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Reaction ^{20}Ne(^{3}He,α)^{19}Ne at 18 MeV*

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Excitation energies of the states in ^{19}Ne are measured via the reaction ^{20}Ne(^{3}He,α)^{19}Ne up to an excitation of ~10.6 MeV. Angular distributions for several states are measured and analyzed by use of the conventional distorted-wave Born approximation. Relative spectroscopic factors are extracted and compared with the predictions of the spectroscopic-factor sum rule. The analysis fails to confirm an assignment of $j=\frac{3}{2}$ for the excited states at 6.01 and 6.74 MeV.

I. INTRODUCTION

Prior to 1969 there was very little experimental information on the energy-level structure of ^{19}Ne although model calculations for the structure of the mass-19 system had been a topic of considerable interest.[1] Early measurements involving the reaction ^{19}F(p,n)^{19}Ne established the existence of six excited states below 2.8 MeV with some spin and parity assignments.[2] More recent investigations of the reactions ^{20}Ne(^{3}He, α)^{19}Ne and ^{17}O(^{3}He, n)^{19}Ne have fixed the spin and parity assignments of these first six states[3] and extended the known excitation-energy region to $\lesssim$5.1 MeV.[4,5]

Recent work by Gill *et al.*[6] has accurately established the excitation energies of the first six states and confirmed the spin and parity assignments of Olness and Warburton.[3] The measurements by Garrett, Middleton and Fortune (GMF)[7] of α-particle energies from the reaction ^{20}Ne(^{3}He, α)^{19}Ne yield excitation energies in agreement with previous values, and they report several additional levels between 5.1 and 7.1 MeV in excitation.

The present measurement of the reaction ^{20}Ne(^{3}He, α)^{19}Ne at $E_{^3\mathrm{He}} \simeq 18$ MeV proposes excitation energies for 21 more states in ^{19}Ne between 7.1- and 10.6-MeV excitation, which extends well into the excitation-energy region in which states may be investigated by the ^{16}O + ^{3}He resonance reactions .[8] Excitation energies determined for previously reported levels are generally in quantitative agreement. Some extracted spectroscopic factors differ appreciably from the values of GMF.[7] The distorted-wave Born-approximation (DWBA) calculations for a few of the higher excited states do not lead to conclusive orbital angular momentum transfer assignments.

II. CALIBRATION AND ENERGY LEVELS

For accurate energy-level determination it is essential to maximize the statistical accuracy of the spectra, to be able to calculate the energy distribution within a single spectral line for spectrum stripping, and to ensure a stable and accurate calibration. A computer code developed to calculate spectral line shape has been shown to predict accurately the shape and energy width of observed groups in energy spectra.[9] The use of the code was instrumental in designing a gas target system for maximum count rate and minimum detected energy spread. The gas cell used had a surface-barrier detector placed inside the target gas volume sealed by a beam entrance window of 0.5-μm nickel. Parameters pertinent to energy resolution and those values used in the present experiment have been reported.[9] Isotopically enriched gas of 99.7% ^{20}Ne was used and all calibration spectra were digitally stabilized.

A. Calibration

For calibration and Q-value analysis, six reaction angles were chosen with nominal values of $\theta = 27.8$, 32.8, 37.5, 47.5, 52.5, and 57.5° with a possible error of ±0.1°. Gas pressure was maintained at ~50 Torr for the two forward-angle spectra and at ~100 Torr for the other four spectra. The spectra for $\theta = 27.8$ and 37.5° are shown in Fig. 1. Centroids and yields of energy groups in the

spectra were extracted by use of the calculated line shapes.[9] The solid curves in Fig. 1 represent the results of the spectrum fitting. Calibration points in the spectra were derived from the reactions ^{20}Ne(^{3}He, ^{4}He)^{19}Ne with $Q = 3713.1 \pm 1.7$ keV,[10] ^{20}Ne(^{3}He, ^{3}He)^{20}Ne, and ^{20}Ne(^{3}He, ^{3}He′)^{20}Ne* exciting the first, second, fourth, and sixth excited states at $E_x = 1635.3 \pm 1.8$, 4249 ± 2.5, 5623 ± 3, and 7174 ± 4 keV.[11]

