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^{24}Mg states observed via ^{20}Ne$(\alpha,\alpha_0)^{20}$Ne

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We report differential cross-section measurements at up to 16 angles for the reaction ^{20}Ne$(\alpha,\alpha_0)^{20}$Ne for $3.8 \le E_\alpha \le 11$ MeV in steps ≤ 15 keV. The target was a differentially pumped windowless gas target of high-purity Ne, buffered by He to reduce the rate of Ne outflow. A total of 39 levels in ^{24}Mg ($12.5 < E_x < 18.2$ MeV) were analyzed by writing the reaction amplitude for spinless positive-parity particles as a nonresonant term which varies linearly with energy plus a sum over only resonant partial waves. In addition, 56 other levels and 22 possible levels were also identified over the same energy region.

I. INTRODUCTION

Early scattering data[1] of MeV α particles by ^{20}Ne showed rich resonant structure corresponding to ^{24}Mg states. The zero spin of both the α particle and the ^{20}Ne ground state permit unambiguous spin and parity assignment to these states if isolated and if differential cross sections at a sufficient number of angles is known. With modern computers and analysis techniques, often level assignments and parameter extraction are still possible even for badly overlapping levels if one has reliable and extensive differential cross sections. The present work provides $\sim 10\,000$ such extensive differential cross-section measurements taken some 16 years ago to exploit the multidetector differentially pumped gas scattering chamber which had been modified to reduce the outflow of neon gas to tolerable levels.[2] Previous data[3] were limited to ≤ 4 angles, $E_\alpha \le 4$ MeV or > 10.25 MeV.[4,5,2] The present data, at up to 16 angles, fills the gap between $E_\alpha = 3.8$ MeV and 11 MeV. We also have some inelastic α scattering data which we will report on later.

II. EXPERIMENTAL PROCEDURE

A locally developed He$^-$ source[6] for our Pelletron-charged EN tandem provided ~ 1 μA of He^{++} through the differentially pumped neon-gas target and multidetector scattering chamber.[6] A helium buffer gas introduced just behind the last beam defining aperture reduced neon outflow by a factor of 3 without appreciable back flow of helium into the chamber[7] (as measured by monitoring elastically scattered α's from helium). A precision quartz Bourdon gauge measured the pressure of natural neon of 99.99% minimum purity and also gave a signal to regulate the pressure.[8] The natural abundances of the three stable neon isotopes are ^{20}Ne:^{21}Ne:^{22}Ne $=90.48\%:0.27\%:9.25\%$. A suppressed Faraday cup[9] in a vacuum region behind a thin metal foil collected the exiting He^{++} beam. Up to 16 detector telescopes at various angles measured simultaneously the α scattering cross sections. Each telescope consisted of a totally depleted surface barrier detector and a double slit system with a G factor[10] calibrated[6] earlier by p-p elastic scattering. Each detector's spectrum was stored by a computer (permitting on-line monitoring) and written on magnetic tape for off-line analysis. Figure 1 shows a sample spectrum. A local program ANALUS[11,12] performed background subtractions and extracted yields.

The generally small statistical errors are shown only if larger than the datum point. Systematic errors ($\sim 2\%$) discussed in Refs. 7 and 11 include beam heating of the target gas, G-factor calibration, angle uncertainty, gas pressure, temperature, contamination (e.g., by backflowing helium), integrated beam charge, and beam-energy calibration.

Over most of the excitation range the energy steps were 10 or 15 keV. In some areas of sharp but closely spaced structure the energy steps were only a few keV.

III. RESULTS

Figures 2–4 show our $\sim 10\,000$ elastic-scattering differential cross sections as a function of α energy for the 16 angles studied. Since the resulting data compaction make these plots only useful for qualitative considerations, we have deposited the 68 pages of differential cross sections with the AIP Physics Auxiliary Publications Service.[13]

For a reasonably isolated resonance, even a qualitative examination of its behavior at angles near where various $P_L(\cos\theta)$ have zeros or maxima often is sufficient to assign unambiguously the L (and hence J^π) of the corresponding compound nuclear state in ^{24}Mg. One may also estimate Γ and the resonant energy. However, for extracting more accurately the resonant parameters, especially if several states interfere, one needs the quantitative analysis described in Sec. IV.

Unfortunately the number of relevant ^{24}Mg states are large and our computer facilities available at analysis time were not adequate to handle the complexity needed to achieve the spectacular fits over extended energy ranges that Caskey and Riedhauser have since reported.[14,15] Nevertheless, Figs. 5–8 give samples of some of our good fits.

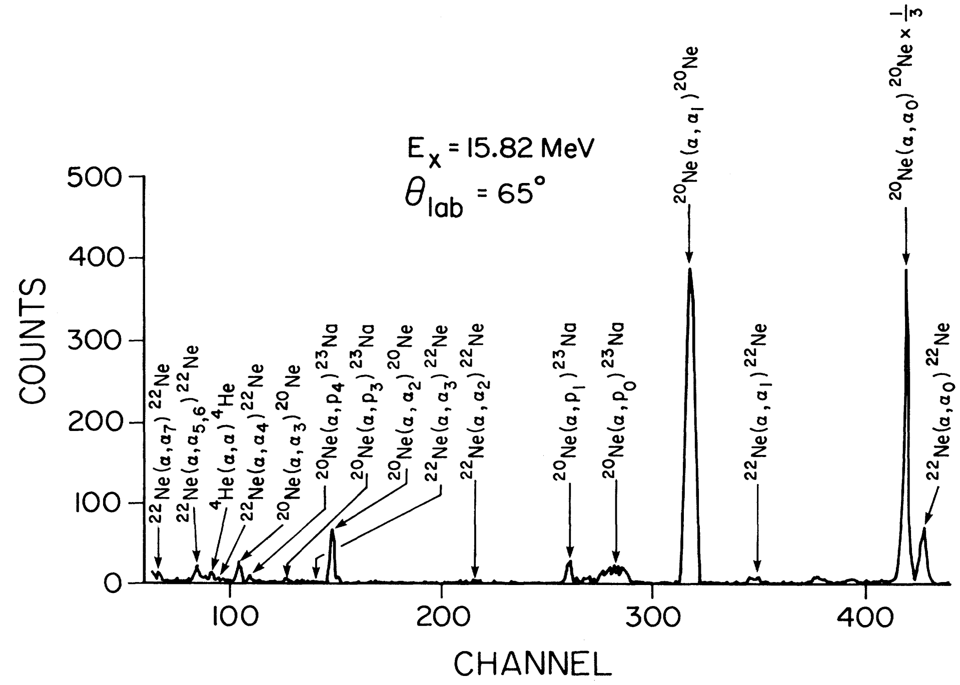

FIG. 1. Spectrum of alphas scattered at $\theta_{\text{lab}}=65°$ at $E_{\text{c.m.}}=6.508$ MeV from neon. Protons from the $^{20}\text{Ne}(\alpha,p_0)$ reaction have not deposited their full energy in the detector. Other proton peaks, as well as α's from ^{22}Ne scattering, are easily identified in the spectrum.

IV. ANALYSIS

The most complete decription of any reaction is provided in the S-matrix formalism. For a spin system $0^+ + 0^+ \to 0^+ + 0^+$, $l_{\max}+1$ S-matrix elements, where $l_{\max}$ is the largest orbital angular momentum contributing to the scattering amplitude, are required. The resonant parameters are then derived from the energy dependence of the various S matrix elements. However, one must choose from many independent solutions at one energy and follow that solution from energy to energy, an almost hopeless task. Instead, the reaction is separated into a nonresonant and resonant amplitudes, following Häusser *et al.*[16] and Billen.[11] The nonresonant amplitude $\rho(\theta,E)$ varies linearly with energy, as does the phase difference $\phi_l(\theta,E)$ between each resonance and the nonresonant background:

$$\frac{d\sigma}{d\Omega}(\theta,E)=\left|\rho(\theta,E)\exp[i\chi(\theta)]+\frac{i}{2k}\sum_{l=l_r}(2l+1)\frac{\Gamma_0}{\Gamma}[\exp(2i\beta_l)-1]\exp[2i\phi_l(\theta,E)]P_l(\cos\theta)\right|^2 , \tag{1}$$

where $\chi(\theta)$ is the phase of the nonresonant term, which in actual computation is set equal to zero as there is one overall phase that can be ignored, and where the sum is over resonances in the fitting region. The resonant phase shift is given by

$$\beta_l=\arctan\left[\frac{\Gamma/2}{E_r-E}\right] . \tag{2}$$

The parameters $\rho(\theta,E)$ and $\phi_l(\theta,E)$ were adjusted separately at each angle θ, but the resonant parameters E_r,Γ, and the partial width Γ_0, were the same for all angles and energies of the fitting region. The gas target thickness was typically ~1 keV but is, of course, a function of angle. Hence for a very narrow resonance the resulting additional laboratory width is angular dependent and this makes a good fit difficult.

Neglect of nearby resonances or tails of more distant broad states also may result in unsatisfactory fits. Even then, qualitative considerations from simple inspection at various angles often can give estimates for Γ, E_α, and assign or restrict J^π: see the discussion in Sec. III. This procedure plus the finite-size energy steps perhaps tends to overestimate Γ for narrow resonances. For any resonance strong interference between levels of comparable Γ may make both levels extremely difficult to assign unless one achieves quantitative fits.

Table I summarizes our results. Those levels whose pa-

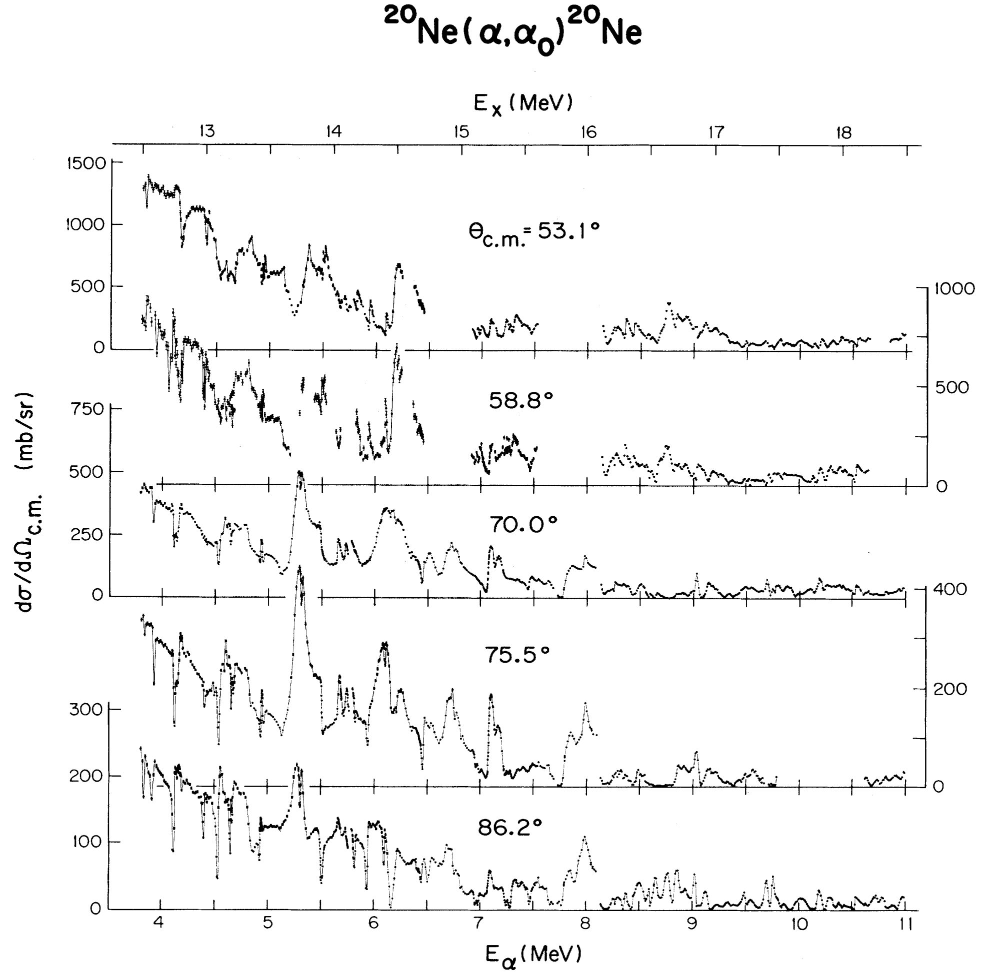

FIG. 2. Excitation functions for elastically scattered alphas from ^{20}Ne at forward angles.

