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Structure in the 180° scattering of ^{12}C by ^{27}Al

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An excitation function for elastic and inelastic scattering at $\theta_{c.m.} = 180° \pm 2.0°$ has been measured for $^{12}C + ^{27}Al$ in the energy range $14 \lesssim E_{c.m.} \lesssim 25$ MeV. The data exhibit a strong enhancement at $E_{c.m.} \simeq 19.5$ MeV with a width of ~2 MeV. Elastic scattering angular distributions at $E_{^{12}C}(\text{lab}) = 30$, 32, 35, and 40 MeV show oscillatory structure in the angle range $40° \lesssim \theta_{c.m.} \lesssim 110°$. It is not possible to describe the elastic scattering data with an energy independent optical model.

[NUCLEAR REACTIONS $^{12}C + ^{27}Al$, measured $\sigma(\theta, E)$ elastic and inelastic scattering, $\theta_{c.m.} = 180° \pm 2.0°$, $14 < E_{c.m.} < 25$ MeV. Measured $\sigma(\theta)$ elastic, $E_{c.m.} = 20.8$, 22.2, 24.2, and 27.6 MeV $14° \leq \theta_{c.m.} \leq 110°$, deduced optical model parameters.]

I. INTRODUCTION

The observation of gross structure in the backward angle elastic scattering of ^{12}C and ^{16}O from ^{28}Si by Barrette *et al.*[1] has motivated considerable experimental and theoretical efforts to understand this phenomenon.[2-8] In contrast to $^{12}C + ^{28}Si$, no prominent structures have been observed for $^{13}C + ^{28}Si$ (Ref. 4) and the cross section is two orders of magnitude smaller than for the $^{12}C + ^{28}Si$ case. Other nuclei in the *sd* shell for which gross structures in the elastic scattering have been reported are ^{12}C, $^{16}O + ^{20}Ne$,[9] $^{16}O + ^{24}Mg$,[3] $^{12}C + ^{32}S$,[4,5] and $^{12}C + ^{40}Ca$.[6,7] Weaker structures have been reported for $^{16}O + ^{29,30}Si$,[10] however, the cross sections are one order of magnitude smaller than those for $^{16}O + ^{28}Si$. In this work, data indicating the presence of gross structure at 180° in the elastic and inelastic scattering of ^{12}C from ^{27}Al are presented. This study was prompted by the presence of large angle structures, similar to those observed in ^{12}C, $^{16}O + ^{28}Si$, for both $\alpha + ^{28}Si$ and $\alpha + ^{27}Al$,[11] suggesting that structure observed in $^{12}C + ^{28}Si$ might also be observed in $^{12}C + ^{27}Al$. In addition, the forward angle elastic scattering angular distribution of ^{12}C on ^{27}Al at $E_{^{12}C}(\text{lab}) = 55$ MeV shows oscillations, which start at about $\theta_{c.m.} = 50°$ and persist to $\theta_{c.m.} > 110°$,[12] a situation similar to that for $^{12}C + ^{28}Si$.[13] In this paper additional forward and midangle elastic scattering angular distributions in the energy range $E(\text{lab}) = 30-40$ MeV are presented which show that the oscillations persist at lower energies.

II. EXPERIMENTAL METHOD

The experiment was performed using an ^{27}Al beam (beam current ~30 nA) from an inverted sputter ion source accelerated through the Florida State University super FN tandem. The lab energy range covered in this experiment was 45 to 80 MeV, the upper limit being the maximum energy at which a useful beam intensity could be obtained. The Al beam was extracted as AlH_2^-, formed by letting ammonia gas flow onto an Al cone.[14] The time-of-flight detection system described below was used to make certain that the accelerated beam was ^{27}Al rather than ^{28}Si. Self-supporting ^{12}C targets of ~50 $\mu g/cm^2$ areal density were used. The Al beam was stopped by an Ni foil of 8.8 mg/cm^2 thickness. The Ni foil was surrounded by an electron suppression ring maintained at −500 V with respect to the foil, so that accurate measurement of the integrated beam current was possible. The whole assembly could be rotated to change the effective thickness of the Ni foil. A liquid N_2 cooled trap around the target prevented any significant carbon buildup during the run. The ^{12}C recoils were detected at $\theta_{lab} = 0° \pm 1°$ using the F. S. U. 3-m quadrupole spectrometer with time-of-flight particle identification. Pulses from a channel plate detector were used to provide a start signal for the time-of-flight measurement, while a cooled 450-mm^2 Si surface barrier detector provided the stop signal and was used as the total energy detector. The time resolution of the system was ~450 ps. A monitor detector at 25° recorded the yield of elastically scattered ^{27}Al as a check on the target thickness. The efficiency of the spectrometer was determined by comparing the elastic scattering yield of ^{12}C from an Au target with the quadrupole magnets switched on and off. The charge state corrections for the beam current integration were determined using the semi-empirical formula given by Betz.[15] The product of detector solid angle times the target thickness, necessary for determining the absolute cross section, was obtained by measuring ^{16}O scattering at 20 MeV for $\theta_{lab} < 15°$, where the cross section is given by Rutherford scattering. The excitation function was measured over the entire energy range twice, and the two measurements agree very well. Owing to the energy straggling in the Ni foil, the peaks from transitions to the ground state and excited states of ^{27}Al (up to ~2 MeV) could not be resolved. The yields measured thus represent a sum of yields to the ground and the first five excited states of ^{27}Al, and hence we are able to compare the present data only with the summed elastic and inelastic scattering data for ^{12}C + ^{28}Si. However, it should be noted that (p,p') (Ref. 16) scattering results indicate that the first five excited states of ^{27}Al are well described by the weak coupling of a $d_{5/2}$ proton hole to the 2_1^+ state of ^{28}Si. Hence, the yields to these states should be comparable to that of the 2^+ state in ^{28}Si. The forward and midangle elastic scattering angular distributions were measured in a standard 46-cm scattering chamber with an array of two single Si surface barrier detectors and three ΔE-E telescopes, each separated by 10° intervals. The product of target thickness times the detector solid angle was found by measuring ^{12}C scattering at 12 MeV for $\theta_{lab} < 15°$ where the cross section is given by Rutherford scattering.

