons or deuterons. A good feature of the gas cell spectra was the virtually zero background.

The deuteron groups corresponding to elastic scattering from Ne^{20} and Ne^{22} can be seen at the high-energy end of the spectrum in Fig. 2, near the distance $d=70$ cm. Inelastically scattered deuterons leaving Ne^{22} and Ne^{20} in their first excited states appear at $d=44.5$ and 35.5 cm, respectively. The second excited-state group for Ne^{22} is just visible at $d=7.5$ cm. A small elastic group from nitrogen contamination can be seen at $d=57.5$ cm. All the proton groups shown are due to reactions in Ne^{20}

[12] W. W. Buechner, M. Mazari, and A. Sperduto, Phys. Rev. **101**, 188 (1956).

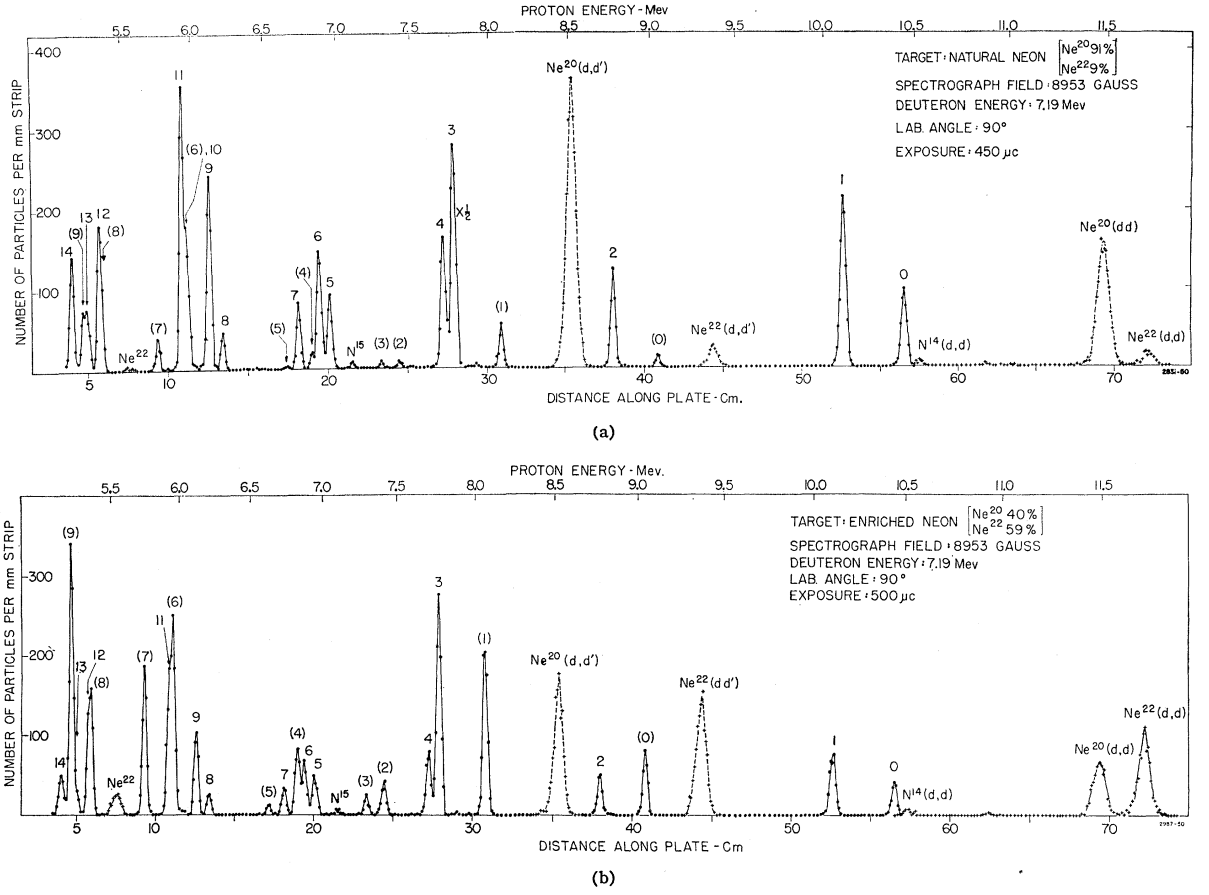

FIG. 2. Typical spectra, obtained at the same deuteron bombarding energy (7.19 Mev) and the same spectrograph field setting, for a natural neon gas target (upper diagram) and for a target of gas enriched to 59% in Ne^{22} (lower diagram). In both cases about 1% of air was also present. The groups shown by crosses and broken curves represent elastically and inelastically scattered deuterons; those with circles and full curves are proton groups from the reactions $Ne^{20}(d,p)Ne^{21}$ (numbered without parentheses) and $Ne^{22}(d,p)Ne^{23}$ (numbered with parentheses). The groups corresponding to numbers (6) and 10 in the upper diagram were more clearly defined in spectra obtained at lower field settings and with lower bombarding energies. The energy scales are for the protons and refer to the third-height points on the peaks; for the deuterons, the energy scale is one-half that for the protons.

