Low-Lying Energy States in Ne^{20} from the $F^{19}(d,n)Ne^{20}$ Reaction*

R. E. BENENSON,† H. Y. CHEN, AND L. J. LIDOFSKY
Columbia University, New York, New York

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Six neutron groups from the $F^{19}(d,n)Ne^{20}$ reaction corresponding to the lowest states in Ne^{20} have been observed at six angles of observation. The major part of the experiment employed nuclear emulsions and an average deuteron energy of 3.57 Mev. The importance of stripping appears to depend on the particular level involved; in particular, angular distributions leading to unambiguous assignments by stripping theory appear only for the ground, 1.63-Mev, and 6.75-Mev levels. The ground-state assignment appears to be energy dependent when the present $l_p=2$ value is compared to the $l_p=0$ value previously reported for a higher bombarding energy. The 4.25-Mev level in Ne^{20} gives rise to an angular distribution which could be either $l_p=2$ or $l_p=3$, but the fit to theory is not satisfactory for either case. A qualitative argument is given favoring the latter value. No assignment can be made to the 4.97- and 5.63-Mev levels.

A brief second experiment with a fast neutron spectrometer was performed in order to obtain an absolute differential cross section at 0° for Ne^{20} left in its 6.75-Mev level. The reduced width obtained from this cross section is compared with a published reduced width for this same level obtained by elastic scattering of alpha particles by O^{16}.

I. INTRODUCTION

THE first few excited states of the Ne^{20} nucleus are of interest for comparison with three nuclear models: the shell model, the collective model, and the alpha-particle model. Extensive calculations based on the shell model have been made on nuclei of mass numbers 18 and 19 by Elliott and Flowers,[1] and they suggest that the calculations can be extended to mass-20 nuclei. Furthermore, of the nuclei immediately above O^{16}, Ne^{20} has the strongest deformation,[2] making it of interest for interpretation by the collective model. Finally, Ne^{20} can be considered as five alpha particles.

Extensive studies have been made on the virtual levels of Ne^{20} through the scattering of alpha particles[3,4] by O^{16}. However, of the five known bound states only the ground and first excited states have been given definite spin and parity assignments. A direct method of assigning spin limits and parities to the bound levels of Ne^{20} would appear to be by deuteron stripping on F^{19}, and two measurements of this kind have been reported, one by an English group[5] using a deuteron energy of around 9 Mev, and the other by a Japanese group[6] using a deuteron energy of 2.17 Mev. The former obtained good stripping distributions for the ground and first excited states but failed to observe the second through sixth excited states altogether. The Japanese workers at their low bombarding energy did not obtain familiar stripping distributions, and their data indicated the presence of weak neutron groups inconsistent with the level scheme[7] for Ne^{20}. Wilkinson has suggested that at low bombarding energies angular distributions for high-Q reactions would be greatly distorted from recognizable patterns.[8]

The 6.75-Mev level in Ne^{20} is a virtual level for alpha emission, and determination of cross sections for its formation provides a useful comparison of reduced widths from stripping theory and from elastic scattering of alpha particles by O^{16}.

II. EXPERIMENTAL PROCEDURE

The very high Q of the $F^{19}(d,n)Ne^{20}$ reaction for the low-lying levels of Ne^{20} poses a difficulty in attempting to resolve the third, fourth, and fifth excited state groups by conventional methods of neutron spectroscopy. The deuteron bombardment energy chosen in the present experiment was a compromise between two requirements: first, that the deuterons have sufficient energy to overcome the Coulomb barrier, and secondly, that the separation of neutron groups in energy relative to their mean energy be as large as possible. The average deuteron energy at the center of the evaporated lead fluoride target of the first run was considered to be 3.57 Mev based on the estimate made by weighing that the target thickness was 140 kev. Both Ilford C-2 400-micron emulsions and a fast neutron spectrometer were set up. During the first run there was not time to optimize performance on the latter and calibrate it; in addition, the resolution requirements ($\Delta E/E\sim 6\%$ in some cases) seemed quite severe for the instrument. It did serve to indicate that neutron background in the energy region of interest was very small, as did background emulsions exposed simultaneously.

The usual problems of scanning were aggravated by the length of the tracks and their scarcity.

No provision for continuous monitoring of the lead fluoride target had been made, and when calculation of

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† Permanent address: City College of New York, New York, New York.