rameters derive from fitting by Eq. (1) have uncertainty estimates listed. These errors are not from a complete error matrix calculation but come from Billen's *ad hoc* procedure,[11] which neglects correlations between parameters: the program varies each parameter (with all others held fixed) until the χ^2 doubles. This parameter change is our error estimate and is probably optimistic. All level parameters with no assigned error result from visual estimates: either no fits were attempted or they were unsuccessful. Uncertain resonances or spin assignments are in parentheses. The energy uncertainty for each resonance is probably not much better than 10 keV, a little worse for wider resonances. This error arises principally from uncertainty in the beam-energy calibration; poor knowledge of the pressure profile and He/Ne mixture at the beam-entrance collimator; and difficulty in estimating the resonant energy (for unfit resonances), especially in the presence of background. Energy resolution depends primarily on target length and would therefore be slightly different for each detector's slit assembly and angle. This is typically 2 keV, which is smaller than our smallest step size, and is insignificant for most of our observed resonances. It was not adjusted for in the fits. Because of the method of analysis, errors in $\Gamma_{\mathrm{c.m.}}$ and Γ_0/Γ are lower limits.

Observations from previous work are indicated in the right-hand-side columns of Table I. Table II gives the χ^2 per degree of freedom for the fitted regions of 1 to 5 resonances each.

The levels and some fits are discussed in more detail in Sec. V.

V. DISCUSSION OF FITS AND IMPLIED ^{24}Mg STATES

Many studies of ^{24}Mg at our excitation energy have located and assigned the major states, see Table I. We will not comment where our data and analyses are consistent with earlier work, even though our partial-wave fits often yield new (e.g., Γ_α/Γ) and/or improved resonance parameters. Instead our focus will be on new states and disagreements with previous work. Many resonances have only visual estimates of energies and widths, and we have often made speculative J^{π} assignments (or limits) based upon the angular behavior. In these cases, not surprisingly, the agreement with other work is less, since with poor parameters one is less confident that the levels seen in other reactions correspond.

Region A: $E_{\alpha}<5$ *MeV*. At some angles we have marginal evidence for a very weak narrow resonance at $E_{\alpha}=4.01$ MeV. Although many others have seen a narrow state near this excitation energy, the suggested spin assignments of 3^- or 4^+ would be inconsistent with our seeing it at 143.1° and 70°.

Figure 5 shows a reasonable fit ($\chi^2=3.1$) in the neighborhood of $E_{\alpha}\sim4.15$ MeV, which employs four resonances: a strong 2^+ seen often before, with a weak possible (4^+) that improves the fit and for which there is some previous evidence in ^{24}Mg(e,e'),[24] and a 0^+ and 1^- doublet about which previous sightings are ambiguous. The fit might be improved by inclusion of even more narrow structure, for example, around $E_{\alpha}=4.1$ MeV (cf. $\theta=53°$ and 70°) and at 4.2 MeV ($\theta=91°$ and hence even-J, $\theta=107°$, and hence probably not 4^+). But structure that is finer than the data step size do not, in general, give an improved fit. This unfit structure may have a deleterious effect on resonance parameters and their errors, especially if it is of the same J^{π}, see Sec. IV above, e.g., the above 2^+ that in our case appears wider than previous work.

While the $E_{\alpha}=4.400$ MeV resonance was too narrow to fit satisfactorily, the unambiguous 4^+ assignment is consistent with previous work except for the (p,γ) reaction[30] which, however, may include unnatural parity

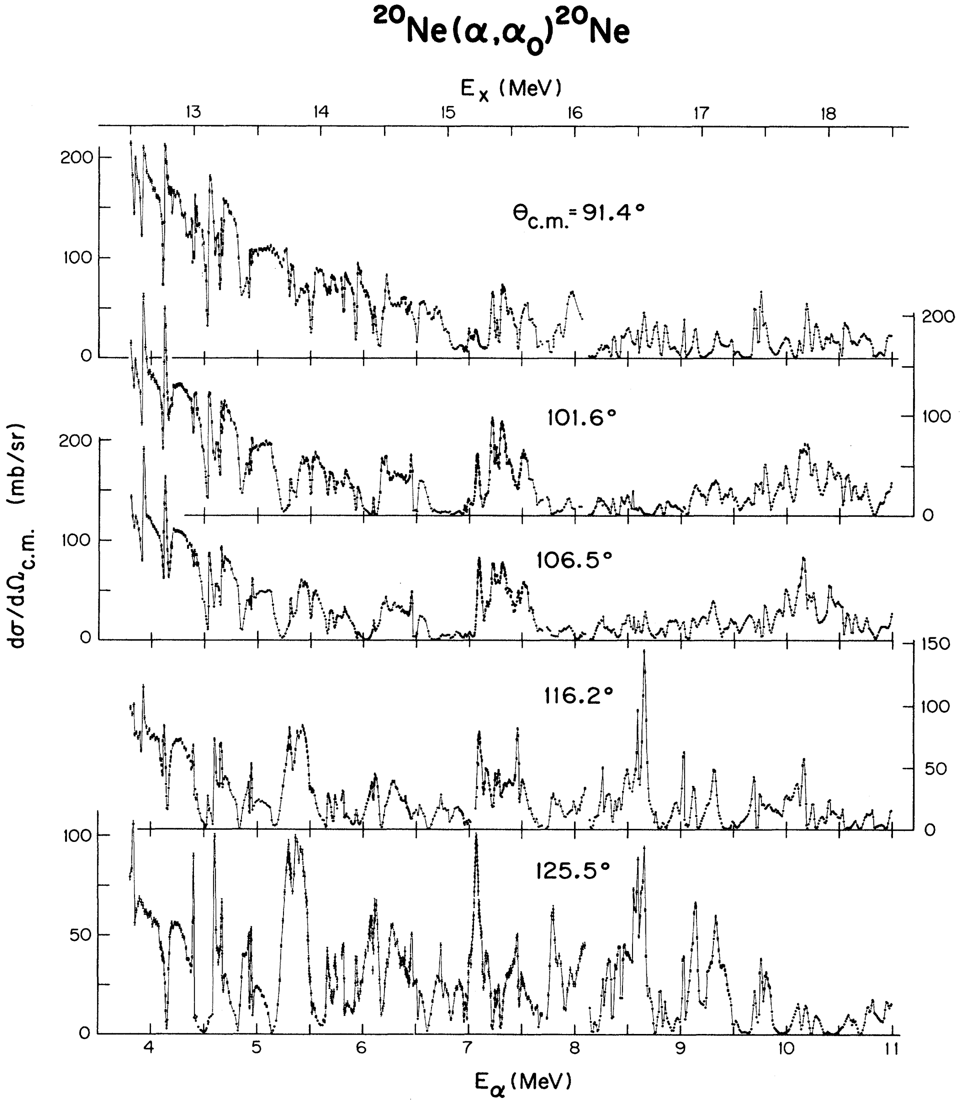

FIG. 3. Same as Fig. 2 for intermediate angles.

states in ^{24}Mg.

There is a narrow ($\Gamma \simeq 10$ keV) resonance at $E_\alpha = 4.427$ MeV, even spin (cf. 91.4° and 86.2° data) and probably 6^+, since the 125.5° and 70.0° data show resonant yield (near zeros of P_2 and P_4) while the resonance almost vanishes at 75.5° (near a zero of P_6), though 0^+ may still be possible.

There is a single point deviation in the data trend at a number of angles at $E_\alpha = 4.478$ MeV. This seems to vanish at 86.2° and 91.4°, implying odd spin. It probably corresponds to the narrow state observed[33] in (p,p_1) at $E_x = 13.031$ MeV. This is some 10 keV below our E_x, but they report an average discrepancy, of unknown origin, of -4 keV for 20 other resonances.

Except for the widths being too large, the two 2^+ levels at $E_\alpha = 4.535$ and 4.654 MeV are consistent with earlier studies; however, the χ^2's for our fits are not good (see Table II) and may arise from neglect of other nearby states: heavy-ion reactions report 5^- and 8^+ assignments, and (p,α) reactions indicate 3^-, in the neighborhood (see Table I).

Our 4^+ state at $E_\alpha = 4.668$ MeV probably corresponds to the 4^+ state at ~ 13.13 MeV suggested by Ref. 38 to account for their α-α correlations in ^{16}O(^{12}C,α)^{24}Mg(α)^{20}Ne.