and Ne^{22}, except for a small one marked N^{15}. Those groups numbered without parentheses correspond to levels in Ne^{21}, and those with parentheses, to Ne^{23} levels. Since the angle of observation was restricted to 90 degrees, the distinction between the two isotopes was made first by observing the relative changes in energy of the proton groups as the deuteron bombarding energy was varied. Later, when a sample of neon gas enriched to 59% in Ne^{22} became available,[13] the isotopic assignments were very easily confirmed. A spectrum obtained with the mass-22 enriched neon is shown in the lower part of Fig. 2. The experimental conditions were the same as for the natural neon run. From the ratios of the heights of corresponding peaks in these two runs and also in a companion pair of exposures made with a lower spectrograph field, it was possible to identify with reasonable certainty twenty-seven excited states in Ne^{21} and seventeen in Ne^{23}.

[13] Obtained from the Stable Isotope Division of the Oak Ridge National Laboratory, Oak Ridge, Tennessee.

In order to obtain reaction Q values and excitation energies, it was necessary with each run first to adopt a consistent method of specifying the energies of observed groups of protons or deuterons, and then to estimate the corresponding incident deuteron energy at the point of bombardment, as well as the energy lost by the reaction products in leaving the gas cell. In accordance with usual practice in this laboratory, the energy of each group was specified by observing the distance along the photographic plate corresponding to the point at one-third the maximum peak height. The relationship between the positions along the plate and the corresponding radii of curvature of the particles in the magnetic field was established through measurements on polonium alpha particles. As in previous work here, the $B\rho$ for these particles was assumed to be 331.59 kilogauss-centimeters. In our case, where the observed groups were appreciably wider than the polonium alpha-particle peaks used in the spectrograph calibration, this procedure was equivalent to selecting arbitrarily a

particular value of the incident deuteron energy (in the range of values introduced by the nonuniform input window of the gas cell) and measuring the reaction product energies which corresponded with this value.

This incident deuteron energy and the energy losses of outgoing particles were then obtained as follows: Starting with the initial energy E_d of the deuteron beam before reaching the gas cell (known to a few kev from the field setting of the beam-analyzing magnet), it was found that the observed energies of the deuteron groups elastically scattered from Ne^{20} and Ne^{22}, and also from N^{14} and O^{16} when present, gave a fairly precise measure of the total deuteron energy loss ($\Delta E_i+\Delta E_0$). Here, ΔE_i represents the energy loss before the scattering, which is the difference between E_d and the required deuteron bombarding energy, and ΔE_0 is the energy loss (at a specified deuteron energy) after the scattering. In relating corresponding values of ΔE_0 for deuteron groups with different energies (and also for proton and alpha-particle groups), the assumption was made that the differential stopping power of the neon gas plus Formvar window (average over-all $Z\sim 7$) was the same as if all the stopping material had been air; differential range-energy relations for protons, deuterons, and alpha particles in air[14] were therefore used in all the calculations. Knowing the sum ($\Delta E_i+\Delta E_0$), we could then easily obtain separate estimates of ΔE_i and of ΔE_0 as the values which best fitted the energies observed for all the following: (1) the inelastically scattered deuteron groups corresponding to the first excited states of Ne^{20} and Ne^{22}, assumed to be at 1.632 ± 0.004 and 1.277 ± 0.004 Mev, respectively[15]; (2) some proton groups from the reactions $N^{14}(d,p)N^{15*}$ and $O^{16}(d,p)O^{17*}$, which were observed in several runs where a little air was present in addition to the neon gas and which were also observed in some comparison runs made with air only in the target cell (in the nitrogen reactions, Q values of 1.451 ± 0.005, 1.308 ± 0.0015, and 1.045 ± 0.0015 Mev, corresponding to the fourth, fifth, and sixth excited states of N^{15} were assumed[16,17]; for the oxygen reaction, the Q value 1.048 ± 0.002 for the transition to the first excited state of O^{17} was used[17,18]); and (3) the ground-state alpha-particle group in the reaction $O^{16}(d,\alpha)N^{14}$, assuming a Q value of 3.115 ± 0.003 Mev.[19]

TABLE I. Ground-state Q values (in Mev) for the $Ne^{20}(d,p)Ne^{21}$ and $Ne^{22}(d,p)Ne^{23}$ reactions.