[1] J. P. Elliott and B. H. Flowers, Proc. Roy. Soc. (London) **A242**, 57 (1957).
[2] G. Rakavy, Nuclear Phys. **4**, 375 (1957).
[3] J. R. Cameron, Phys. Rev. **90**, 839 (1953).
[4] L. C. McDermott, K. W. Jones, H. Smotrich, and R. E. Benenson, Phys. Rev. **118**, 175 (1960).
[5] J. M. Calvert, A. A. Jaffe, and E. E. Maslin, Proc. Phys. Soc. (London) **A68**, 1017 (1955).
[6] S. Morita and K. Takeshita, J. Phys. Soc. Japan **13**, 1241 (1958).
[7] F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. **11**, 1 (1959).
[8] D. H. Wilkinson, Phil. Mag. **3**, 1185 (1958).

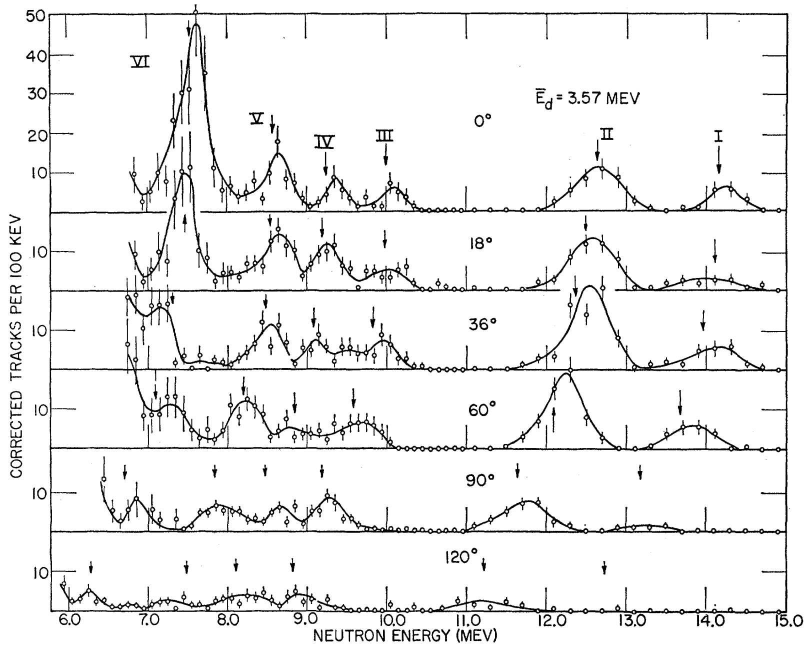

FIG. 1. Neutron energy spectra at six angles of observation for the reaction $F^{19}(d,n)Ne^{20}$. Each spectrum is normalized to the same area of emulsion as the others; the number of tracks in an energy interval have been corrected for emulsion efficiency. The arrows indicate calculated positions for the established level energies: I, ground state; II, 1.63-Mev level; III, 4.25-Mev level; IV, 4.97-Mev level; V, 5.63-Mev level; VI, 6.75-Mev level.

the reduced width from stripping gave an extremely small fraction of the reduced width from elastic scattering, the likelihood that the target disintegrated under bombardment could not be discounted. Accordingly, the gas-recoil fast neutron spectrometer[9] was set up at 0° since the flux of neutrons which leave Ne^{20} in its 6.75-Mev level is strongest at this angle. A gas CF_4 target was employed; the estimated target thickness was 210 kev, and the over-all bombarding energy at target center is considered to be 3.50±0.05 Mev. The Van de Graaff generator energy was obtained using the generating voltmeter since the nuclear magnetic resonance apparatus of the analyzing magnet was inoperative on the day of the run. Another brief observation at 18° was made during the same run in order to clear up an ambiguity connected with the 4.97-Mev level.

That the CF_4 sample used was better than 99% pure was determined by gas chromatography.