At $E_\alpha = 4.834$ MeV, a good χ^2 is achieved with a 0^+ assignment, which is convincing as it can be clearly seen near 90°; however, the width is considerably larger than reported elsewhere, and Γ_0/Γ exceeds 1 by 33%. There is probably a 1^-, consistent with the (p,α_0) result[33] at an

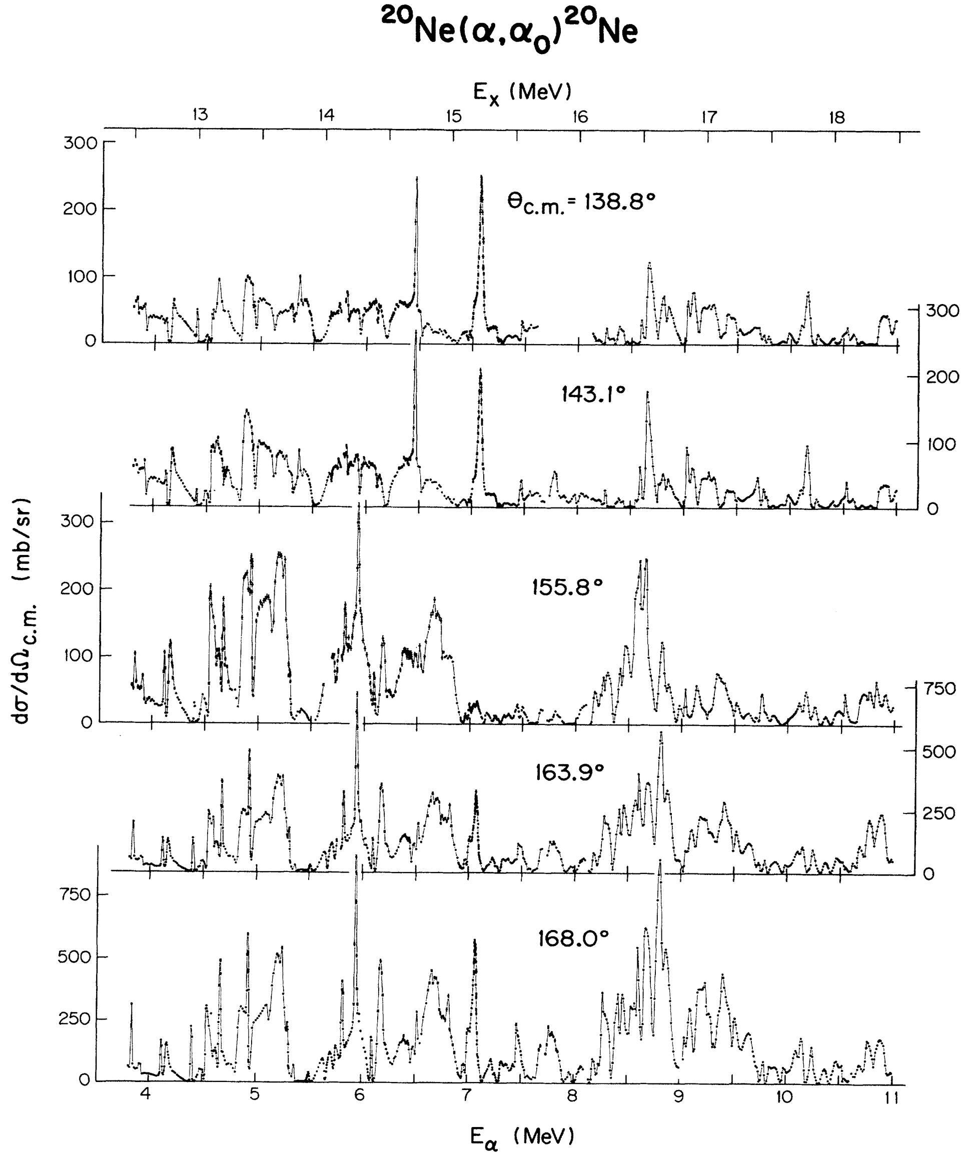

FIG. 4. Same as Fig. 2 for back angles.

TABLE I. Summary of resonant parameters and comparison with previous work. Error estimates are given only for the data that were fitted by Eq. (1) and represent only the error associated with the fitting procedure. Less certain resonances, determined from inspection of the excitation functions, or uncertain spin-parity assignments (and their corresponding partial widths) are indicated in parentheses. An asterisk by the J^{π} indicates a possible doublet, only one of which need be the indicated spin and/or parity.

E_{α} (MeV±keV)[a]	E_x (MeV)	J^{π}	$\Gamma_{\mathrm{c.m.}}$ (keV)[a]	Γ_{α}/Γ ×100[a]	Previous work E_x	J^{π}	Γ	Ref.	
3.883	12.504	$4^{+\mathrm{b}}$	≤8		12.509^{c}	4^{+}	<1	3	α,α_0
					12.501^{d}		2.3±0.3	17	α,γ
					12.506^{e}	$(2^{+},4^{+})$		18	α,γ
					12.508	$L=4^{\mathrm{f}}$		19	$^{24}\mathrm{Mg}(p,p')$
					12.49	$4^{+\mathrm{g}}$		20	HI
					12.497^{h}	4^{+}		21	p,α
3.922±2	12.578	2^{+}	5.2±0.9	72±4	12.579^{c}	2^{+}	6±1	3	α,α_0
					12.576^{e}	2^{+}		18	α,γ
					12.572^{d}		6.2±0.6	17	α,γ
					12.56	$2^{+\mathrm{i}}$		22	$^{24}\mathrm{Mg}(\alpha,\alpha')$
					12.578	$L=2^{\mathrm{f}}$		19	$^{24}\mathrm{Mg}(p,p')$
					12.564	$0^{+},1^{-},2^{+\mathrm{j}}$		23	p,α
					12.567^{h}	2^{+}		21	p,α
					12.6	$2^{+\mathrm{k}}$		24	$^{24}\mathrm{Mg}(e,e')$
(4.01)	12.65		narrow	weak	12.653	$3^{-\mathrm{l}}$		25	p,α
					12.656^{d}		0.9±0.3	17	α,γ
					12.651	$3^{-\mathrm{j}}$		23	p,α_0
					12.663	$L=3^{\mathrm{f}}$		19	$^{24}\mathrm{Mg}(p,p')$
					12.641^{e}			18	α,γ
					12.6516^{m}		1.1±0.6	26	p,γ
					12.6531		0.8±0.1	27	p,α
					12.6514^{n}		<0.5	28	p,γ
					12.6605^{n}		4.0±0.5	28	p,γ
					12.653^{h}			21	$p,p;p,\alpha$
					12.660			29	p,α
					12.64	4^{o}		30	p,γ
(~4.10)	12.73								
4.114±1	12.738	2^{+}	11±2	74±6	12.739	$L=2^{\mathrm{f}}$		19	$^{24}\mathrm{Mg}(p,p')$
					12.734^{e}	2^{+}		18	α,γ
					12.734^{d}		8.3±0.5	17	α,γ
					12.729	$2^{+\mathrm{p}}$		31	p,α
					12.7297^{m}		6.7±1.0	26	p,γ
					12.7307		7.9±0.5	27	p,α
					12.739^{q}	2^{+}		32	$\alpha,p;\alpha,\alpha\gamma$
					12.8	$2^{+\mathrm{k}}$		24	$^{24}\mathrm{Mg}(e,e')$
					12.725	$2^{+\mathrm{r}}$	$\Gamma_0=7.0(\pm10\%)$	33	p,α_0
					12.729	$1^{-},2^{+\mathrm{j}}$		23	p,α
					12.736^{s}			34	$^{24}\mathrm{Mg}(p,p')$
					12.730	$0^{+},1^{-},(2^{+})^{l}$		25	p,α
					12.729^{t}		5±10 %	35	$p,\alpha\gamma$
4.117±2	12.741	(4^{+})	2±2	18±4	12.7	$(4^{+})^{\mathrm{k}}$		24	$^{24}\mathrm{Mg}(e,e')$
4.153±7	12.771	0^{+}	34±18	40±14					
4.161±2	12.777	1^{-}	28±4	66±6	12.772^{t}		25±20%	35	$p,\alpha\gamma$
					12.774^{s}			34	p,p'
					12.775^{q}		$28\pm9^{\mathrm{u}}$	32	$\alpha,p';\alpha,\alpha'\gamma$
					12.773	$(0^{+})^{\mathrm{v}}$	30±5	27	p,α
					12.773	$0^{+},1^{-}(2^{+})^{l}$		25	p,α
					12.772	$1^{-},2^{+\mathrm{j}}$		23	p,α
					12.764	$2^{+\mathrm{r}}$	$\Gamma_0=30\pm20\,\%$	33	p,α
(4.2)	12.81	$(\mathrm{even})^{\mathrm{b}}$	narrow		12.804^{e}	2^{+}		18	α,γ
					12.805^{q}	2^{+}		32	$\alpha,p';\alpha,\alpha'\gamma$
					12.8	$L=2^{\mathrm{w}}$		36	$^{24}\mathrm{Mg}(\alpha,\alpha')$
					12.797	$0^{+},1^{-},2^{+\mathrm{j}}$		23	p,α
					12.7938	$2^{+\mathrm{r}}$	$\Gamma_0=0.8$	33	p,α_0
					12.7985^{m}		0.9±0.6	26	p,γ
					12.84	$2^{+\mathrm{i}}$		22	$^{24}\mathrm{Mg}(\alpha,\alpha')$

TABLE I. (*Continued*).

E_α (MeV±keV)^{a}	E_x (MeV)	J^π	$\Gamma_{\mathrm{c.m.}}$ (keV)^{a}	Γ_a/Γ $\times 100^{a}$	Previous work				
					E_x	J^π	Γ	Ref.	
					12.804^{d}		2.3 ± 0.3	17	α,γ
					12.8084^{n}		1.5 ± 0.1	28	p,γ
					12.800^{h}	(2^+)		21	p,α
					12.812	$L=2^{f}$		19	^{24}Mg(p,p')
					12.800	$(0^+,1^-),2^{+\,l}$		25	p,α
					12.806			29	p,α
4.400	12.976	$4^{+\,b}$	≤ 8		12.972^{q}	$4^+,5^-,(6^+)$		32	$\alpha,p';\alpha,\alpha'\gamma$
					12.969^{d}		3.3 ± 0.3	17	α,γ
					12.961		6.7 ± 0.2	27	p,γ
					12.973	$L=4^{f}$		19	^{24}Mg(p,p')
					12.96	1^{x}		30	p,γ
					12.945			29	p,α
(4.427)	12.999	$(6^+)^{b}$	~ 10						
(4.478)	13.041	odd^{b}	≤ 10		13.031		3.7 ± 0.5	33	p,p_1
4.535 ± 2	13.089	2^+	14 ± 3	53 ± 7	13.14	$2^{+\,i}$		22	^{24}Mg(α,α')
					13.1	$L=2^{w}$		36	^{24}Mg(α,α');(p,p')
					13.1	2^{+k}		24	^{24}Mg(e,e')
					13.082	$(0^+),1^-,2^{+\,l}$		25	p,α
					13.083^{e}	2^+		18	α,γ
					13.0824		9.8 ± 0.2	27	p,α
					13.079^{m}		7.8 ± 1.0	26	p,γ
					13.088	$L=2,3^{f}$		19	^{24}Mg(p,p')
					13.078			29	$p,\gamma;p,p$
					13.079^{t}		$7\pm20\,\%$	35	$p,\alpha\gamma;p,p'$
					13.089^{q}	(2^+)		32	$\alpha,p\gamma;\alpha,\alpha\gamma$
					13.083^{d}		11.9 ± 0.6	17	$\alpha,\gamma;\alpha,\alpha\gamma$
					13.041	$2^{+\,j}$		23	p,α
					13.080	$3^-,(1^-)^{j}$		23	p,α
					13.082^{h}	3^-		21	$p,\alpha;p,p$
					13.076	$3^{-\,r}$	$\Gamma_0=0.25\pm10\,\%$	33	p,α
					13.0794^{n}		6.0 ± 0.5	28	p,γ
					13.07	$5^{-\,g}$		20	HI
					13.070	$(5^-)^{y}$		41	HI
					13.07	$5^{-\,z}$		44	HI
					13.06			37	HI
4.654 ± 2	13.188	2^+	12 ± 3	59 ± 8	13.181	$L=2^{f}$		19	^{24}Mg(p,p')
					13.183^{s}			34	^{24}Mg(p,p')
					13.167	$(0^+,2^+,3^-)^{r}$	5.5 ± 0.5	33	p,α_0
					13.120	$2^{+\,j}$		23	p,α
					13.174	$(2^+)^{j}$		23	p,α
					13.192	$0^+,1^-,2^{+\,l}$		25	p,α
					13.1751^{m}			26	p,γ
					13.179^{d}		5.6 ± 0.4	17	α,γ
					13.19			37	HI
					13.1761		6.5 ± 0.5	27	p,α
					13.175^{t}		$4\pm20\,\%$	35	$p,\alpha\gamma$
					13.20	$(8^+)^{y}$		41	HI
					13.13	$(7^-,8^+)^{\alpha}$		52	HI
4.668 ± 2	13.200	4^+	14 ± 3	57 ± 6	13.20	$4^{+\,\beta}$		38	HI
					13.194^{d}		2.7 ± 0.4	17	α,γ
					13.192	$(0^+)^{v}$	<10	27	p,α
					13.185	$(1^-)^{r}$	3 ± 1	33	p,α
4.834 ± 1	13.338	$0^{+\,*}$	42 ± 3	$\sim 100^{\gamma}$	13.329^{d}		33 ± 3	17	α,γ
					13.344	$L=3^{f}$		19	^{24}Mg(p,p')
					13.321	$1^{-\,r}$	$\Gamma_0=25\pm20\,\%$	33	p,α
					13.35			39	α,γ
4.925	13.414	$(4^+)^{b}$	~ 4		13.416^{d}		3.2 ± 0.7	17	α,γ
					13.4099		4 ± 1	27	p,α
					13.4101^{m}		4.1 ± 0.7	26	p,γ