The centroids of the calibration groups are represented in the calibration curve in the upper portion of Fig. 2, which shows the deviation of these centroids, in units of keV, from a straight-line calibration for the calibration spectra with $P \sim 100$ Torr. A systematic trend in the deviation for each particle group is apparent. This can be reduced to a nearly random effect if one assumes a small inaccuracy in the detector-angle settings and makes a corresponding correction to yield new calculated energies. All energy losses and straggling are properly considered in the calculation. The lower portion of Fig. 2 illustrates the result along with a nonlinear calibration used later in the ^{19}Ne energy-level determination. A similar procedure was followed to establish a calibration for the spectra with $\theta = 27.8$ and 32.8°.

B. Energy Levels

The energy levels in ^{19}Ne extracted directly in the present measurement are listed in the second column of Table I. The errors assigned to the values of the present work are in each case greater than the root-mean-square deviations from the average value extracted from the six calibration spectra; however, many levels were not identified in all spectra. These uncertain levels are identified by parentheses surrounding the excitation-energy values. Excitation energies were not extracted in the region from the 7th through the 14th excited states because of the elastic scattering contributions from ^{16}O and ^{14}N impurities in the gas target.

Included in Table I are some ^{19}Ne energy levels previously reported.[4,6,7] The level located at 5351-MeV excitation by GMF[7] is not observed in the present work. Some of the levels reported had been previously resolved as doublets.[7] For

