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Resonance behavior in the $^{24}Mg+^{28}Si$ system

A. H. Wuosmaa, S. Saini, P. H. Kutt, S. F. Pate, and R. W. Zurmühle
Physics Department, University of Pennsylvania, Philadelphia, Pennsylvania 19104

R. R. Betts
Physics Division, Argonne National Laboratory, Argonne, Illinois 60439
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We have measured excitation functions for elastic and inelastic scattering of the nonsymmetric alpha-particle system of $^{24}Mg+^{28}Si$, in the energy range 90.95 MeV $< E_{\rm lab} <$ 106.25 MeV. We observe narrow structures similar to those seen in the nearby $^{24}Mg+^{24}Mg$ and $^{28}Si+^{28}Si$ systems. Elastic scattering angular distributions reflect the contribution of two or three l values for structures at $E_{\rm c.m.}=50.51$ and 52.53 MeV, with the dominant partial waves in the range of $l=33$ to $38\hbar$. A statistical fluctuation analysis of the data for the low lying excitations confirms the nonstatistical nature of these resonances.

In recent years several experiments have shown that resonance phenomena, similar in many respects to those seen in the well studied $^{12}C+^{12}C$ system, occur in systems involving pairs of much heavier nuclei, such as $^{28}Si+^{28}Si$ (Ref. 1) and $^{24}Mg+^{24}Mg$ (Ref. 2). These resonances provide evidence for the existence of states of unusual structure at high excitation energy and angular momentum in the composite nucleus. Resonances appearing in these systems possess several notable characteristics; they are narrow ($\Gamma_{\rm c.m.}=150$–250 keV), occur at very high excitation energies in the composite system ($E_x=60$–80 MeV), have high spins near the grazing l values in the entrance channel ($I=34$–$40\hbar$), and are strongly correlated in the elastic and several inelastic channels. The occurrence of such resonances is by no means universal, however, as other studies have revealed that several nearby systems lack similar structure. For instance, the non-alpha-particle systems of $^{28}Si+^{30}Si$ and $^{30}Si+^{30}Si$ show no hint of resonant behavior.[3] Perhaps even more striking is the absence of any similar structure for the symmetric alpha-particle systems of $^{32}S+^{32}S$ and $^{40}Ca+^{40}Ca$.[4,5]

At present there is no clear understanding of the mechanism by which these unusual states are populated and of their microscopic structure, although some progress has been made in this direction, through the study of the existence of highly deformed states in these nuclei at high angular momentum.[6] Although previous studies have provided much insight into the phenomenon of resonances in heavy systems, our understanding of them is far from complete, and further investigation is necessary. We wished to further clarify the systematics of resonance behavior in this mass region, and, in particular, to determine whether resonances were confined to symmetric heavy alpha-particle systems. With this in mind, we have turned our attention to the nonsymmetric $^{24}Mg+^{28}Si$ system.

We performed our experiments using a ^{24}Mg beam from the Brookhaven National Laboratory tandem Van de Graaff accelerator. Excitation functions were measured in the range $90.95 < E_{\rm lab} < 106.25$ MeV, in steps of $\Delta E_{\rm lab}=150$ keV. Two much longer runs at $E_{\rm lab}=93.95$ and 97.55 MeV were performed to acquire angular distribution data. The targets used consisted of 15 μg/cm^2 ^{28}Si on a 15 μg/cm^2 ^{12}C backing, and 30 μg/cm^2 ^{28}Si on a 15 μg/cm^2 ^{12}C backing for excitation functions and angular distributions, respectively.