III. EXPERIMENTAL RESULTS

The emulsion spectra observed at the six angles of observation are shown in Fig. 1. The arrows are the calculated positions of the groups corresponding to the level positions obtained from reference 7. The spectra have been corrected for the probability of tracks leaving the emulsion[10] and for the variation of the neutron-proton scattering cross section with energy. Slightly different acceptance requirements were employed than those listed in reference 10, namely, the maximum allowable angles both in the plane of the emulsion and in dip were 15°. In order to check if the correction formula published in reference 10 was applicable, one point was recalculated for a neutron energy of 14 Mev where the correction was largest. Graphical integration was used, and the calculation included the effect of range shortening with increased recoil angle. However, the calculation did not include either the effect on recoils of Coulomb scattering or anisotropy of the *n-p* cross section. The agreement with the formula was within 0.5% so that the formula was employed directly.

Figures 2, 3, and 4 show, respectively, the angular distributions of the neutron groups for the ground-state and 1.63-Mev level, the 4.25-Mev and 4.97-Mev levels, and the 5.63- and 6.75-Mev levels. A special remark has to be made about the error bars in the case of the 4.25-, 4.97-, and 5.63-Mev levels. As can be seen from Fig. 1 the corresponding neutron groups were not completely resolved. In addition to the usual statistical uncertainty, another uncertainty had to be added which will be referred to as "resolution uncertainty." The circled points at the centers of the bars were obtained by estimating from the histogram the maximum and minimum number of tracks belonging to a given group and taking the mean of these two values. The square root of this mean value was considered the statistical standard deviation. The number of tracks between either extreme point was considered to be a 95% confidence interval for the resolution uncertainty. The number of tracks between the mean and either extreme point was then divided by two to reduce the confidence interval to 67% to be consistent with the statistical confidence interval. The error bar represents the square root of the sum of these two uncertainties squared and normalized according to the area of plate scanned. The

[9] R. E. Benenson and M. B. Shurman, Rev. Sci. Instr. **29**, 1 (1958).
[10] H. T. Richards, Phys. Rev. **59**, 796 (1941).

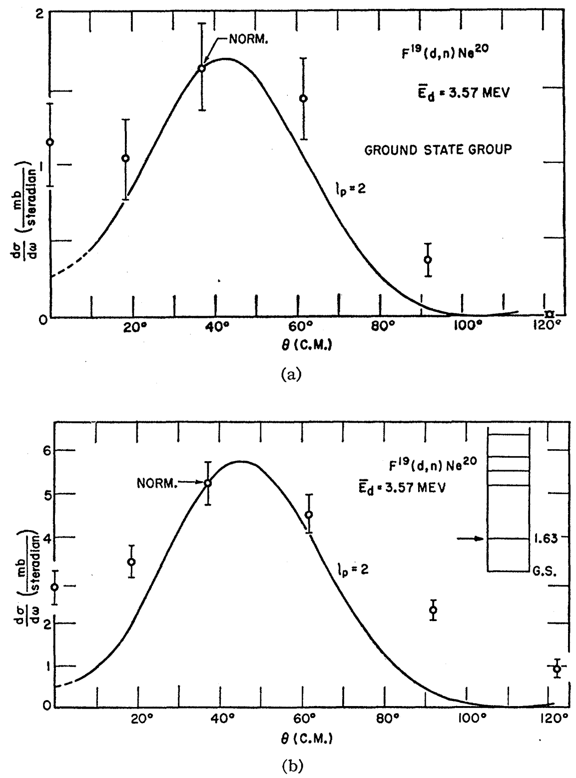

FIG. 2. Angular distributions in the center-of-mass system for the ground and first excited states. Arrow indicates points at which experimental distribution is normalized to theoretical distribution. See text with regard to significance of error bars. The estimated uncertainties in the ordinate scale factors are ±30%.

theoretical curves were obtained from the tables of Lubitz[11] using an $r_0 = 5.0$ f.

Figure 5 is the spectrum observed at 0° using the fast neutron spectrometer. Calibration of the spectrometer both for energy and efficiency was made by substituting deuterium for the CF_4 in the gas target and using the published $D(d,n)He^3$ reaction cross sections[12] and calculated neutron energies. The dashed line in Fig. 5 represents an experimental monoenergetic neutron spectrum fitted to the incompletely resolved 6.75-Mev level spectrum. Approximate absolute differential cross sections can then be assigned at 0° to the 4.97-, 5.63-, and 6.75-Mev levels when correction is made for variation of spectrometer efficiency with energy. Since the bombarding energy for this run was closely that of the emulsion run, estimates of absolute differential cross sections for the various groups can then be made by relating areas under the curves of the spectra of Fig. 1 to the area under the peak for the 6.75-Mev level. The ordinate scales of Fig. 4 were obtained from the direct measurement at 0°, while those in Fig. 2 and Fig. 3 were obtained by relating areas under peaks to the 6.75-Mev level group area at 0°.