TABLE I. (*Continued*).

E_α	E_x		$\Gamma_{\rm c.m.}$	Γ_α/Γ	Previous work				
(MeV±keV)[a]	(MeV)	J^π	(keV)[a]	×100[a]	E_x	J^π	Γ	Ref.	
					13.4030	$(1^+,2^+)$[r]		33	p,p
					13.404[e]	$(1^-,2^+)$		18	α,γ
					13.413	(2^+)[j]		23	p,α
4.935	13.422	(odd)[b]	~8		13.440	$L=3$[f]		19	^{24}Mg(p,p')
					13.413	$1^-,2^+$[l]		25	p,α
					13.4056	3^-[r]	$\Gamma_0=0.75\pm10\,\%$	33	p,α_0
					13.4126		6±1	27	p,α
(4.948)	13.433	(even)[b]	narrow						
4.95	13.43		~17		13.48	2^+[i]		22	^{24}Mg(α,α')
					13.42	6^+[β]		38	HI
					13.428[d]		15±2.5	17	α,γ
					(13.429)[e,δ]			18	α,γ
					13.434[d]		<1	17	α,γ
					13.440	$L=3$[f]		19	^{24}Mg(p,p')
					13.445		3.2±0.2	27	p,α
					13.4376	2^+[r]		33	p,p
					13.45			40	HI
					13.45			41	HI
					13.44			42	HI
					13.44			43,44	HI
5.128±2	13.583	1^-	33±5	44±4	13.579[d]		21±2.3	17	α,γ
					13.579	1^-[l]		25	p,α
					13.5764		23±3	27	p,α
					13.5777[m]		8.0±1.0	26	p,γ
					13.570	$(1)^-$[r]	$\Gamma_0=30\pm20\,\%$	33	p,α
5.245	13.680		≤13	weak	13.671	$0^+,1^-,2^+$[l]		25	p,α
					13.671		8.7±0.5	27	p,α
					13.669[d]		4.8±0.8	17	α,γ
					13.668[t]		7±20 %	35	$p,\alpha\gamma$
					13.6680[m]		7.8±1.0	26	p,γ
					13.663	2^+[r]	$\Gamma_0=0.3$	33	p,α_0
5.27	13.70	(3^-)[b]	~130		13.7	3^-[k]		24	^{24}Mg(e,e')
5.307±1	13.732	2^+	13±3	42±5	13.715	2^+[l]		25	p,α
					13.7158		4.8±0.5	27	p,α
					13.714[d]		4.3±0.3	17	α,γ
					13.708	2^+[r]	$\Gamma_0=2.2\pm10\,\%$	33	p,α_0
5.364	13.779	(4^+)[b]	~21		13.78			37	HI
					13.761	$4^+,5^-$[l]		25	p,α
					13.793	1^-[r]		33	$p,\alpha_0;p,p_0$
					13.75	5^-[β]		38	HI
					13.7520	5^-	$\Gamma_0=1.2$	33	p,α_0
5.463	13.862	(6^+)[b]	<8		13.84	6^+[β]		38	HI
					13.84			41	HI
					13.846[d]		<1	17	α,γ
					13.8			22	^{24}Mg(α,α')
5.489±3	13.883	2^+	32±8	26±3	13.96	2^+[i]		22	^{24}Mg(α,α')
					13.9	$L=2$[w]		36	^{24}Mg(α,α')
					13.9	2^+[k]		24	^{24}Mg(e,e')
					13.884		~28	27	p,α
					13.881[d]		12±1.8	17	α,γ
					13.867	2^+[r]	$\Gamma_0=13\pm10\,\%$	33	p,α_0
					13.88			45	p,α
5.513±1	13.903	4^+	18±3	42±2	13.9	$L\geq4^+$[k]		24	^{24}Mg(e,e')
					13.90			45	p,α
					13.913	(2^+)[r]		33	$p,p;p,\alpha_1$
5.63	14.02	(even, not $2^+,4^+$)[b]							
5.665±2	14.030	1^-	21±4	57±7	14.020[e]	1^-		18	α,γ
					14.02	1^-[ϵ]		45	p,γ
					14.018[d]		6.2±0.7	17	α,γ
					14.01			39	α,γ

TABLE I. (*Continued*).

E_α (MeV±keV)$^{\rm a}$	E_x (MeV)	J^π	$\Gamma_{\rm c.m.}$ (keV)$^{\rm a}$	Γ_α/Γ ×100$^{\rm a}$	Previous work				
					E_x	J^π	Γ	Ref.	
5.693	14.053	$(0^+,4^+)^{\rm b}$	<4	weak					
(5.713)	14.070	(odd)$^{\rm b}$	~17	weak	$14.072^{\rm d}$		24±5	17	α,γ
					$14.076^{\rm e}$			18	α,γ
(5.730)	14.084	even (not $2^+)^{\rm b}$	<4		$14.093^{\rm d}$	4^+	1.4±0.4	17	α,γ
					$14.076^{\rm d}$	$6^+,(4^+)$	<1	17	α,γ
					14.10	$(2^+,4^+)^{\zeta}$		46	α,γ
					14.10			37	HI
					$14.071^{\rm t}$		6±20 %	35	$p,\alpha\gamma$
					14.0803	$2^{+\,\rm r}$	$\Gamma_0=1.0\pm10$ %	33	p,α_0
(5.737)	14.090		~21		14.09	$1^{-\,\rm r}$	$\Gamma_0=20\pm20$ %	33	p,α_0
					$14.095^{{\rm e},\,\delta}$			18	α,γ
5.819±1	14.158	4^+	11.2±1.9	39±5	14.15	$4^{+\,\rm i}$		22	^{24}Mg(α,α')
					14.14	$4^++6^++8^{+\,\beta}$		38	HI
					14.146	$4^+,(3^-,5^-)^{\zeta}$		46	α,γ
					$14.139^{\rm e}$			18	α,γ
					$14.142^{\rm d}$		1.8±0.4	17	α,γ
					$14.143^{\rm d}$		6.2±0.7	17	α,γ
					$14.148^{\rm d}$			17	α,γ
5.938±1	14.257	4^+	16±2	69±5	$14.237^{\rm d}$		11.3±1.4	17	α,γ
					14.227	$4^{+\,\rm r}$	$\Gamma_0=2\pm10$%	33	p,α
6.047±12	14.348	(3^-)	112±29	33±5	14.3	$3^{-\,\rm k}$		24	^{24}Mg(e,e')
					$14.323^{\rm e}$	$2^+,3^-,4^+$		18	α,γ
					14.32	$4^{+\,\zeta}$		46	α,γ
					~$14.3^{\rm d}$		broad$^{\eta}$	17	α,γ
					$14.321^{\rm d}$	4^+	<1	17	α,γ
6.097±2	14.390	4^+	12±3	42±7	14.41	$4^{+\,\rm z}$		44,43	HI
					14.41	$(4^+)^{\rm y}$		41	HI
					14.3625	$(4^+)^{\rm r}$	$\Gamma_0=15\pm20$ %	33	$p,\alpha_0;p,p_0$
					14.38			40	HI
6.174	14.454	$4^{+\,\rm b}$	46	40–50	14.45			37	HI
					14.458	$2^{+\,\rm r}$	$\Gamma_0=5\pm10$ %	33	p,α_0
6.303	14.562	odd (not $3)^{\rm b}$	<13	weak	14.54	$2^{+\,\rm i}$		22	^{24}Mg(α,α')
					14.5	$L=2^{\rm w}$		36	^{24}Mg(α,α')
					14.56			41	HI
					14.54			40	HI
6.32	14.58	odd (not $5)^{\rm b}$	61						
6.399±6	14.641	6^+	11±9	5±3	14.65			40	HI
					14.65			47	^{24}Mg(e,e')
					14.65	$(4^+)^{\rm r}$	$\Gamma_0=60$	33	p,α_0
6.456±1	14.689	5^-	9±1	78±5	14.67			43	HI
					14.68			37	HI
					14.6630	$3^{-\,\rm r}$	$\Gamma_0=3\pm10$ %	33	p,α
6.515	14.738	$4^{+\,\rm b}$	13	40	14.74			41	HI
					14.7	$2^{+\,\rm k}$		24	^{24}Mg(e,e')
					14.73			45	p,α
(6.665)	14.863	$(2^+)^{\rm b}$	≤13		14.90	$2^{+\,\rm i}$		22	^{42}Mg(α,α')
					14.842	$2^{+\,\rm r}$	$\Gamma_0=0.5\pm10$ %	33	p,α
					14.9	$L=2^{\rm w}$		36	^{24}Mg(α,α')
(6.68)	14.88		~121		14.81	$1^{-\,\theta}$		39	α,γ
6.735	14.921	$(0^+,1^-)^{\rm b}$	~10		14.90			40	HI
					14.92			41	HI
6.815	14.988	$(4^+,5^-)^{\rm b}$	~20		14.967	$J^{\rm nat\,r}$	10±3	33	p,α
					14.9	$\geq 4^{+\,\rm k}$		24	^{24}Mg(e,e')
					15.00	$(1)^{-\,\rm r}$	$\Gamma_0=75$	33	
6.962	15.110	$4^{+\,\rm b}$	15						
6.990	15.134	$4^{+\,\rm b}$	15		15.15	$4^++7^{-\,\beta}$		38	HI
					15.13	$4^{+\,\rm g}$		20	HI
					15.15		≤30	40,48	HI

TABLE I. (*Continued*).