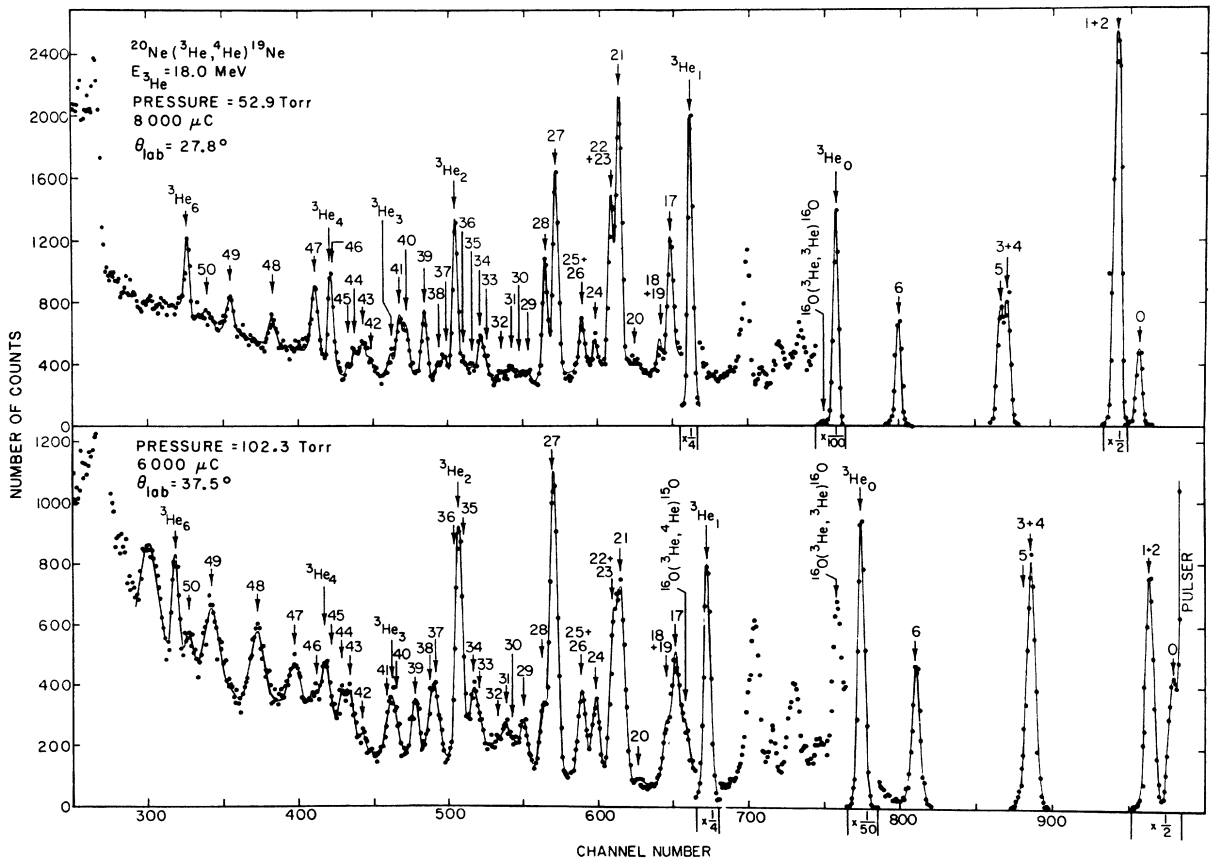

FIG. 1. Typical calibration spectra at 27.8 and 37.5°.

TABLE I. Excitation energies in ^{19}Ne (given in keV).

^{19}Ne Level No.	Present work	GMF (Ref. 7)	Gill *et al.* (Ref. 6)	Present work Corrected excitation
1	235.9 ± 2	238 ± 10	238.2 ± 0.2	239.7 ± 2 [a]
2	272.8 ± 2	273 ± 10	275.1 ± 0.2	276.6 ± 2 [a]
3	1493.6 ± 3	1524 ± 20	1507.9 ± 0.4	1504.0 ± 3 [a]
4	1522.0 ± 3		1536.3 ± 0.5	1532.4 ± 3 [a]
5	1602.2 ± 3	1615 ± 10	1615.4 ± 0.6	1611.5 ± 3 [a]
6	2776.6 ± 3	2793 ± 10	2794.6 ± 1.5	2791.7 ± 3
7		4036 ± 10		
8		4142 ± 10		
9		4200 ± 10		
10		4379 ± 10		
11		4551 ± 10		
12		4625 ± 10		
13		4712 ± 10		
14		4783 ± 20		
15	5070 ± 10	5093 ± 10		5086 ± 10
16		5351 ± 10		
17	5408 ± 10	5426 ± 10		5423 ± 10
18	5502 ± 20	5463 ± 20		
19		5545 ± 10		5517 ± 20
20	5822 ± 20	5831 ± 10		5837 ± 20
21	5999 ± 10	6012 ± 10		6014 ± 10
22		6089 ± 10		6104 ± 15
23	6089 ± 15	6149 ± 20		
24	6274 ± 10	6290 ± 10		6289 ± 10
25				
26	6424 ± 10	6433 ± 20		6438 ± 10
27	6727 ± 10	6744 ± 10		6741 ± 10
28	6844 ± 10	6866 ± 10		6858 ± 10
29	7054 ± 10	7064 ± 20		7068 ± 10
30	(7164 ± 15)			(7178 ± 15)
31	7240 ± 10			7253 ± 10
32	(7313 ± 15)			(7326 ± 15)
33	(7518 ± 15)			(7531 ± 15)
34	7601 ± 20			7614 ± 20
35	7687 ± 10			7700 ± 10
36	(7775 ± 10)			(7788 ± 10)
37	7981 ± 15			7994 ± 15
38	8050 ± 15			8063 ± 15
39	8224 ± 10			8236 ± 10
40	8428 ± 10			8440 ± 10
41	8511 ± 10			8523 ± 10
42	(8798 ± 25)			(8810 ± 25)
43	8903 ± 10			8915 ± 10
44	9001 ± 10			9013 ± 10
45	(9088 ± 20)			(9100 ± 20)
46	9229 ± 20			9240 ± 20
47	9478 ± 25			9489 ± 25
48	9875 ± 50			9886 ± 50
49	10 397 ± 30			10 407 ± 30
50	10 603 ± 20			10 613 ± 20

[a] Energy separations within each multiplet are fixed at the values determined by Gill *et al.* (Ref. 6).

the ten corresponding states between 5.0- and 7.1-MeV excitation the values obtained in the present work are systematically about 15 keV less than those of GMF.