Reaction	Present work	Previous work (a)	(b)
$Ne^{20}(d,p)Ne^{21}$	4.534 ± 0.009	4.529 ± 0.007	4.526 ± 0.009
$Ne^{22}(d,p)Ne^{23}$	2.971 ± 0.009	2.964 ± 0.007	2.968 ± 0.008

[a] D. M. Van Patter *et al.*, see reference 5.
[b] K. Ahnlund, see reference 6.

TABLE II. Excited states of Ne^{21} (energies in Mev).

Level	$Ne^{20}(d,p)Ne^{21}$ (present work)	$F^{19}(He^3,p)Ne^{21}$ (Errors $=\pm 10$ kev)[a]	Previous work[b,c]
1	0.349 ± 0.007	0.352	0.349 ± 0.006[b] 0.343 ± 0.010[c]
2	1.750 ± 0.007	1.736	1.735 ± 0.016[c]
3	2.800 ± 0.007	2.789	2.788 ± 0.012[b]
4	2.870 ± 0.007	2.864	2.852 ± 0.021[c]
5	3.666 ± 0.007	3.664	
6	3.737 ± 0.007	3.733	
7	3.889 ± 0.007	3.883	
8	4.435 ± 0.007	4.433	
9	4.528 ± 0.007	4.525	
10	4.685 ± 0.009	4.681	
11	4.729 ± 0.008	4.727	
12	5.338 ± 0.008	5.334	
13	5.434 ± 0.008	5.427	
14	5.550 ± 0.008	5.541	
15	5.632 ± 0.009	5.624	
16	5.694 ± 0.009	5.683	
17	5.777 ± 0.009	5.770	
18	5.822 ± 0.009	5.813	
19	5.997 ± 0.009	5.986	
20	6.036 ± 0.012	6.029	
21	6.176 ± 0.010	6.170	
22	6.267 ± 0.010	6.259	
23	6.450 ± 0.012	6.446	
24	6.555 ± 0.010	6.543	
25	6.606 ± 0.010	6.597	
26	6.647 ± 0.012	6.633	
27	6.748 ± 0.010	6.743	

[a] S. Hinds and R. Middleton, see reference 9.
[b] K. Ahnlund, from $Ne^{20}(d,p)Ne^{21}$. See references 6 and 7.
[c] A. Sperduto, from $Na^{23}(d,\alpha)Ne^{21}$. See reference 8.

Representative values obtained for ΔE_i and ΔE_0 were, respectively, 78 kev for an initial deuteron energy of 7.2 Mev (the nickel window contributing 53 kev) and 35 kev for a scattered deuteron energy of 5.8 Mev (the Formvar window contributing 12 kev). It should be noted that the uncertainty in the initial deuteron energy E_d was largely taken up in the value finally arrived at for ΔE_i so that the figures obtained for the effective deuteron bombarding energy and for ΔE_0 in a particular run were each accurate to within a few kev. The cell loss calculations were made for a number of runs at different initial deuteron energies and showed very satisfactory internal consistency. It was estimated that the probable error introduced into the Q value measurements because of uncertainties in target cell losses was ± 5 kev. Allowing also for uncertainties in the calibration and for systematic errors, we estimated that the over-all probable error in the final results, averaged over six runs, for the Q values of the $Ne^{20}(d,p)Ne^{21}$ and $Ne^{22}(d,p)Ne^{23}$ reactions was ± 9 kev. In the calculations of level excitations, the errors were smaller in most cases because only energy differences were then involved.

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[15] F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. **11**, 1 (1959).
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TABLE III. Excited states of Ne^{23} (energies in Mev).

Level	$Ne^{22}(d,p)Ne^{23}$ (present work)	Previous work[a,b]
1	1.018±0.007	0.98±0.08[a]
2	1.703±0.007	1.75±0.12[a]
3	1.826±0.008	1.80[b]
4	2.314±0.008	
5	2.520±0.008	
6	3.218±0.008	(3.0)[b]
7	3.433±0.008	
8	3.836±0.010	
9	3.988±0.008	
10	4.270±0.015	
11	4.431±0.012	
12	4.748±0.012	
13	4.867±0.015	
14	4.995±0.015	
15	5.036±0.015	
16	5.186±0.015	
17	5.226±0.015	

[a] A. Zucker and W. W. Watson, see reference 2.
[b] R. Middleton and C. T. Tai, see reference 3.