E_α (MeV±keV)[a]	E_x (MeV)	J^π	$\Gamma_{\text{c.m.}}$ (keV)[a]	Γ_α/Γ ×100[a]	Previous work				
					E_x	J^π	Γ	Ref.	
					15.15			47	^{24}Mg(e,e')
					15.137			49	p,p'
7.036±3	15.172	4^+	57±7	44±3	15.18	2^+[r]	$\Gamma_0=5\pm10\,\%$	33	p,α
					15.20	2^+[i]		22	^{24}Mg(α,α')
					15.2	2^+[k]		24	^{24}Mg(e,e')
7.078±1	15.207	5^-	36±3	73±3	15.21	$(7^-,6^+,9^+)$		41	HI
7.101±3	15.226	4^+	27±6	24±3					
7.140	15.259	$(1^-,3^-)$[b]	~8						
(7.20)	15.31				15.300	J^{nat}[r]	12±3	33	p,α_0
7.246±3	15.347	4^+	21±4	49±5					
7.283±3	15.378	4^+	31±7	39±5	15.4	$\geq 4^+$[k]		24	^{24}Mg(e,e')
					15.38		80±30[r]	33	p,α
7.353	15.436	(2^+)[b]	13		15.40	2^+[i]		22	^{24}Mg(α,α')
					15.40	J^{nat}[r]	22±6	33	
7.402	15.477	(2^+)[b]	15						
7.461±1	15.526	6^+	18±2	36±2	15.54			41	HI
					15.54			37	HI
(7.50)	15.56								
7.554±3	15.604	2^+	31±8	25±4	15.595	J^{nat}[r]	24±5	33	p,α
					15.56	2^+		22	^{24}Mg(α,α')
7.65	15.68	(0^+)[b]	≤15						
7.68	15.71	(4^+)[b]			15.7	2^+[k]		24	^{24}Mg(e,e')
					15.75			47	^{24}Mg(e,e')
7.773	15.786	4^+[b]	13		15.80			41	HI
					15.81			37	HI
					~15.8			50	p,γ
					15.80			42	HI
7.815	15.821	odd[b]	87						
7.845	15.846		<13	weak					
7.885	15.879	4^+[b]	42		15.9	$\geq 4^+$[k]		24	^{24}Mg(e,e')
					15.9			22	^{24}Mg(α,α')
7.995	15.971	odd[b]	~35						
(7.995)	15.971	(even)[b]	narrow		16.07	6^+[z]		44	HI
					16.07	(6^+)[y]		41	HI
					16.07			42	HI
8.185	16.129	(3^-)[b]	29		16.09			37	HI
8.225	16.162		<8						
8.265	16.196	6^+[b]	8		16.2	2^+[i]		22	^{24}Mg(α,α')
					16.20			40,48	HI
					16.23			37	HI
8.355	16.271	4^+[b]	30						
8.392	16.302	even[b]	10		16.30		≤20	51	HI
					16.30	8^+[β]		38	HI
(8.41)	16.32		narrow	weak					
8.433	16.336	$(4^{+}*)$[b]	13						
8.496±4	16.388	2^+	37±10	43±6					
8.550	16.433	7^-[b]	10		16.46	7^-[β]		38	HI
8.594±1	16.470	6^+	8±2	58±6	16.46			40,48	HI
					16.48			37	HI
8.656±2	16.521	6^+	31	63±5	16.59	6^+[z]		44,43	HI
					16.53			40,48	HI
					16.55		≤30	51	HI
					16.55	$8^+ + 9^-$[β]		38	HI
					16.5	3^-[k]		24	^{24}Mg(e,e')
					16.52			47	^{24}Mg(e,e')
					16.56	(10^+)[α]		52	HI
8.747	16.597	4^+[b]	30		16.59			41	HI
					16.59			42	HI
					16.6	$L=2$[w]		36	^{24}Mg(α,α')

TABLE I. (*Continued*).

E_α (MeV±keV)$^{\rm a}$	E_x (MeV)	J^π	$\Gamma_{\rm c.m.}$ (keV)$^{\rm a}$	Γ_a/Γ $\times 100^{\rm a}$	Previous work E_x	J^π	Γ	Ref.	
8.755	16.604	$(5^-)^{\rm b}$	≤ 8						
8.830	16.666	(even)$^{\rm b*}$	30						
(8.91)	16.73	(odd)$^{\rm b}$	≤ 8						
8.960	16.775	$(4^+,6^+)^{\rm b*}$	30						
9.035	16.837	$(6^+)^{\rm b*}$	22		16.84		≤ 20	51	HI
					16.84	$8^{+\beta}$		38	HI
					15.85			53	γ,xn
9.071±6	16.867	(5^-)	73±17	(32±4)	16.88			52	HI
					16.88			37	HI
9.137±3	16.922	6^+	44±6	46±3	16.93			48	HI
					16.9	$2^{+\rm k}$		24	^{24}Mg(e,e')
					16.90			54	γ,n
					16.90			47	^{24}Mg(e,e')
					16.86	$6^{+\rm g}$		20	HI
9.242±3	17.010	7^-	15±10	15±4	17.03			40,48	HI
					16.98			37	HI
					17.0	$L=2^{\rm w}$		36	^{24}Mg(α,α')
9.327±3	17.080	6^+	44±6	35±3	17.06			37	HI
					17.08			47	^{24}Mg(e,e')
9.390±2	17.133	5^-	26±6	24±3	17.1	$(1^-,3^-)^{\rm k}$		24	^{24}Mg(e,e')
(9.46)	17.19	(not 4^+, not 6^+, odd)$^{\rm b}$	≤ 8						
9.494±2	17.219	4^+	17±3	29±4	17.20			40,48	HI
					17.20			44	HI
(9.58)	17.29	odd (not 5)$^{\rm b}$	~ 46	weak	17.33			47	^{24}Mg(e,e')
					17.3	$2^{+\rm k}$		24	^{24}Mg(e,e')
					17.30			54	γ,n
9.710	17.399	$6^{+\rm b}$	20		17.4	$L=2^{\rm w}$		36	^{24}Mg(α,α')
					17.40			53	γ,xn
9.755	17.437	$6^{+\rm b}$	20		17.46			43	HI
					17.5	$\ge 4^{+\rm k}$		24	^{24}Mg(e,e')
(9.80)	17.47	(even)$^{\rm b}$	~ 25						
(9.835)	17.503		~ 25						
9.969±3	17.615	5^-	23±8	17±3	17.59			40,48	HI
					17.58			43,44	HI
					17.60	$(6^+)^\kappa$		55	HI
					17.52			52,42	HI
					17.60			47	^{24}Mg(e,e')
					17.65			54	γ,n
(9.98)	17.62	$(2^+)^{\rm b}$	~ 100						
10.11	17.73	$4^{+\rm b}$	~ 25						
10.12	17.74		~ 20						
10.16	17.77	(not 4^+)$^{\rm b}$	~ 42						
10.23	17.83	(not 4^+)$^{\rm b}$	~ 42						
10.359±3	17.940	4^+	56±8	40±3	17.9	$(4^++6^+)^\kappa$		55	HI
					17.90			47	^{24}Mg(e,e')
					17.95			43	HI
10.41	17.98	$6^{+\rm b}$	~ 17						
10.467±3	18.030	5^-	50±8	29±2					
10.538	18.089	*	20						
10.610	18.149	$5^{-\rm b}$	20		18.13			4	α,α'
10.625	18.161	$7^{-\rm b}$	<8		18.21			47	^{24}Mg(e,e')
					18.19			55	HI
10.665	18.195	(even), not $4^{+\rm b}$	~ 25						
(10.725)	18.245	(even)$^{\rm b}$	~ 8						
10.75	18.27	$7^{-\rm b}$	~ 21						
10.82	18.32	$(0^+,6^+)^{\rm b*}$	~ 17						
10.93	18.42	$(6^+)^{\rm b}$	~ 17						
10.98	18.46	odd$^{\rm b}$	~ 13						

TABLE I. (*Continued*).

[a] Errors determined as explained in text.
[b] J^π assignments by visual inspection of excitation functions
[c] Recalculated E_x from quoted E_α with modern Q value. Error in $E_x \pm 4$ keV. Γ in lab. Level at > 12.6 MeV is hypothesized from behavior of data at end of range.
[d] Recalculated E_x from quoted E_α with modern Q value. Error in $E_x \pm 4$ keV.
[e] Recalculated E_x from quoted E_α with modern Q value. Error in $E_x \pm 4$ keV, except as indicated.
[f] Based on optical model analysis of ^{24}Mg(p,p') data.
[g] From angular correlation measured in Litherland-Ferguson geometry II in ^{12}C$(^{16}$O$,\alpha)^{24}$Mg$(\alpha)^{20}$Ne(g.s.).
[h] Recalculated E_x from quoted E_p with modern Q value.
[i] DWBA fit of ^{24}Mg(α,α').
[j] From analysis of ^{23}Na$(p,\alpha_0)^{20}$Ne angular distribution.
[k] Identification of multipole resonances in ^{24}Mg(e,e') by multipole expansion method.
[l] From angular distribution of ^{23}Na(p,α).
[m] Error in E_x ranges from 0.5 to 1.0 keV.
[n] Error in E_x ranges from 0.25 to 0.50 keV.
[o] Spin assignment based on γ decay scheme.
[p] From α-γ correlation measurement in ^{23}Na$(p,\alpha\gamma)^{20}$Ne.
[q] Recalculated E_x from quoted E_α with modern Q value. Error in $E_x \pm 13$ keV.
[r] ^{23}Na(p,α_0) partial widths (Γ_0) and total widths in the lab. J^π determined from fit to (p,p_0), (p,p_1), (p,α_0), and/or (p,α_1) channels.
[s] Error in $E_x \pm 3$ keV.
[t] Energies are not independently determined.
[u] May be seeing more than one peak.
[v] Assigned a possible spin 0 based on observation in (p,α_0) channel but not in (p,α_1) or (p,p_1) channels.
[w] $L=2$ assignments from DWBA fit to ^{24}Mg(α,α').
[x] Spin assignment based on angular correlation of γ decay.
[y] Possible spin-parity assignments based on comparison of measured cross section with Hauser-Feshbach calculations.
[z] Spins based on ^{12}C$(^{16}$O$,\alpha_1)^{24}$Mg$(\alpha_2)^{20}$Ne.
[α] Comparison of angular distribution from the reaction ^{12}C$(^{14}N,d)^{24}$Mg compared to Hauser-Feshbach calculations.
[β] Spins determined from ^{16}O$(^{12}$C$,\alpha)^{24}$Mg$(\alpha)^{20}$Ne(g.s. and 1.63) double $(\alpha$-$\alpha_0)$ and triple $(\alpha$-α-$\gamma)$ angular correlations.
[γ] Strength actually exceeds 1 (1.3 ± 0.05), but this may be due to another resonance, as suggested by previous work. That there is more than an odd J resonance can be seen in the excitation function at 91.4° $(P_{\text{odd}}(90°)=0)$.
[δ] Error in $E_x \pm 8$ keV.
[ε] Based on ^{23}Na(p,α_0) angular distributions.
[ζ] From angular distribution and γ-decay schemes in ^{20}Ne(α,γ).
[η] Determined from visual inspection of Ref. 17 excitation function.
[θ] From angular distribution of ^{20}Ne(α,γ_0)
[κ] From ^{12}C$(^{16}$O$,\alpha)^{24}$Mg$(\alpha)^{20}$Ne double $(\alpha$-$\alpha)$ and triple $(\alpha$-α-$\gamma)$ correlations. Spin assignments are only suggestive.