The discrepancy in excitation-energy values is particularly disturbing in the case of the sixth excited state, where we have assigned a probable error of 3 keV. The values of the present work given in Table I are based on the assumption that ^{3}He particles and ^{4}He particles of the same energy produce events in the same channel in the multichannel analyzer. On this assumption the energy of α particles leaving ^{19}Ne in the sixth excited state can be determined very accurately in the present work and almost independently of the calibration curve because of the isolation of this group $^4He_6$, and its close proximity to the elastic scattering group. As partially illustrated in the lower portion of Fig. 2, the root-mean-square deviation from the mean of six values of excitation energy taken from the calibration spectra is 2.0 keV. By measuring the energy of $^4He_6$ relative to the energy for elastic scattering, the error introduced by assuming reasonable errors in bombarding energy, reaction angle, and gas pressure is less than 1 keV.

C. Pulse-Height Correction

The observed difference between excitation energies has led us to extract energies for the first five excited states and compare them with the accurate results of Gill *et al.*,[6] which are also listed in Table I. The spectrum fitting for the unresolved doublet near 250 keV and the triplet near 1500 keV is accomplished under restricted conditions. The Q-value difference between any two components within a multiplet is fixed at the values found by Gill *et al.* Since the widths are fixed by the line-shape calculation,[9] the fitting of the triplet has only five parameters: three cross sections, a constant background, and one centroid. A result of this fitting procedure is shown in Fig. 3. The

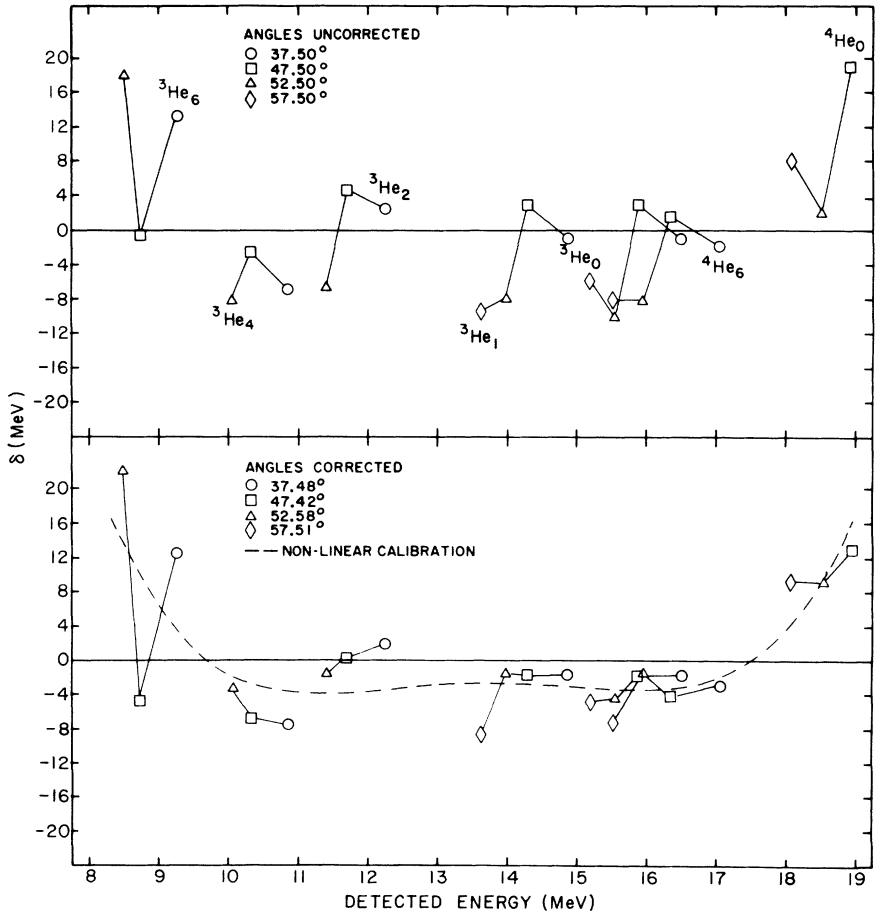

FIG. 2. Deviation of the detected particle energy from a linear calibration curve for 37.5, 47.5, 52.5, and 57.5° spectra. ($\delta = E_{\mathrm{CALIB}} - E_{\mathrm{DET}}$.)