In Table I the Q value results are given, together with values obtained in previous experiments with solid targets, for both reactions. The agreements are well within the quoted errors.

Tables II and III list in their second columns the results obtained for the energies of the excited states of Ne^{21} and Ne^{23}. The Ne^{21} list is expected to be complete up to the highest excitation energy reached, apart from any closely spaced doublets; in the Ne^{23} case it is possible that weakly excited levels above an excitation energy of about 4 Mev may have been missed. Table II also shows, for comparison, recent results from the $F^{19}(He^3,p)Ne^{21}$ reaction and previous accurate measurements. Table III includes all previously known data for Ne^{23}.

The simultaneous observation, during the course of these experiments, of inelastically scattered deuterons leaving Ne^{20} and Ne^{22} in their second excited states has allowed estimates of the excitation energies of these states. The values obtained are 4.250±0.008 Mev for Ne^{20} and 3.356±0.008 Mev for Ne^{22}. The result for Ne^{20} is in good agreement with the value 4.248±0.006 Mev obtained by Buechner and Sperduto,[20] and this gives added confidence in the reliability of the new result for the second excited state of Ne^{22}.

IV. DISCUSSION

It is of some interest to compare the level schemes of Ne^{21} and Ne^{23} with those of other nuclei in the same mass region and to consider whether they can be accounted for in terms of Nilsson's model for odd-mass deformed nuclei.[10] Considerable success has already been achieved in the description according to this model of a number of nuclei in the range $A=19$ to 31, the case of Mg^{25} and Al^{25} being especially notable.[21] The rotational bands are determined by the orbits available for the last odd particle, which for the two mass-25 nuclei is the thirteenth (a neutron in Mg^{25} and a proton in Al^{25}). In this case, members of four rotational bands have been identified, a ground-state band with $K=5/2^+$, two with $K=1/2^+$, and one with $K=1/2^-$. Now in Ne^{23} also, the last odd particle is the thirteenth, a neutron, although there are two fewer protons in the core. It would therefore be an interesting test of the model to see whether the same band structure as in the case of Mg^{25} and Al^{25} could be demonstrated in Ne^{23}. The correspondence would not necessarily be so close as that between the two mass-25 nuclei because, first, a slight difference in the distortion parameter β would result in a difference in the excitation energies at which the bases of the various bands appear (the position of the $K=1/2^-$ band is particularly sensitive to β). Secondly, a difference in the moments of inertia or in the interaction parameters would affect to some extent the level spacings within each band.

In order to make a conclusive analysis of Ne^{23} in this way, it would be necessary to know the spins and parities of a number of the levels, as well as their energies. At present, we have such data only for the ground state ($5/2^+$ or $3/2^+$) and first excited state ($1/2^+$), derived from the stripping curves obtained by Burrows *et al.*[4] However, a plausible comparison can be made, and it turns out that reasonable values are obtained for the various parameters (A, a, and B in reference 21) describing the bands if one assumes a $K=5/2^+$ band formed by levels 0, 3, and 9; a $K=1/2^+$ band comprising levels 1, 2, 6, and 12; and a second $K=1/2^+$ band for the levels 4, 5, 7, and 8. This interpretation is illustrated in Fig. 3, where the values of the parameters $A(=\hbar^2/2I)$, a, and B appropriate to three assumed bands in Ne^{23} are shown at the top left. On the right-hand side of the diagram, the analysis of the Al^{25} levels, according to Litherland *et al.*,[21] is given, together with the values for the same collective-model parameters. In order to emphasize the similarity between the two level schemes, the apparent bands in Ne^{23} have been displaced vertically until their respective lowest states are at the same excitation energy as the bases of the corresponding Al^{25} bands, and the spacings in each band have then been multiplied by the factors shown. All the levels of Ne^{23} up to 4-Mev excitation are accounted for in this way. If this interpretation is correct, it implies that the $K=1/2^-$ band must come in at a somewhat higher excitation energy in Ne^{23} than in the mass-25 case. This analysis must be regarded as largely speculative at present. It is hoped to put it on a firmer basis as a result of experiments now in hand to determine further properties of the Ne^{23} levels, both from their modes of decay and from the stripping patterns.