E_x some 17 keV lower. Possibly both resonances exist at almost the same energy and the anomalous Γ_0/Γ for the 0^+ fit comes from neglecting the 1^-.

At least four narrow closely spaced resonances exist for $E_\alpha \simeq 4.93$ MeV, but we were unable to fit any of them. The angular behavior of the lowest one suggests 4^+.

Region B: $5 \le E_\alpha < 5.9$ *MeV*. In this region the six levels of Table I that have errors assigned to the parameters had satisfactory fits $(\chi^2/\text{d.f.} \le 2.6$, see Table II). Our parameters and assignments generally correspond well with previous work, except that again our extracted widths are larger, sometimes much larger if indeed the same level is involved in the other work.

The region in Fig. 6 is well fitted by a single 1^- resonance at $E_\alpha = 5.128$ MeV. This assignment is supported in (p,α) work,[25,33] but the $\Gamma_0 = 30$ keV reported in Ref. 33 is twice our $\Gamma(\Gamma_0/\Gamma) = 15$ keV.

A weak resonance at $E_\alpha = 5.245$ MeV was observed. Also, a broad resonance $(\Gamma \simeq 130$ keV)—most probably a 3^- as it (almost) vanishes from the excitation functions at 91.4°, 138.8°, and 143.2°, at $E_\alpha = 5.27$ MeV—can be seen best at 125.5° where the $E_\alpha = 5.307$ MeV 2^+ vanishes. However, the interference structure exhibited in the data, for example, at 91.4°, indicates that other states are probably present.

A narrow 2^+ resonance was fitted at $E_\alpha = 5.307$ MeV. This was supported in (p,α),[25,33] though the reported width in this,[27] and in (α,γ) (Ref. 17) was at least a factor of 2 less. The existence of a possible nearby 5^- (Ref. 38) may explain why our Γ assignment is broadened.

The resonance at $E_\alpha = 5.364$ MeV is seen around 90° so it is definitely of even spin, probably 4^+. However, the angular behavior is sufficiently ambiguous that we may have two resonances at about this energy. Although heavy-ion studies[38] identify a 5^- at slightly lower E_x, subsequent (α,γ) work[17] gives a narrow width, though strongly excited in the α_0 channel at $E_\alpha = 5.340$ MeV, so our step size was probably too coarse to display it. The 5^- state also appears in (p,α) studies,[33,25] though Ref. 25 suggested that 4^+ was also a possibility.

There is a weak, narrow (single-point-deviation) resonance at $E_\alpha = 5.463$ MeV at 70.0°, 91.4°, and 125.5° which excludes $2^+, 4^+$ and all odd spin assignments. Its absence at 75.5°, 106.5°, and 130.0°, all near zeros of P_6,

TABLE II. χ^2 per degree of freedom (d.f.) for the various fitting regions.

$E_x(^{24}\text{Mg})$ (MeV)	χ^2/d.f.	$E_x(^{24}\text{Mg})$ (MeV)	χ^2/d.f.
12.578	3.6	15.172 15.207 15.226	1.3
12.738 12.741 12.771 12.777	3.1	15.347 15.378	5.4
13.089	12.0	15.526	1.6
13.188 13.200	6.7	15.604	3.2
13.338	1.3	16.388	4.8
13.583	1.1	16.470 16.521	4.1
13.732	2.0	16.867 16.922 17.010 17.080 17.133	2.2
13.883 13.903	1.8	17.219	3.7
14.030	2.6	17.615	6.8
14.158	1.9	17.940	4.5
14.257 14.348 14.390	3.9	18.030	2.8
14.641 14.689	1.25		

is consistent with a 6^+. The (α,γ) study[17] reports a ≤ 1 keV wide state at $E_\alpha = 5.444$ MeV, which they believe is the state identified in heavy-ion work[38] as a 6^+.

The 5.47–5.54-MeV region was well fitted by two resonances: a 2^+ at $E_\alpha = 5.489$ MeV and a 4^+ at $E_\alpha = 5.513$ MeV. The $E_\alpha = 5.489$ MeV 2^+ is exceptional in that we extract a slightly narrower width ($\Gamma = 32 \pm 8$ keV) than that for a 2^+ observed at $E_x = 13.867$ MeV in the (p,α) reaction[33] (48 ± 7 keV), though our Γ_{α_0}/Γ is in close agreement.

The 5.63–5.76-MeV region is complicated by perhaps six different resonances. At $E_\alpha = 5.63$ MeV at 91.4° a one point dip flags a narrow even spin level, which also gives a peak at 53.2°, 70.0°, 116.2°, 125.5°, and 130.0° and, hence, is probably not 2^+ nor 4^+. Only one resonance was successfully fitted, a 1^- at $E_\alpha = 5.665$ MeV. The $E_\alpha = 5.693$ MeV level observed at 86.2°, 91.4°, 125.5° and probably 75.5°, hence likely 0^+ or 4^+, is clearly a new but weak and narrow level.

Around $E_\alpha = 5.735$ there appear to be two close resonances: a narrow resonance at $E_\alpha = 5.730$ MeV that is of even spin but not 2^+, and a broader resonance at $E_\alpha = 5.737$ MeV.

Region C: $5.9 \leq E_\alpha < 7$ *MeV*. While region *C* looks no more complicated than *B*, we achieved only a few good fits. Apparently interference effects are important enough not only to frustrate fits, but also produce inconsistencies when trying to assign J^π from angular behavior of resonances.

The two narrow 4^+ resonances within 100 keV of 6 MeV have unambiguous assignments from both the angular behavior and from the fitting procedure. However, to achieve a χ^2/d.f. of 3.9 still requires an additional broad (3^-) resonance ($\Gamma > 100$ keV) at $E_\alpha = 6.047$ MeV, though such a state is not obvious in any of the plots. Some (p,α) data[33] support the 4^+ assignments and one of the widths but not the Γ_α/Γ. While there is some support from ^{24}Mg(e,e') data[24] for our 3^- state, we still feel that its existence in our data is uncertain, and the parentheses so indicate.

Yet another 4^+ is suggested at $E_\alpha = 6.174$ MeV. There is a report of a 2^+ at $E_x = 14.458$ MeV in (p,α_0), but with a much weaker α_0 partial width,[33] so there may be two states.

Two nearby narrow resonances ($E_\alpha = 6.399$ and 6.456

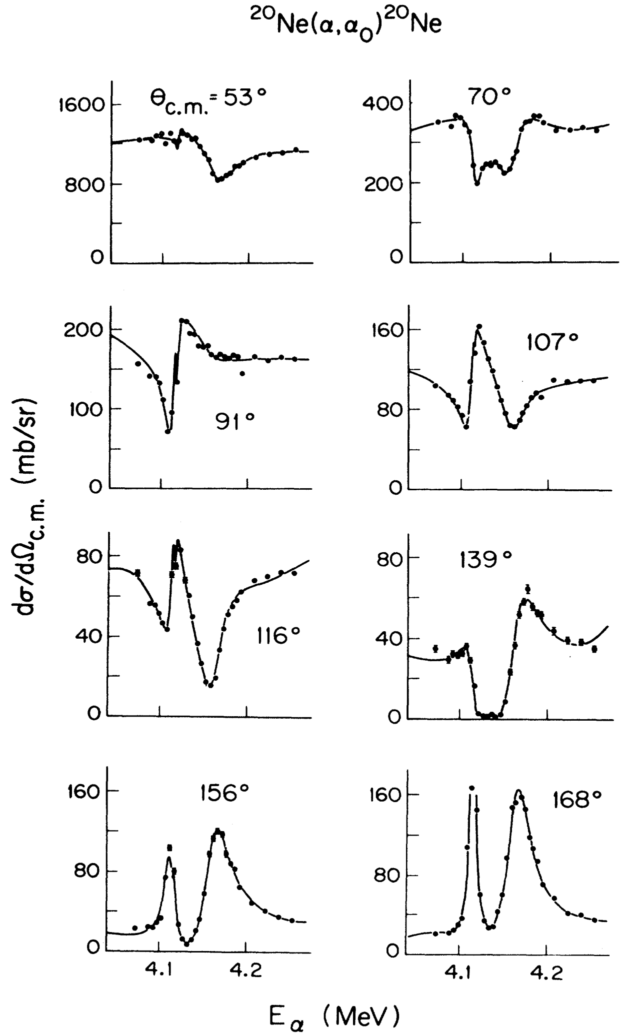

FIG. 5. Excitation functions at selected angles for the region $E_\alpha = 4.05$–4.25 MeV (see Sec. V). The curves are the fit by Eq. (1) with four resonances at $E_\alpha = 4.114$ MeV (2^+), 4.117 MeV (4^+), 4.153 MeV (0^+), and 4.161 MeV (1^-). A possible narrow, even J resonance at $E_\alpha = 4.20$ MeV was not included in the fit.

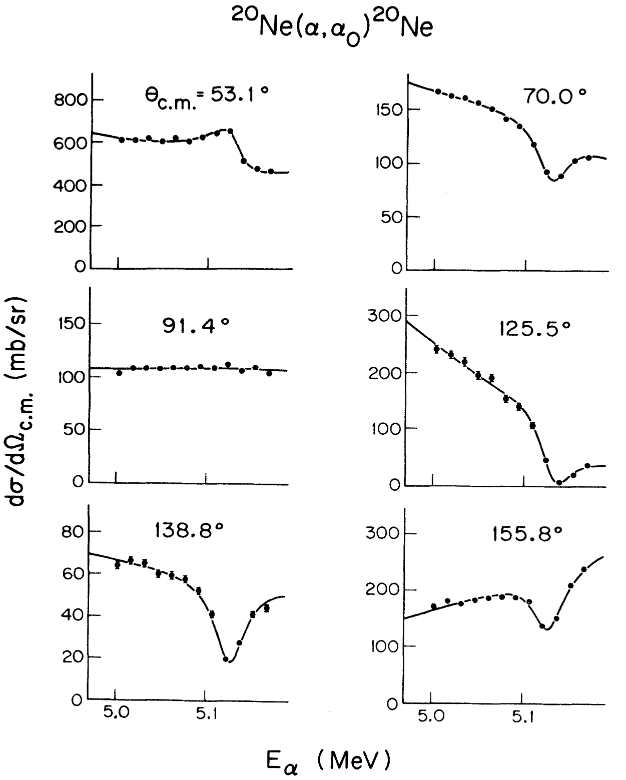

FIG. 6. Excitation functions at selected angles for the 1^- resonance at $E_\alpha = 5.128$ MeV (see Sec. V).