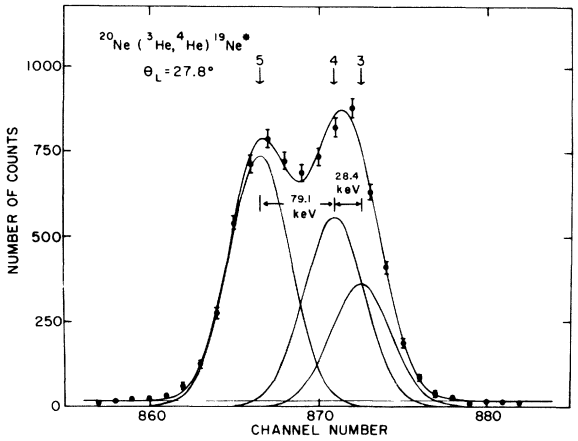

FIG. 3. Spectrum fitting of the excited triplet near 1500-keV excitation. The Q-value separations are fixed at 79.1 and 28.4 keV as determined by Gill *et al.*, and the line shapes are fixed by direct calculation.

energy-level values of the present work given in Table I for the first five levels are based on centroid extractions from the 27.8 and 32.8° spectra only, since reliable extraction of such closely spaced centroids from the other four calibration spectra is impractical because of slightly poorer energy resolution.

The results show that for the first six excited states the values of the present work fall increasingly lower than previously reported values, up to ~18 keV lower for the sixth excited state. Two different effects could produce such results; either the Q value for the ground-state transition is ~20 keV too small, or different calibration curves must be used for ^{3}He and ^{4}He. The Q value for $^{20}Ne(^3He, ^4He_0)^{19}Ne$ is well documented[10] to be 3713.1 ± 1.7 keV.

A recent study[12] of the detection of ^{3}He and ^{4}He particles near 40 MeV by silicon surface-barrier detectors confirms that variations in the output signal from the detector may result from nuclear interactions within the detector. In the absence of actual calculations of this energy defect, we have found that a 0.1% pulse-height deficit of the ^{3}He events relative to the ^{4}He events and the subsequent recalibration brings our results into excellent agreement with those of GMF and Gill *et al.* The final values in the last column of Table I reflect this agreement and extend the correction to the higher excited states.

Recently Häusser *et al.*[13] have found the excited states of ^{20}Ne to be 2 to 5 keV lower than some of the values used in the calibration of the present work. In spite of this the energies for the states of ^{19}Ne above 7-MeV excitation would be affected very little, since the pulse-height-deficit factor is not absolutely fixed.

III. DWBA ANALYSIS AND DISCUSSION

The measured angular distributions were analyzed by use of the local zero-range DWBA code JULIE,[14] using a zero lower-cutoff radius. The differential cross section for a pickup reaction may be written in the form

$$\sigma_{EXP}(\theta) = N \sum_{l,j} S_{l,j} \sigma_{l,j}(\theta), \quad (1)$$

where $\sigma_{EXP}(\theta)$ is the experimentally measured cross section, $\sigma_{l,j}(\theta)$ is the cross section computed by JULIE for the pickup of a particle from the l, j orbit, and $S_{l,j}$ is the corresponding spectroscopic factor including the isospin vector-coupling coefficient. The factor N is not well determined for (^{3}He, ^{4}He) reactions, and theoretical and experimental estimates vary from approximately 10 to 50. It is interesting to note that in a study of the reaction $^7Li(^3He, ^4He)^6Li$, Zander *et al.*[15] have found that a normalization factor is unnecessary if finite-range calculations are performed using a complete interaction potential.

The optical parameters used in the DWBA calculations for $^{20}Ne(^3He, ^4He)^{19}Ne$ are the same as those used by GMF[7] for purposes of comparison of extracted spectroscopic factors. A careful optical-model analysis of our elastic scattering data results in entrance-channel parameter sets which differ only slightly from the two sets of