IV. DISCUSSION OF RESULTS

Ground State

The angular distribution appears consistent with proton capture having $l_p = 2$. The results of the Japanese group show a somewhat similar shape although their peak was at a larger angle than the theoretical curve. On the other hand, Calvert *et al.*[5] obtained an angular distribution completely consistent with an $l_p = 0$ capture. The latter result is what would be predicted by simple stripping theory for the transition between the $J = \frac{1}{2}$ F^{19} ground state and the $J = 0$ Ne^{20} ground state. To make the expected d^2s^2 configuration of the four nucleons of Ne^{20} outside the O^{16} closed shell, F^{19} appears to be capturing a *d*-wave particle. However, F^{19} is expected to be in a predominantly d^2s configuration[1] which implies that some rearrangement of nucleons in their shells during capture is involved. A somewhat similar situation appears in the case of $F^{19}(d,p)F^{20}$ where the angular distribution of neutrons leaving F^{19} in

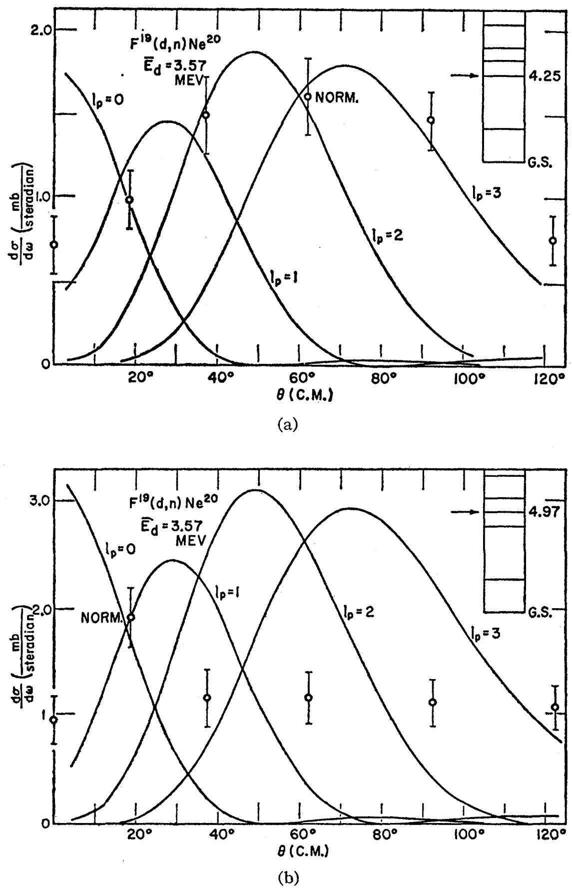

FIG. 3. Angular distributions in the center-of-mass system for the 4.25- and 4.97-Mev levels. The estimated uncertainties in the ordinate scale factors are ±40%.

[11] C. R. Lubitz, *Numerical Table of Butler-Born Approximation Stripping Cross Sections*, University of Michigan, Ann Arbor, Michigan, 1957 (unpublished).

[12] J. L. Fowler and J. E. Brolley, Revs. Modern Phys. **28**, 103 (1956).

ground state varies strongly with energy.[13,14] A study of the energy dependence of the ground-state neutron angular distribution would be desirable to find the crossover from the $l_p=2$ to the $l_p=0$ distribution.

1.63-Mev Level

The $l_p=2$ stripping angular distribution is completely consistent with the $J=2^+$ assignment to this level.[7] At small angles the experimental distribution lies appreciably higher than the theoretical curve based on Butler theory. This fact can be explained by recent developments in stripping theory using distorted waves.[15]

4.25-Mev Level

The angular distribution of neutrons leaving Ne^{20} in the 4.25-Mev level appears to be a mixture of an $l_p=2$ and an $l_p=3$ angular distribution. As an argument to emphasize the choice of the distribution as $l_p=3$ some