The reaction products were detected with a recoil coincidence setup similar to that described previously in the literature[1] utilizing two large area, high resolution solid state detectors. These detectors were placed 8 cm from the target, at lab angles of 43° and 52° on either side of the beam, and subtended an angular range of $\Delta\theta_{\rm lab}=13.6°$. The detectors were cooled to $-34\,°$C in order to reduce the detector leakage current and associated noise. The recoil coincidence efficiency of this arrangement was $>95\%$ for elastic scattering, and decreased to 0% at a Q value of approximately -20 MeV. To provide particle identification we used a technique by which we measured the difference in time of flight between the two reaction fragments. This method of particle identification has several advantages for our measurement. For example, one need not sacrifice energy resolution, as with a heavy ion E-ΔE telescope, or solid angle, as with a recoil coincidence experiment involving two position sensitive detectors. Figure 1 shows a particle identification spectrum of events corresponding to elastic scattering from the angular distribution run at a bombarding energy of 97.55 MeV. The horizontal axis represents the difference in time of flight between the two fragments, and the vertical axis the energy signal from one of the two detectors. ^{24}Mg and ^{28}Si are clearly separated and easily identified, and one may even discern the peaks in the angular distribution. Our typical timing resolution was approximately 400 ps [full width at half maximum (FWHM)]. This method also allows us to distinguish elastic and inelastic scattering from alpha transfer events leading to exit channels such as

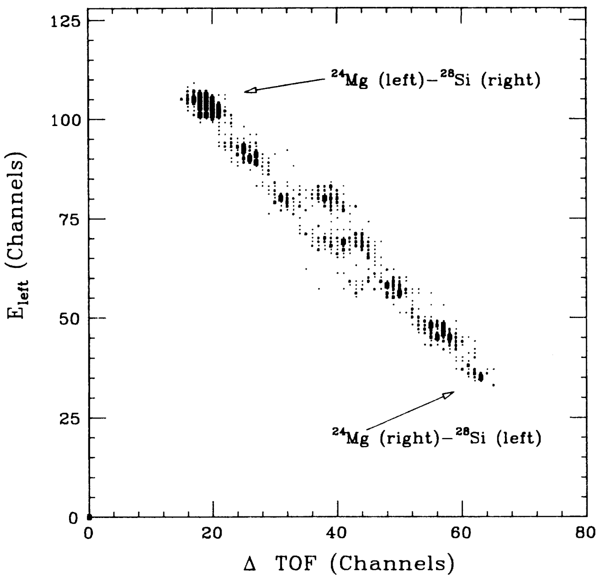

FIG. 1. Particle identification spectrum gated on elastic scattering. The horizontal axis corresponds to the time of flight difference, and the vertical axis the energy of one of the fragments. The two possible detector combinations of the reaction fragments are well separated and the lobes of the elastic scattering angular distribution are clearly visible. The time of flight difference between the two groups is 0.65 ns.

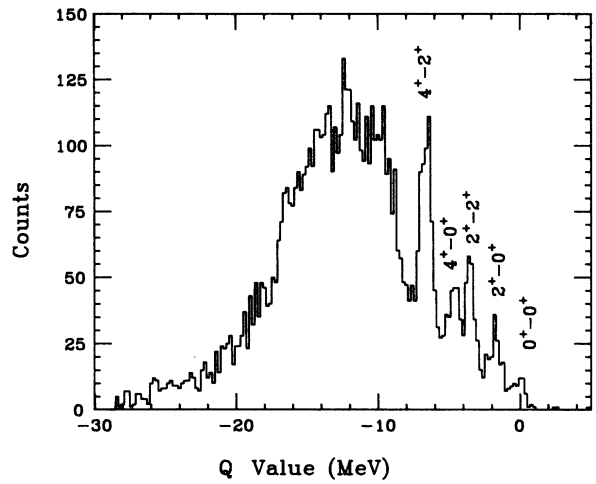

FIG. 2. Q-value spectrum measured at a bombarding energy of $E_{\rm lab}=97.40$ MeV. The peak labeled 2^+-0^+ contains contributions from both the ^{24}Mg 2^+ (1.37 MeV) and the ^{28}Si 2^+ (1.78 MeV) states. The peak labeled 4^+-0^+ contains contributions from the ^{24}Mg 4^+ (4.12 MeV) and the ^{28}Si 4^+ (4.62 MeV) states. The peak labeled 4^+-2^+ contains contributions from both 2^+ and 4^+ excitations.