MeV) yielded a remarkably low χ^2/d.f. of 1.25 when assigned 6^+ and 5^-, respectively. These are the first such (definite) spin assignments to any state in this neighborhood.

Our program could not fit any other part of region *C* so all other assignments are speculatively inferred from angular behavior: even the state's existence in some cases could be questioned because inconsistencies in angular behavior suggest strong interference effects. In most cases, there are no confirming assignments from other workers and reactions. Least ambiguous and less open to question are the nonfitted 4^+ assignments: the 6.174, 6.515, 6.962, and 6.990 MeV states. (Undoubtedly there are many more states than we list in Table I.)

Region D: $7 \leq E_\alpha < 8$ *MeV*. Figure 7 shows samples of the good fit (χ^2/d.f. $= 1.3$) of the first 10% of this region. The fit involved a strong 5^- and two moderately strong 4^+ resonances. The strong 5^- shows clearly at 70° where P_4 vanishes, and the 4^+ states at 58.8°, 91.4°, and 155.8°, all of which are angles near where P_5 vanishes. Table I shows no previous work indicating any of these assignments; however, the $E_x = 15.18$ MeV 2^+ level seen by (p,α),[33] and at 15.2 MeV by ^{24}Mg(α,α'),[22] and by ^{24}Mg(e,e') is not necessarily inconsistent with our data: the small $\Gamma_\alpha/\Gamma = 0.12$ reported,[33] might permit the fit to include it in the background amplitudes. The poorly fitted structure below 7.05 MeV (Fig. 7) at 58.8° and 91.4°, which mainly vanishes at 125.5° where P_2 vanishes, might correspond to such a 2^+ state. (Unfortunately, at the time we did not try including a 2^+ state in this region.)

A possible narrow resonance at $E_\alpha \sim 7.140$ MeV seems absent at 86.2°, 91.4°, and 143.1°, consistent with it being 3^-, but 1^- may not be excluded. There may be a level at ~ 7.20 MeV that could correspond to a natural parity level reported in (p,α).[33]

While we could fit the region around 7.26 MeV with two 4^+ resonances, the χ^2 wasn't good, presumably because the separation of the levels is comparable to their widths. This may explain why (p,α) work[33] reports an 80±30 keV level here and why a level with $J_\pi \geq 4^+$ was observed in ^{24}Mg(e,e').[24]

Structure seen around 7.35 and 7.40 MeV we could not fit, but its presence at 70.0°, 75.5°, and 91.4°, and its absence at 125.5° suggest 2^+ assignments. The lower state may correspond to the natural parity level at this energy ($E_x \simeq 15.40$ MeV) reported via the (p,α) reaction,[33] though the width seen there, 22±6 keV, seems somewhat larger than we would estimate.

Our successful fit (χ^2/d.f. $= 1.6, 6^+$) to a moderately strong state at $E_\alpha = 7.461$ MeV is the first J^π assignment to this level, although the state may correspond to one reported in heavy-ion reaction studies.[37,41]

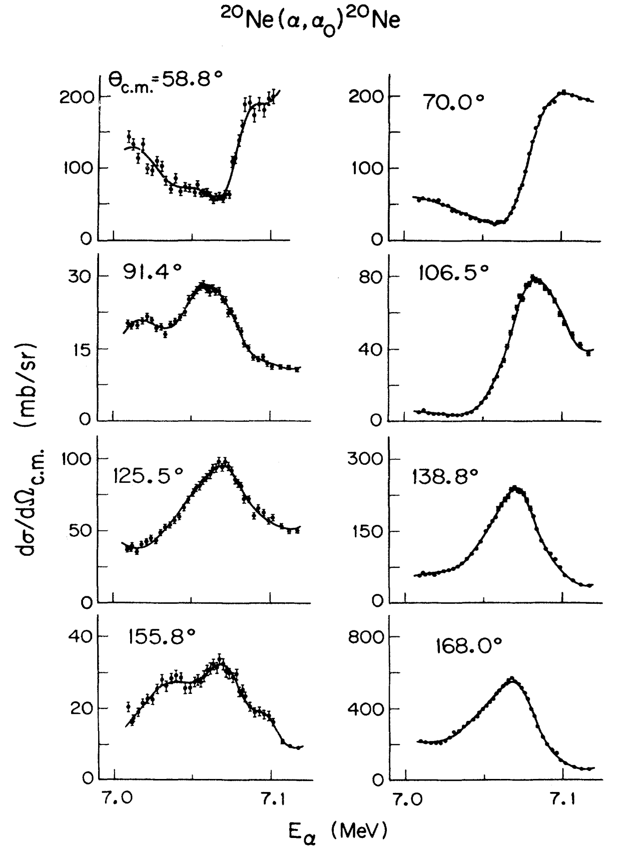

FIG. 7. Excitation functions at selected angles for the region $E_\alpha = 7.01$–7.12 MeV (see Sec. V). The curves are the fit by Eq. (1) with three resonances at $E_\alpha = 7.036$ MeV (4^+), 7.078 MeV (5^-), and 7.101 MeV (4^+).

The region above the 2^+ at 7.554 MeV and below 8 MeV obviously has many resonances (see Figs. 2–4), but we obtained no successful fits. The substantial data gaps at the two forward angles and at 138.8° are certainly part of the problem; nevertheless, we see the need for at least eight levels in this region. The only previous work supporting any of these assignments is for the $E_\alpha = 7.885$ MeV 4^+ where ^{24}Mg(e,e') (Ref. 24) report $J^\pi \geq 4^+$ strength.

Region E: $8 \leq E_\alpha < 9.05$ *MeV*. While Figs. 2–4 show many strong resonances in this region, especially at the back angles, we could fit only three of them (at $E_\alpha = 8.496$, 8.594, and 8.656 MeV) with rather poor χ^2/d.f. Strong interference effects with neglected nearby levels may explain this inconsistency, and, in fact, the 2^+ assignment for the 8.496 MeV level is inconsistent with some suggestions of its presence at 125.5° [P_2(125.3°)=0].

A resonance at $E_\alpha = 8.185$ MeV vanishes at 91.4° and 86.2° and is therefore odd. As it seems to be very weak at 143.2°, this may be a 3^- [P_3(143.1°)=0].

A very narrow resonance can be observed at $E_\alpha = 8.225$ MeV, e.g., at 168.0°, but has no J^π assigned, as it is too weak to make judgements about its angular behavior.

At $E_\alpha = 8.265$ MeV a resonance is weakly observed at 91.4° and 86.2° (probably even), at 143.2° (not 8), at 70.0° (not 4), and at 125.4° (not 2). That it is very weak at 75.5° [P_6(76.2°)=0], gets weaker from 58.8° to 53.2° [P_6(48.6°)=0] changes from a dip (at 101.6°) to a peak (at 106.5°) near the P_6(103.8°) zero, is weak at 130.0° [P_6(131.4°)=0], and changes from a dip (at 155.8°) to a peak (at 163.9°) near the P_6(158.8°) zero, supports a 6^+ assignment for this resonance.

At $E_\alpha = 8.355$ MeV a resonance observed at 91.4° and 86.2° (even), at 143.2° and 163.9° (not 8), at 101.6° and 130.0° (not 6), at 53.2° and 125.5° (not 2), but gets weak at 143.2° [P_4(149.4°)=0], 106.5° [P_4(109.9°)=0] and ambiguously still weakly seen (though just) at 70.0° [P_4(70.1°)=0]. With the total excursion in $d\sigma/d\Omega \simeq 250$ mb/sr at 168.0°, this can only be a 4^+.

At $E_\alpha = 8.392$ MeV changes in slope in the 91.4° and 86.2° data indicate an even spin resonance. It is seen at 143.2° (not 8), 125.5° (not 2), and rather weakly at 70.0° (not 4). It is not observable at far back angles; it is so weak as to be washed out by the nonresonant background. It is not observed at 130.0° [P_6(131.4°)=0], but is weakly observed at 75.5° [P_6(76.2°)=0]. This resonance thus remains ambiguous, other than being of even spin. Heavy-ion work[38] reported an 8^+.

At $E_\alpha = 8.433$ MeV a resonance is observed at 91.4° and 86.2° (even), at 143.2° and 163.9° (not 8), at 101.6° and 130.0° (not 6), 53.2° and 125.5° (not 2), and at 106.5° and (somewhat ambiguously at lower energy) 70.0° (not 4). As a 0^+ would be too weak to explain the cross section excursions, this is probably a doublet, one of which may be 4^+, based on the angular changes in interference with the background.

A 7^- is observed at $E_\alpha = 8.550$ MeV that perhaps corresponds to a previous heavy-ion report[38] of a 7^- within ~30 keV in E_x.

A peak at $E_\alpha = 8.747$ MeV at 91.4° implies even spin. The peak occurs at other angles but vanishes at 70.0° except for a single datum point at a slightly higher $E_\alpha = 8.755$ MeV. Hence the 8.747 MeV peak is probably 4^+; the higher narrow one may be 5^-. Another single data point anomaly at $E_\alpha = 8.91$ MeV is seen at 70.0°, 58.8°, 53.2°, and 75.5° but not 91.4° so it may be odd (or just very weak).

Some of the unfitted resonances cannot be assigned a definite J^π though they are reasonably strongly excited. This leads us to conclude that there is more than one resonance, and these levels have been indicated as doublets in Table I. For example, the resonance at $E_\alpha = 9.035$ MeV is clearly observed at 91.4° (implying even J), at 143.2° [P_8(142.8°)=0], 70.0° [P_4(70.1°)=0], 125.5° [P_2(125.3°)=0], 155.8° and 163.9° [P_6(158.8°)=0], or at 75.5° [P_6(76.2°)=0]. However, it does appear to be weak at 130.0° [P_6(131.4°)=0] and at 101.6° and 106.5° [P_6(103.8°)=0]. Furthermore, the sign of the interference changes between these last two angles is consistent with the $L=6$ wave going through zero at 103.8°. As it is too strong to be a 0^+, we are forced to the conslusion that it must be a doublet, one of which is probably a 6^+. Similar problems for J^π assignments exist for the levels at $E_\alpha = 8.830$ and 8.960 MeV.

Region F: $9.05 \leq E_\alpha < 10$ *MeV*. Figure 8 shows sample excitation functions of the good fit (χ^2/d.f. = 2.2) to the first five resonances of this region. We fit two other resonances in this region. Of these seven well-fit resonances, only the 6^+ assignment at $E_\alpha = 9.137$ MeV may correspond to work elsewhere (see Table I, though this unpublished heavy-ion work [20] quotes a 60 keV lower E_x). The $E_\alpha = 9.071$ MeV state is listed as only a possible (5^-) due to the fact that it lies at the boundary of the fit region shown in Fig. 8.