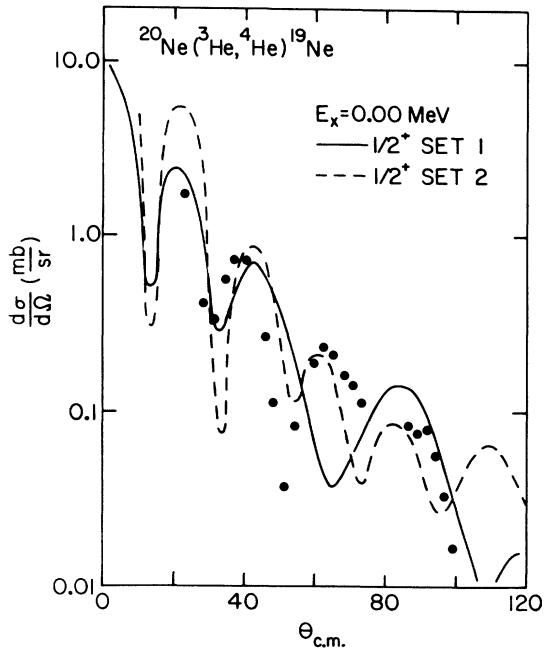

FIG. 4. Angular distributions for the reaction $^{20}Ne(^3He, ^4He_0)^{19}Ne$ at the ^{3}He energy of 18 MeV. Optical-model parameters Set 1 and Set 2 of Ref. 7 are used in the DWBA calculations.

parameters used in the present DWBA calculations.[16]

The α-particle angular distributions for which DWBA calculations have been performed are shown along with the results of those calculations in Figs. 4 and 5. Neither set of optical parameters produce a good representation of the data for the ground-state transition (Fig. 4). The result of parameter Set 1 fits the forward-angle magnitude more closely, while Set 2 better represents the phase. The close correspondence between the data and calculation for the transition to the 2.79-MeV excited state must be considered fortuitous, since a direct pickup mechanism to this $J^\pi = \frac{9}{2}^+$ state would require a large $l = 4$ pair contribution in the ground state of ^{20}Ne. The two strong $l = 1$ transitions to states at 6.01 and 6.74 MeV were also identified by GMF's analysis. Calculations were also performed for the transition to states at 6.29, 6.86, and 8.24 MeV, since the corresponding angular distributions exhibited some structure. No assignments of angular momentum transfer can be made for these states, because of the meager amount of forward-angle data.

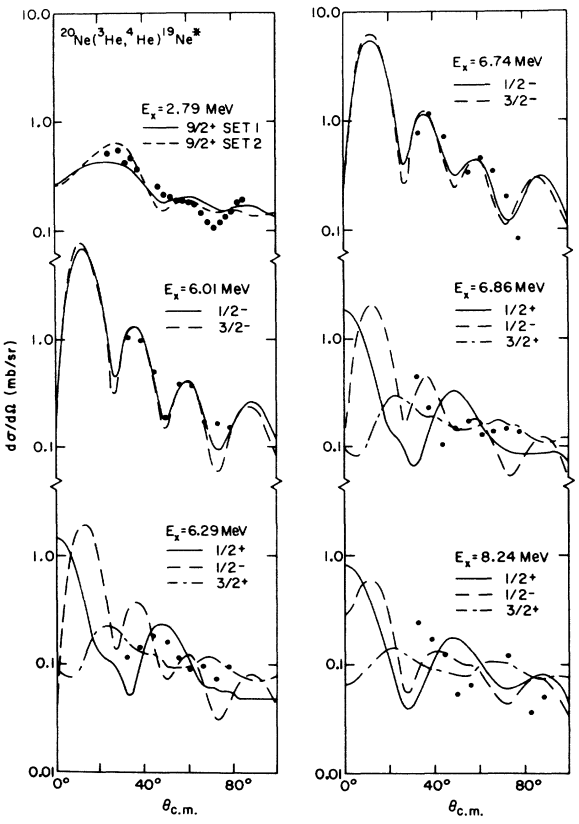

FIG. 5. Angular distributions of ^{4}He particles for several excited states (E_x) in ^{19}Ne populated by the reaction ^{20}Ne(^{3}He,^{4}He)^{19}Ne at the ^{3}He energy of 18 MeV. Optical-model parameters Set 1 of Ref. 7 are used in the DWBA calculations for all excited states. Both sets of optical-model parameters of Ref. 7 are used in the DWBA calculations for the state at $E_x = 2.79$ MeV.