^{20}Ne$+^{32}$S. We find that inelastic scattering dominates the reaction, with the transfer channels being very weak, a result similar to that found in the neighboring ^{24}Mg$+^{24}$Mg and ^{28}Si$+^{28}$Si systems.[7,8]

The energy signals from the two detectors, as well as a time to amplitude converter (TAC) signal measuring the time of flight difference, were recorded event by event. For each event arising from elastic or inelastic scattering, the two energies were added together in playback to generate Q-value spectra. The various peaks in the Q-value spectra were then summed to extract excitation functions. For the angular distribution runs, once the reaction fragments had been identified by their time of flight information, their scattering angles were derived from one of the two energy signals. Data from two small monitor detectors placed at 15° on either side of the beam provided absolute normalization information.

Figure 2 shows a representative Q-value spectrum taken at a bombarding energy of 97.40 MeV. The peaks arising from elastic scattering (0^+-0^+), excitation of the ^{24}Mg 2^+ (1.37 MeV) and the ^{28}Si 2^+ (1.78 MeV) (2^+-0^+), and several other excitations are well resolved. Figure 3 shows excitation functions for the elastic and several inelastic channels, where the cross sections have been averaged over the angular range of the detector setup, $\Delta\theta_{\rm lab}=13.6°$, and corrected for coincidence efficiency. The data labeled 2^+-0^+ contain contributions from both the ^{24}Mg and ^{28}Si 2^+ excitations, which remained unresolved in our experiment. The excitation functions show several narrow structures with center of mass widths of 140–280 keV, well correlated in the elastic and inelastic channels. These peaks are observed at energies of approximately twice the Coulomb barrier, a result similar to that of ^{28}Si$+^{28}$Si (Ref. 1) and ^{24}Mg$+^{24}$Mg (Ref. 2).

The excitation functions shown in Fig. 3 were subjected to a statistical fluctuation analysis similar to that outlined in Ref. 9. The data were averaged using a Gauss-

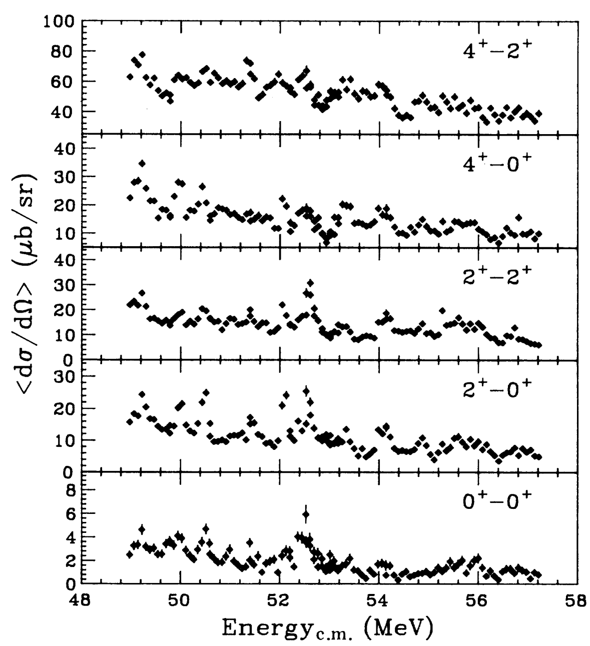

FIG. 3. Excitation functions for elastic and inelastic scattering in ^{24}Mg$+^{28}$Si. The identification of the various channels corresponds to the labeling on Fig. 2.

ian smoothing function with a FWHM of 1050 keV. Figure 4 shows the summed deviation function $D(E)$ and the cross correlation function $C(E)$ obtained from this analysis, as well as the summed cross section from the channels displayed in Fig. 3. The excursions of the summed deviation function $D(E)$ and the cross correlation function $C(E)$ beyond the 99% confidence levels calculated for statistical fluctuations confirm the nonstatistical nature of these resonances. Also, the variances of the deduced density distributions of $D(E)$ and $C(E)$ are $\sigma^2(D)=0.67$ and $\sigma^2(C)=0.93$, respectively, which far exceed the corresponding values of $\sigma^2(D)=0.2$ and $\sigma^2(C)=0.11$ expected for statistical fluctuations.