Seven other unfit resonances are also speculated on in this region. A single data-point anomaly at $E_\alpha = 9.46$ MeV appears only at 70.0° and 75.5° (so $\neq 4^+$ or 6^+) and it is possibly odd. A broad dip is seen at $E_\alpha = 9.58$ MeV at back angles (including 155.8°, so $J \neq 5$), but is hard to pick out at more forward angles, though 91.4° seems flat (J odd). Constructive interference with nonresonant background amplitudes may be emphasizing some weak structure here.

Our 6^+ doublet at $E_\alpha = 9.710$ and 9.755 MeV stands out most clearly in the 91.4° data (even spin) and in the 125.5° (not 2) and 70.0° (not 4) data. It is absent at 75.5° [P_6(76.2°)=0]. The second of these is a weaker assignment in that there is still some evidence of its existence at 130.0° [near P_6(131.4°)=0]. Both resonances change from peaks (at 101.6°) to dips (at 106.5°) near P_6(103.8°)=0.

While the region is cluttered by other structure, we tentatively identify two of the stronger resonances. The one at $E_\alpha = 9.80$ MeV shows strength at 91.4°, 125.5°, 70.0°, and 143.2°, so is even parity, and $\neq 2^+$, 4^+, 6^+, or 8^+, unless it is part of a closely spaced doublet. The other resonance at $E_\alpha = 9.835$ MeV is of odd parity and of angular behavior most consistent with 7^- especially its absence at 138.8° [$P_7(137.9°)=0$] and its weakness at 143.2°.

In this high level-density region, broad resonances are hard to identify except under special circumstances. At $E_\alpha \simeq 10$ MeV the 86.2° and 91.4° data show a strong broad ($\Gamma \simeq 100$ keV) symmetric peak (Figs. 2 and 3) with no obvious large interference structure. Since all $P_{\rm odd}(90°)=0$, we need only a reasonable fluctuation in level density of the even parity states to account for the observation. As the angle increases from 90°, interference with the nearby (well-fit) 5^- level at $E_\alpha=9.967$ MeV grows at 101.6° and at 106.5°, but decreases at 116.2°, and finally vanishes at 125.5°. This behavior is consistent with the broad even-parity level being 2^+ since $P_5(122.6°)=0$ and $P_2(125.3°)=0$. In fact the $d\sigma/d\Omega$ at 125.5° becomes almost zero from 9.90 to 10.0 MeV (though at higher energies a 4^+ level at 10.11 MeV contributes). As one goes to larger angles (138.8° and 143.1°) the interference grows again, but, significantly, remains of the same sign, since both the 5^- and the 2^+ waves went through zeros at nearly the same angle. Since $P_5(155.0°)=0$, the only interference left at 155.8° is of the broad 2^+ with background and nearby levels.

Region G: $10 \le E_\alpha < 11$ *MeV*. Interference effects from the high density of resonances allowed us to fit only two states reasonably well, a 4^+ at $E_\alpha=10.359$ MeV and a 5^- at 10.467 MeV, both with widths of ~50 keV. Our 4^+ assignment is consistent with heavy-ion correlations[55] requiring both 4^+ and 6^+, with speculative assignment of 6^+ to the unfit level at $E_\alpha=10.41$ MeV.

A third resonance at $E_\alpha=10.538$ MeV yielded a poor χ^2/d.f. as a 2^+, and, in fact, structure at 53.2° rules out a 2^+, though it is relatively weak but still noticeable at 125.5°; the data at 70° and 106.5° exclude 4^+; the data at 101.6°, 130°, and 155.8° exclude 6^+; and data at 58.8°, 101.6°, and 143.2° exclude 8^+; though structure in the data at 86.2° and 91.4° require even parity. This leaves a 0^+, though Γ_0/Γ would then have to exceed unity. Therefore, there is probably a doublet at this energy.

In the region $E_\alpha=10.00$ to 10.35 MeV there are several resonances, but by examining the excitation function at 70.0°, where 4^+ levels should vanish, we observe two dips with a strong interference peak between them superimposed on a smooth background. We conclude that there are two non-4^+ levels at 10.16 and 10.23 MeV of about the same width and probably of the same J^π. There also appears to be a $J^\pi=4^+$ at about 10.11 MeV. As the two non-4^+ states cannot be cleanly identified from their angular dependence, we conclude that there must be a complex overlapping of many levels of different J^π.

There are three unfit resonances at $E_\alpha=10.610$ (5^-), 10.625 (7^-) and 10.75 (7^-) MeV, plus several other levels of uncertain J^π. There are probably many broader resonances at this high energy that overlap to such an extent that we cannot extract them from the general background.

VI. SUMMARY AND CONCLUSIONS

While only 40 of the many resonances apparent in Figs. 2–4 were successfully fitted by us, the angular be-

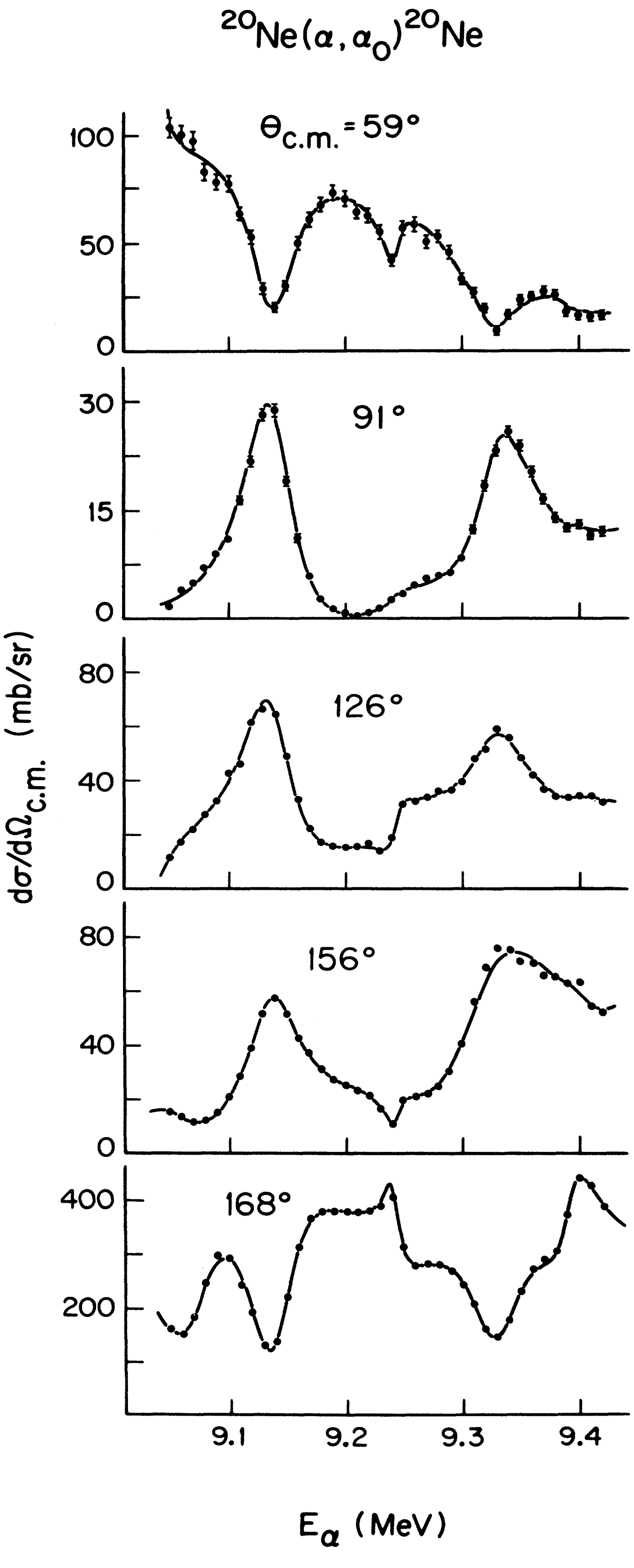

FIG. 8. Excitation functions at selected angles for the region $E_\alpha=9.05$–9.42 MeV (see Sec. V). The curves are the fit by Eq. (1) with five resonances at $E_\alpha=9.071$ MeV (5^-), 9.137 MeV (6^+), 9.242 MeV (7^-), 9.327 MeV (6^+), and 9.390 MeV (5^-).

havior of other resonances permitted reasonable (and sometimes unambiguous) J^π assignments and reasonable estimates of parameters. A total of 117 levels or possible levels have been identified in ^{20}Ne(α,α_0)^{20}Ne, 55 of which have been given definite spin assignments and 48 of which have been limited as to possible spin. Of these 117 levels, to our knowledge, about 50 have been provided with either definite spin assignments or limitations as to spin and parity in previous work.

We seem to see a correlation with the ^{24}Mg(e,e') work at lower energies, but this breaks down at higher energies, presumably because the low spin observed by electron scattering is simply buried as higher spins are excited at higher alpha energies. We seem to see the broader structure ($\Gamma > 5$ keV) identified in ^{24}Mg(p,p').[34] The same may be said of resonances observed in the ^{23}Na+p entrance channel by many previous experiments,[1] though there are many narrow resonances that we do not see.

The level widths reported in Table I ranges from our energy step size of a few keV to ~130 keV and most widths are between 20 and 40 keV. These numbers carry little significance since they probably reflect biases in data taking (step size) and analysis. At the level densities involved, broader levels (unless unusually strong) become visually lost in the interference effects of levels which are a few times the step-size resolution. For computer analysis to pick up a broad level, the fitting region must be broad compared to Γ; otherwise variations in background easily simulate the broad level.

In ^{23}Na(p,α_0), excitation functions were measured[56] at eight angles for $E_p = 4.0$ to 8.0 MeV and a coherence width of $\Gamma = 58 \pm 4$ keV [seen also in (p,α_1)] at a mean energy of $E_x = 17.5$ MeV was identified with the average compound-nucleus level width. This region partially overlaps our energy region and their result agrees well with our observed widths. Above $E_\alpha = 7.5$ MeV, we see resonances with widths from $\Gamma_{\mathrm{c.m.}} = \sim 8$ to 83 keV. Also in ^{23}Na(p,α_0), excitation functions were measured at two angles[45] for $E_p = 2.76$ to 4.50 MeV and a coherence width of $\Gamma \simeq 50$ keV was determined. In ^{23}Na(p,γ)^{24}Mg, from $E_p = 4$ to 12.4 MeV, the coherence width was determined[50] to be about 75 keV.

We have observed noticeably more even-spin than odd-spin resonances (largely $J = 4$), though this may reflect the fact that even spin states are easier to identify around 90° where all the odd-spin states vanish. There may be some tendency for the even J states to be clustered at $E_x \simeq 13.25$ MeV (2), $E_x \simeq 14.75$ MeV (4), $E_x \simeq 16.75$ MeV (6), and, with $J = 0$ resonances reported in Ref. 1, at $E_x \simeq 11.25$ MeV. Such apparent broad (~1 MeV) structure is best observed at far back angles (see Fig. 4). The clustering no doubt partially reflects the fact that, because of barrier penetration effects, the widths for successively higher L's achieve their optimal detection width at higher E_α. However, it might be a sign of "intermediate" structure of ^{24}Mg associated with a ^{12}C+^{12}C "molecule" configuration.

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