Relative spectroscopic factors NS_{lj} are listed in Table II. The values extracted for the first five excited states in the present work are based on cross-section measurements at the two forward angles only. The curves corresponding to the remainder of the values listed under present work, Set 1, are those displayed in Figs. 4 and 5.

In the weak-coupling model there will be five low-lying states in ^{19}Ne with $J^\pi = \frac{1}{2}^-, \frac{3}{2}^-$, formed by coupling of a $1p$ hole to the ground-state rotational band of ^{20}Ne. Although only two of the states can be excited directly, a mixing of weak-coupling wave functions would allow all five states to be

TABLE II. Spectroscopic factors.

Level No.	Excitation energy (MeV)	l_n	J^π_n	$\sigma_{EXP}/\sigma_{JULIE}$ Set 1	Set 2	GMF[a] $\sigma_{EXP}/\sigma_{JULIE}$ Set 1	Set 2
0	0.0	0	$\frac{1}{2}^+$	6.4	26.9	3.8	8.0
1	0.24	2	$\frac{5}{2}^+$	48.8	···	33.0	45
2	0.28	1	$\frac{1}{2}^-$	46.8	59.9	62	···
3	1.51	3	$\frac{5}{2}^-$	8.1	13.8	···	···
4	1.54	2	$\frac{3}{2}^+$	12.6	30.5	23	33
5	1.61	1	$\frac{3}{2}^-$	9.4	13.9	6.5	···
6	2.79	4	$\frac{9}{2}^+$	5.5	16.8	···	···
7	4.04	2	$\frac{3}{2}^+$	···	···	3.0	7.0
11	4.55	1	$\frac{1}{2}^-$	···	···	15	···
			$\frac{3}{2}^-$	···	···	11.5	···
16	5.35	0	$\frac{1}{2}^+$	···	···	0.45	1.3
21	6.01	1	$\frac{1}{2}^-$	38.7	75.3	43	···
			$\frac{3}{2}^-$	31.3	57.8	33	···
24	6.29	0	$\frac{1}{2}^+$	0.5	···	···	···
		1	$\frac{1}{2}^-$	11.1	···	···	···
		2	$\frac{3}{2}^+$	1.8	···	···	···
27	6.74	1	$\frac{1}{2}^-$	37.4	122.3	84	···
			$\frac{3}{2}^-$	33.9	80.4	70	···
28	6.86	0	$\frac{1}{2}^+$	0.7	···		
		1	$\frac{1}{2}^-$	15.0	···		
		2	$\frac{3}{2}^+$	2.6	···		
39	8.24	0	$\frac{1}{2}^+$	0.4	···		
		1	$\frac{1}{2}^-$	4.8	···		
		2	$\frac{3}{2}^+$	1.3	···		

[a]See Ref. 7.

TABLE III. Summed strengths for neutron pickup from various spin identifications and comparison with sum rule.

Case	$(s-d)$ levels	$J^\pi = \frac{1}{2}^-$ levels	$J^\pi = \frac{3}{2}^-$ levels	$N\sum S$ $(s-d)$	$N\sum S$ $(p_{1/2})$	$N\sum S$ $(p_{3/2})$	$\frac{\sum S(s-d)}{\sum S(s-d)} : \frac{\sum S(p_{1/2})}{\sum S(s-d)} : \frac{\sum S(p_{3/2})}{\sum S(s-d)}$
I	0.00 0.24 1.54 4.04 [a] 5.35 [a]	0.28	1.61 4.55 [a] 6.01 6.74	71.25	46.8	86.1	1 : 0.65 : 1.21
II		0.28 4.55	1.61 6.01 6.74	71.25	61.8	74.6	1 : 0.87 : 1.05
III		0.28 6.01	1.61 4.55 6.74	71.25	85.5	54.8	1 : 1.20 : 0.77
IV		0.28 6.74	1.61 4.55 6.01	71.25	84.2	52.2	1 : 1.18 : 0.73
Sum-rule prediction							1 : 1 : 2

[a] Spectroscopic factors for these energy levels are taken from Ref. 7.

observed with a combined spectroscopic strength of the ^{20}Ne ground state coupled to a $1p$-hole state. If a core-excitation reaction mechanism takes place then the other three weak-coupling wave function components could be excited. These two-step cross sections are assumed to be small and are ignored in the sum-rule arguments to follow.