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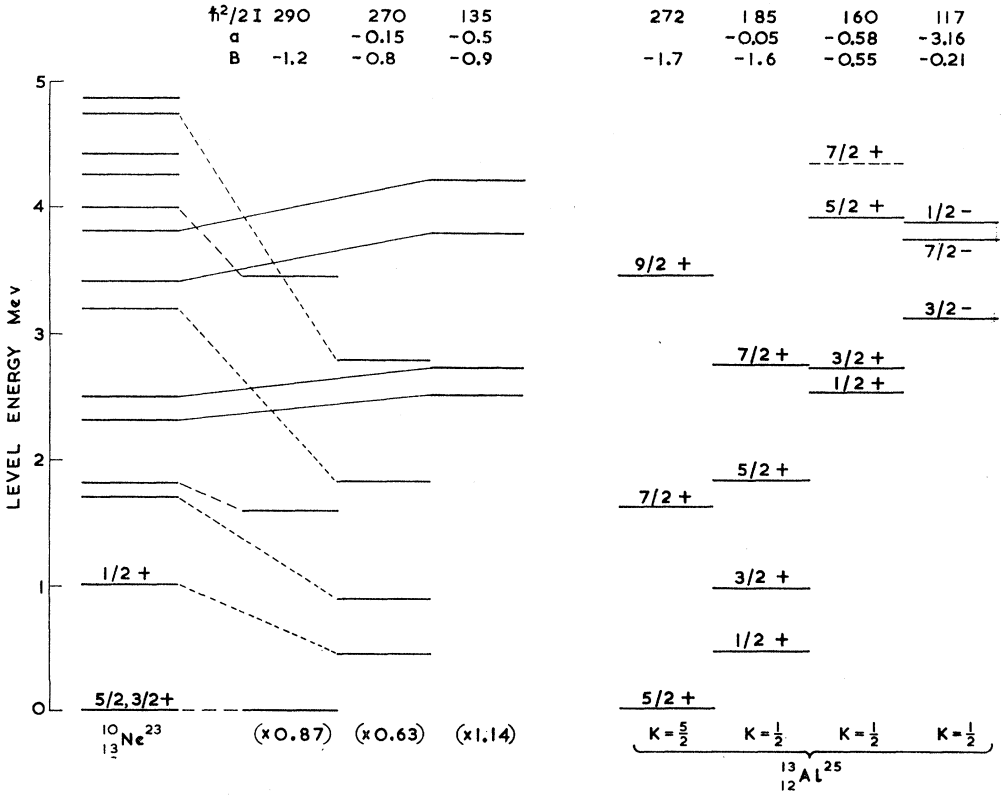

FIG. 3. An analysis of the levels of Ne^{23} in terms of the collective model and their comparison with the levels of Al^{25}. Three bands in Ne^{23} are suggested: a ground-state $K=\frac{5}{2}$ (levels marked by broken lines), and two $K=\frac{1}{2}$ bands (levels marked by dotted and full lines, respectively). The appropriate values of the collective model parameters are given at the top of the diagram. The displacement and normalization of the Ne^{23} bands to effect a comparison with Al^{25} are explained in the text.

In the case of Ne^{21}, the odd particle is the eleventh, and, according to the collective model, an interesting comparison is that with Na^{23}, for which an interpretation in terms of three interacting rotational bands with $K=3/2$, $5/2$, and $1/2$ has been suggested.[22] In the newly determined level scheme for Ne^{21}, there are sufficient states up to an excitation energy of 4 or 5 Mev to make a correspondence with the Na^{23} levels seem feasible. The ground states have the same spins ($3/2^+$) and the same large quadrupole moments.[23] The stripping curves of Burrows *et al.*[4] for the $Ne^{20}(d,p)Ne^{21}$ reaction suggest that the first excited state of Ne^{21} may have spin $5/2^+$, as in Na^{23}, and that one of the pair of levels near 2.8 Mev (unresolved in their experiment) has spin $1/2^+$. This is, more likely, the third excited state at 2.800 Mev, since it was much more strongly excited than the upper level in our experiments, and it could thus correspond with the third excited state of Na^{23}. An analysis similar to that made by Paul and Montague[22] for Na^{23}, using the same rotational model parameters and fitting the $K=1/2$ band to the level at 2.80 Mev, produces a scheme for the first seven states of Ne^{21} which, although quantitatively incorrect, shows the same degree of correspondence as in the Na^{23} case.

The above considerations thus suggest that the collective model may well be applicable to Ne^{21} and Ne^{23} and that further data on the level properties would be highly desirable.

V. ACKNOWLEDGMENTS

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