Figure 5 shows elastic scattering angular distributions measured for resonance energies of $E_{\text{c.m.}}=50.51$ and 52.53 MeV. Both have prominent oscillatory features, with minima near $\theta_{\text{c.m.}}=90°$. The angular distribution data also show considerable interference between a few competing l values. To estimate the contributions made by the dominant partial waves, we used a fit to the angular distribution data of the form

$$\frac{d\sigma}{d\Omega} \propto \left| \sum_l a_l e^{i\phi_l} P_l(\cos\theta_{\text{c.m.}}) \right|^2 .$$

Figure 5(a) shows a fit involving $l=33\hbar$, $34\hbar$, and $35\hbar$, superposed over the angular distribution data for $E_{\text{c.m.}}=50.51$ MeV. The three l values contribute with roughly equal amplitudes. Similarly, Fig. 5(b) shows a fit with $l=36\hbar$, $37\hbar$, and $38\hbar$ (solid line) superposed over the angular distribution data for $E_{\text{c.m.}}=52.53$ MeV. At this energy, $l=37\hbar$ has the largest amplitude; however, $l=38\hbar$ also makes a strong contribution. For comparison a pure $P_{37}^2(\cos\theta_{\text{c.m.}})$ (dashed line) has also been plotted over the data. These results suggest that the dominant angular momenta lie near $34\hbar$ and $37\hbar$ for the structures at $E_{\text{c.m.}}=50.51$ and 52.53 MeV, respectively. These angular momenta are close to the grazing l values at these energies obtained from optical model calculations. The potential parameters used for the calculation of the grazing l values were derived from fits to forward angle angular distribution data taken at slightly lower energies,[10] and are listed in Table I. Due to the strong interference between the resonant and nonresonant l values, it is not possible to make a firm spin assignments for these resonances from the present data.

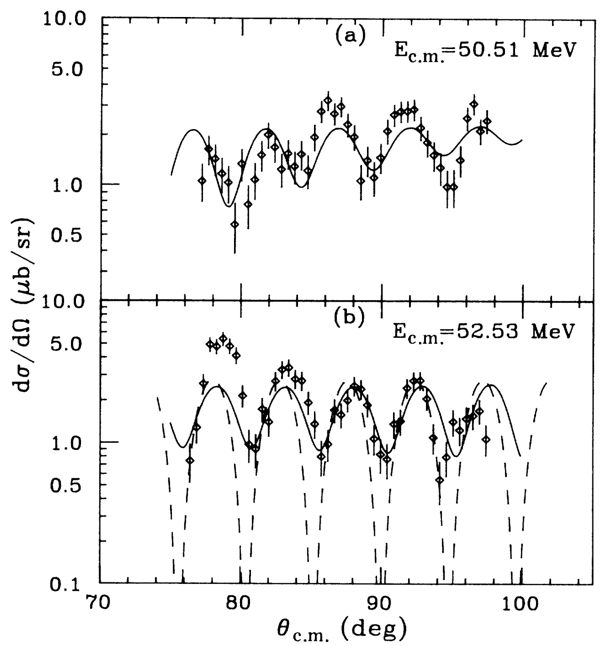

FIG. 5. Elastic scattering angular distributions measured at (a) $E_{\text{c.m.}}=50.51$ MeV and (b) $E_{\text{c.m.}}=52.53$ MeV. The solid curve in (a) is a fit involving $l=33$, 34, and 35 with amplitudes of 0.65, 0.70, and 0.60, respectively. The solid curve in (b) is a fit with $l=36$, 37, and 38 with amplitudes of 0.10, 1.00, and 0.60, respectively. The dashed curve in (b) is $P_{37}^2(\cos\theta_{\text{c.m.}})$.