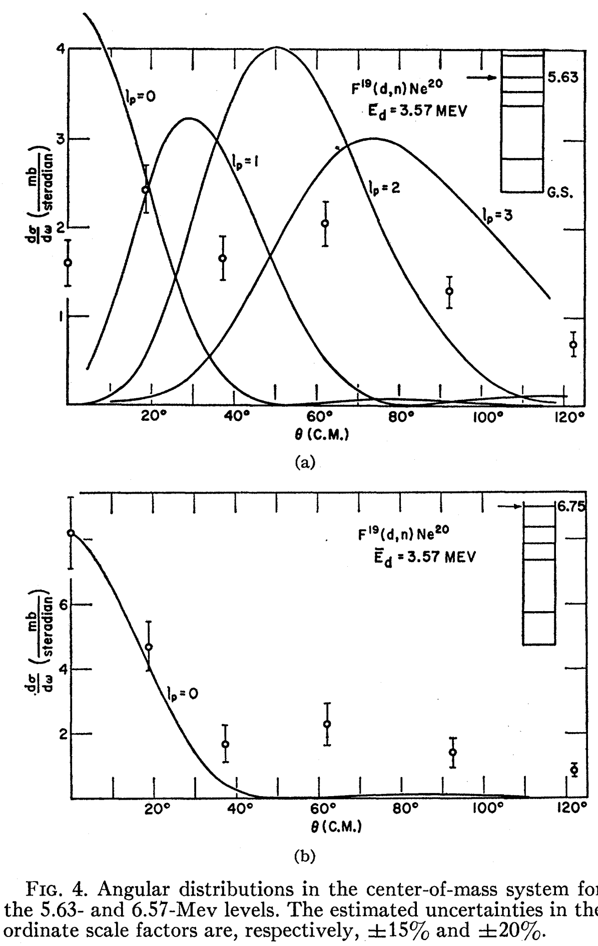

FIG. 4. Angular distributions in the center-of-mass system for the 5.63- and 6.57-Mev levels. The estimated uncertainties in the ordinate scale factors are, respectively, ±15% and ±20%.

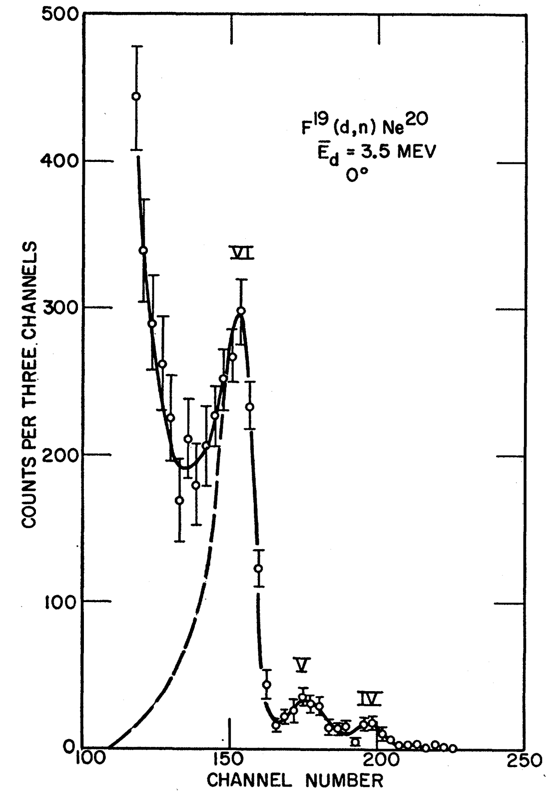

FIG. 5. Spectrum of pulse heights obtained at 0° using the fast-neutron spectrometer and a multichannel analyzer. Note the suppressed zero on abscissa scale. This spectrum has not been corrected for variation of spectrometer efficiency with neutron energy. The groups are labeled as in Fig. 1. The dashed curve represents an experimental monoenergetic neutron spectrum fitted to the not completely resolved group-VI peak.

qualitative account might be taken of the distortion of the nucleus from a spherical shape. In particular, a stripping angular distribution peak moves inward in the Butler theoretical distribution as the nuclear radius is increased. Capture of an f-wave proton by the F^{19} nucleus would likely be more associated with an interaction radius larger than the mean nuclear radius tending to increase a predicted height of the smaller angle points to some extent and spreading out the theoretical angular distribution more for an $l_p=3$ proton than for lower l_p values. An $l_p=3$ assignment implying a relatively high J value is also more consistent with the fact that the 4.25-Mev level decays preferentially by gamma emission to the 2^+ 1.63-Mev level rather than the 0^+ ground state.[16]