The five low-lying states in ^{19}Ne at 0.27, 1.61, 4.55, 6.01, and 6.74 MeV have been identified[7] with the five $1p$ states from the weak-coupling model. The relative-spectroscopic-factor sum rule of the weak-coupling model is compared with the results of the present work in Table III for various combinations of energy levels given J^π assignments of $\frac{1}{2}^-$ and $\frac{3}{2}^-$. Relative spectroscopic factors for states not observed in the present work are taken from published results.[7]

Any prior favoritism for case II, in which states at 6.01 and 6.74 MeV have $J^\pi = \frac{3}{2}^-$, and the state at 4.55 MeV has $J^\pi = \frac{1}{2}^-$, is somewhat diminished in view of the results of Table III for the following reasons. None of the summed relative $1p_{1/2}$ strengths in cases II–IV deviate by more than 20% from the sum-rule prediction, and in all cases the summed relative $1p_{3/2}$ strengths fall precipitously below the sum-rule prediction. In addition the appreciable cross sections observed for excitation of the $J^\pi = \frac{9}{2}^+$ state at 2.79 MeV and the $J^\pi = \frac{5}{2}^-$ state at 1.50 MeV indicate that the cross section for core-excitation processes may not be small, thus opening the entire sum-rule argument to question. In view of these possibilities, no preference is made for $J^\pi = \frac{3}{2}^-$ or $\frac{1}{2}^-$ assignments for the energy levels in question.

The energy level at 7614 ± 20 keV, listed in Table I, may be the $J^\pi = \frac{3}{2}^+$, $T = \frac{3}{2}$ state previously reported at 7620 ± 25 keV by Hardy *et al.*[17] Assuming this to be the case, a DWBA analysis of our extracted cross section places an upper limit on the isospin impurity of this state at 2 to 4%. Although the data are poor, it should be noted that the differential cross section extracted from the calibration spectra is nearly isotropic.

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Photodisintegration of the Trinucleons

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We calculate the photodisintegration integrated (σ_{int}) and bremsstrahlung-weighted (σ_b) cross sections of the trinucleons (H^3 and He^3) by applying the sum rules of Levinger and Bethe. The ground state of the trinucleon is assumed to be a mixture of symmetric S state, the mixed symmetric S' state, and the D states; the radial dependence of all these states being (a) Gaussian and (b) Irving. We obtain the parameters of the radial part of these wave functions from a variational calculation of the binding energy of the triton using the velocity-dependent potential of Nestor *et al.* Our results for σ_{int} show good agreement with experiments.

A comparison with similar calculations using hard-core potentials shows the inability of σ_{int} calculations to distinguish between hard-core and velocity-dependent potentials. This feature of σ_{int} calculations, which is common at least to all the nuclei in the 1s shell, is explained in terms of the well-known range-depth relationship for the two-body potentials.

I. INTRODUCTION

Most of the earlier calculations[1-4] on the photodisintegration integrated $[\sigma_{int} = \int_0^\infty \sigma(W)dW]$ and bremsstrahlung-weighted $\{\sigma_b = \int_0^\infty [\sigma(W)/W]dW\}$ cross sections of the trinucleons are not realistic, because either the tensor component or hard core (or velocity dependence) in the two-body potential used in them is neglected. Only recently Lucas[5] and Davey and Valk[6] have employed hard-core realistic forces containing tensor components to calculate σ_{int} and σ_b for the three-nucleon systems. But so far no such calculation has been performed with a realistic velocity-dependent potential. In the present paper we apply the sum rules of Levinger and Bethe[7] to present the first such calculation of σ_{int} and σ_b of trinucleons using a velocity-dependent potential, viz., that of Nestor *et al.*[8](only singlet-even and triplet-even parts of the potential have been considered). The static central and tensor parts of the potential contain Majorana exchange force, while the velocity-dependent part is assumed to have Wigner character. We assume the ground-state wave function to be a mixture of the spherically symmetric S state, the mixed symmetric S' state, and the D states. The radial dependence of all these states is assumed to be (a) Gaussian and (b) Irving, whose parameters are determined by a variational calculation of the binding energy of the triton (H^3). On account of the charge