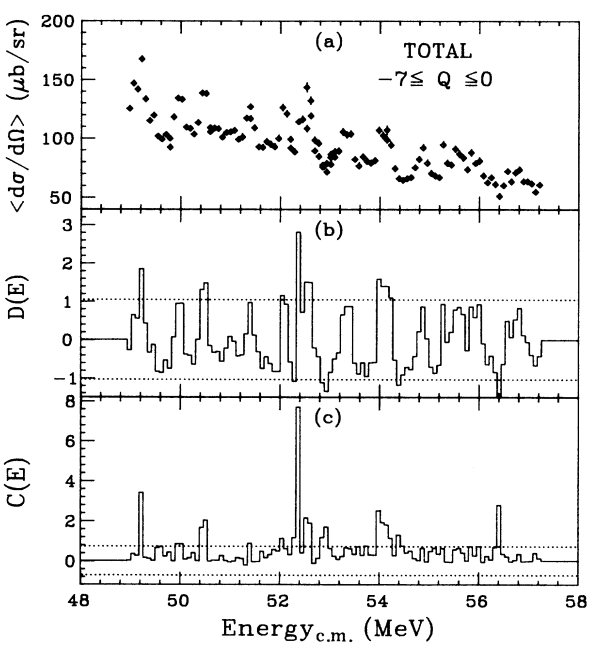

FIG. 4. Results of a statistical fluctuation analysis of the present data similar to that presented in Ref. 9. (a) Total cross section summed from $E_x=0.0$–7.0 MeV, (b) summed deviation function $D(E)$, and (c) cross correlation function $C(E)$. The dotted lines correspond to the 99% confidence levels calculated for statistical fluctuations.

Several peaks in the excitation function were subjected to a resonance analysis assuming single isolated resonances in order to extract estimates of the resonance parameters. For the angular distribution of the elastic transition we assumed $d\sigma/d\Omega \propto P_l^2(\cos\theta_{\text{c.m.}})$ with l values consistent with the grazing angular momentum. For the two resonances where angular distributions were available we used l values taken from fits to these data. Angular distributions of the form $d\sigma/d\Omega \sim 1/\sin\theta$ were assumed for the inelastic transitions, and an energy independent background was subtracted from each resonance. Table II summarizes the results of this analysis. For purposes of comparison, similar data from two reso-

TABLE I. Woods-Saxon optical model parameters for $^{24}Mg+^{28}Si$.[a]

V_0 (MeV)	r_0 (fm)	a (fm)	W (MeV)	r'_0 (fm)	a' (fm)	r_{0C} (fm)
51.50	1.175	0.645	27.5	1.090	0.659	1.2

[a] $R_i=r_{0i}(A_1^{1/3}+A_2^{1/3})$, i=real, imaginary, Coulomb.

nances in the system $^{24}Mg+^{24}Mg$ are shown. The uncertainties in the resonant elastic scattering cross sections are on the order of approximately 12%, while those for the sum of the 2^+-0^+, 2^+-2^+, and 4^+-0^+ resonant cross sections are approximately 8%. The resultant errors on the branching ratios are approximately 20% and 14% for the elastic and summed inelastic channels, respectively. Despite these uncertainties some clear trends emerge from the comparison of the two systems. The branching ratios for the elastic channel, typically from 0.9% to 1.2%, are slightly smaller than the corresponding values for $^{24}Mg+^{24}Mg$, which range from 1% to 2%. The summed branching ratios for the 2^+-0^+, 2^+-2^+, and 4^+-0^+ excitations are quite similar to those seen in $^{24}Mg+^{24}Mg$, with this range of excitation accounting for about 10–15 % of the total width in both systems. In the $^{24}Mg+^{28}Si$ system, excitations up to about 6.5 MeV exhaust approximately 30% of the total resonance strength. While the one- and two-alpha-transfer channels presumably account for a small portion of the remaining strength, a large portion of the total resonance cross section remains unaccounted for. This result is similar to the situation seen in $^{24}Mg+^{24}Mg$ and $^{28}Si+^{28}Si$.