If, indeed, the level is consistent with an $l_p=3$ assignment, stripping theory requires it to be 2^-, 3^-, or 4^- with the first unlikely since an $l_p=1$ distribution would more probably be observed. Broude and Gove[17]

[13] D. A. Bromley, J. A. Bruner, and H. W. Fulbright, Phys. Rev. **89**, 396 (1953).
[14] F. D. Seward, I. Slaus, and H. W. Fulbright, Phys. Rev. **107**, 159 (1957).
[15] D. A. Bromley, *Proceedings of the International Conference on Nuclear Structure* (University of Toronto Press, Toronto, 1960), p. 272.
[16] T. H. Kruse, R. D. Bent, and L. J. Lidofsky, Phys. Rev. **119**, 289 (1960).
[17] C. Broude and H. E. Gove, *Proceedings of the International Conference on Nuclear Structure* (University of Toronto Press, Toronto, 1960), p. 47.

suggested that both this level and the 4.97-Mev level have $J=4$. Were $J=3$ an interesting consistency with the predictions of the alpha-particle model would appear. This model predicts a 3^- level at almost exactly the same excitation energy.[18]

4.97-Mev Level

Aside from the 18° point the angular distribution could well be nearly isotropic. Although there was a temptation to assign a tentative $l_p=1$ label to this distribution since that assignment would give the only semblance of a fit to a theoretical curve, the brief fast-neutron spectrometer observation at 18° alluded to in part II yielded a shallow peak, identifiable as the 4.97-Mev level group and representing a cross section smaller than the corresponding 0° peak. That the 18° point is out of line with the others in the lower part of Fig. 3 is now considered to be a statistical fluctuation, and no l_p value assignment can be made on the basis of these data. This level also decays preferentially to the 1.63-Mev level rather than the ground state[16] so again a low l_p value seems unlikely.

5.63-Mev Level

No single l_p value can be assigned to this level and statistics are too poor to assign a combination of l_p values by fitting theoretical curves. Probably stripping does not compete favorably with compound nucleus formation. The differential cross section at 0° is estimated from Fig. 5 to be 1.7 mb/sr in the laboratory system with estimated uncertainty of 15%.

6.75-Mev Level

This level has been studied by means of the elastic scattering of alpha particles by O^{16} and an assignment of 0^+ has been made by Cameron.[3] The $l_p=0$ angular distribution obtained in the present work is entirely consistent with this assignment. The spectrometer run gave a differential cross section at 0° and $\bar{E}_d=3.5$ Mev of 8.9 mb/sr in the laboratory system with an estimated uncertainty of 20% due mostly to the fitting procedure. This cross section leads to a reduced width calculated from formula (II.29) of the Macfarlane and French review article[19] of $\theta^2=0.021$. A value of $r_0=5.0$ f was used in the calculations. The value of θ^2 can be converted to the reduced width γ^2 (in Mev-cm) of Cameron's article, and the ratio of γ^2 from stripping to that of elastic scattering by alpha particles is 0.36 ± 0.07. As has been remarked in reference 19, stripping-reduced widths usually are smaller than those obtained from reactions in which a compound nucleus is formed.

In conclusion, the levels whose spin assignments have already been made from other work show distinctive stripping patterns. The remaining states do not permit unambiguous assignments, an effect which may in some way be associated either with the predicted strong deviation from sphericity of the nuclei involved or the large angular momenta of the states.

V. REDUCED WIDTHS FOR THE GROUND AND FIRST EXCITED STATES

On the basis of the estimated differential cross sections at peak of the ground state and 1.63-Mev state neutron angular distributions, a calculation of the quantity θ^2 of reference 19 was undertaken assuming both distributions to be pure $l_p=2$ and $r_0=5.0$ f. With these assumptions the calculation yielded a value of θ^2 for the ground state of 0.10, over seven times the value listed in reference 9 based on the $E_d=9$ Mev data and θ^2 for the 1.63-Mev state is 0.065, about 4.6 times the listed value. The very fact that the stripping angular distribution for the ground state changes character as the bombarding energy is reduced tends to throw doubt on the validity of the simplified calculation of θ^2 for these lowest levels of Ne^{20}.

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[18] L. Rosenfeld, *Nuclear Forces* (North-Holland Publishing Company, Amsterdam, 1948).

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