Following the completion of this work, another measurement of excitation functions for the elastic channel $^{24}Mg(^{28}Si,^{28}Si)^{24}Mg$ has appeared in the literature.[11] No narrow structures comparable to those reported here were seen in that work, probably due in part to the wide ($\Delta E_{c.m.}=0.5$ MeV) energy steps taken in Ref. 11. Another important difference between these two investigations is the angle of detection. The data in Ref. 11 were recorded at laboratory angles of 6° and 15°. These angles correspond to center of mass angles of 172° and 150° when the recoiling ^{24}Mg is the particle being detected. As pointed out in Ref. 11, the direct reaction contribution from the α-transfer reaction $^{24}Mg(^{28}Si,^{24}Mg)^{28}Si$ is substantial at these large angles and the detection of weak and narrow resonances is therefore more difficult than in our measurements, which were carried out at center of mass angles near 90°. Furthermore, extensive measurements in the $^{24}Mg+^{24}Mg$ system have revealed resonances in only a rather limited range of beam energies between 84 and 100 MeV. Therefore, the measurements in Ref. 11 are possibly below the energy range in the $^{24}Mg+^{28}Si$ system where such structures can be seen. These considerations may also apply to a recently published study of the $^{28}Si+^{32}S$ reaction,[12] in which no intermediate width structure was reported.

In conclusion, we have observed resonance behavior in the elastic and inelastic scattering of $^{24}Mg+^{28}Si$. Peaks in the excitation functions are narrow, with center of mass widths from 140 to 280 keV, and show strong correlation between the elastic and inelastic channels. A particle identification technique measuring the time of flight difference between reaction products allows us to extract angular distribution data, and these data indicate that the spins of these resonances, $33-37\hbar$, are near the grazing angular momentum at these energies. Many properties of the present system are similar to those seen in the neighboring $^{24}Mg+^{24}Mg$ and $^{24}Mg+^{28}Si$ systems. Branching ratios for elastic and inelastic scattering in $^{24}Mg+^{28}Si$ are similar to those observed in $^{24}Mg+^{24}Mg$.

Including the present work, narrow resonances have

TABLE II. Estimated resonance parameters in $^{24}Mg+^{28}Si$ and $^{24}Mg+^{24}Mg$.[a] The total resonant elastic scattering cross sections were estimated assuming $d\sigma/d\Omega \propto P_{33}^2(\cos\theta_{c.m.})$ for $E_{res}=49.23$, 50.02, and 50.51 MeV, and $d\sigma/d\Omega \propto P_{35}^2(\cos\theta_{c.m.})$ for $E_{res}=52.20$, 52.53, 53.17, and 54.06 MeV. $d\sigma/d\Omega \propto 1/\sin\theta$ was assumed for the inelastic transitions.

	E_R (MeV)	σ_R^{el} (mb)	$\Sigma\sigma_R^{inel}$ (mb)	Γ_{tot} (MeV)	$\frac{\Gamma_{el}}{\Gamma_{tot}}$	$\frac{\Sigma\Gamma_{inel}}{\Gamma_{tot}}$
$^{24}Mg+^{28}Si$	49.23	0.034	0.403	0.18±0.05	0.011	0.13
	50.02	0.034	0.303	0.20±0.04	0.011	0.10
	50.51	0.041	0.375	0.16±0.03	0.012	0.12
	52.20	0.029	0.386	0.14±0.03	0.010	0.14
	52.53	0.051	0.419	0.24±0.05	0.014	0.11
	53.17	0.024	0.254	0.18±0.04	0.009	0.10
	54.06	0.021	0.254	0.28±0.05	0.009	0.11
$^{24}Mg+^{24}Mg$	46.65	0.150	1.130	0.22±0.04	0.018	0.12
	47.75	0.070	0.840	0.15±0.03	0.010	0.12

[a] Reference 2.

now been observed in three systems with the compound systems corresponding to the three adjacent α-particle nuclei with $A=48$, 52, and 56. In contrast, similar structures have not been observed in another $N=Z$ even nucleus $A=64$. The systematics of the A dependence of such resonance behavior is, however, quite incomplete. We still know very little about the presence of similar structure in lighter systems, mostly because of the experimental difficulties associated with ^{20}Ne serving as a target material or beam species. Future measurements in these lighter systems are very important in order to establish a clear understanding of the systematic behavior and the nature of these resonances.

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