III. RESULTS AND DISCUSSION

As a check on the detection system the excitation function for ^{12}C + ^{28}Si was measured first. Figure 1 shows the excitation function for ^{12}C + ^{28}Si scattering leading to the g.s. and first excited state of ^{28}Si, measured with our setup, together with data in the same energy range taken from Barrette *et al.*[1] The elastic and inelastic cross sections from Ref. 1. were summed for comparison with the present data. The present measurements on ^{28}Si reproduce the data of Barrette *et al.* quite well.

The measured excitation function at 180° for scattering to the ground and first five excited states of ^{27}Al is also presented in Fig. 1. A prominent structure is seen in the excitation function at $E_{c.m.}$ ~19.5 MeV with a width of ~2 MeV in the c.m. system. This is about the same width as that observed for the gross structure resonances in ^{12}C + ^{28}Si. The summed elastic and inelastic scattering cross section in the ^{12}C + ^{27}Al case is found to be ~3 times smaller than for ^{12}C + ^{28}Si in the same c.m. energy range. This is in contrast to the case of ^{13}C + ^{28}Si (Ref. 4) where the average elastic scattering cross section is found to be two orders of magnitude smaller than that for ^{12}C + ^{28}Si.

The forward angle elastic scattering angular distributions are presented in Fig. 2. The angular distributions near $E_{c.m.}$ ~20 MeV show similar oscillations for both the ^{12}C + ^{27}Al and ^{12}C + ^{28}Si cases.[13] No energy independent parameter set was found which would give good fits to the data at all the energies. This is in agreement with the results for ^{12}C + ^{28}Si scattering.[13] The solid lines represent the angular distributions calculated with parameter set I of Table I, which gives the overall minimum χ^2 when the angular distributions at all four energies are fitted simultaneously. The dashed lines are the calculated angular distributions with parameter set II of Table I which fits the 40 MeV data best but gives poorer fits to the data at lower energies than that given by parameter set I. The parameter set I was used to generate an excitation function at 180° which is presented in Fig. 3. Also shown in the same figure is the exci-

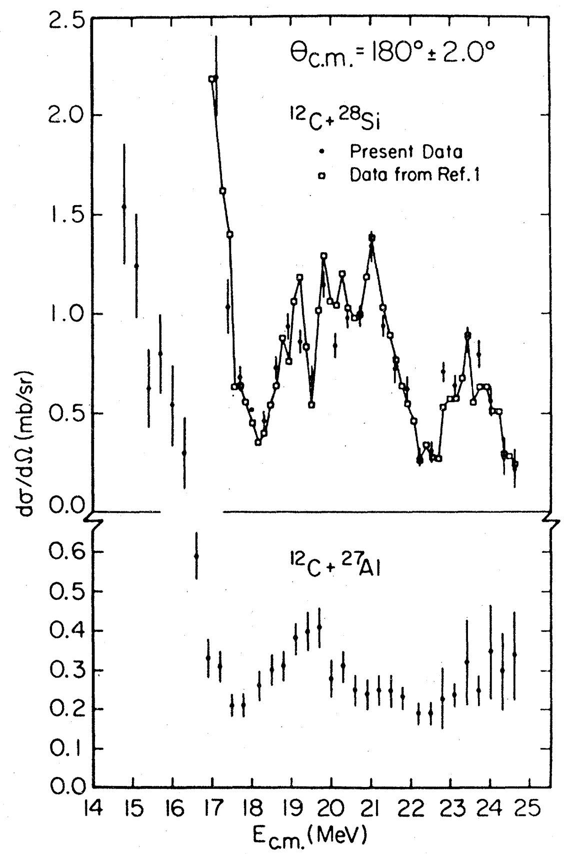

FIG. 1. Excitation function at $\theta_{c.m.}$ = 180° averaged over ±2.0° for the elastic and inelastic scattering of ^{12}C from ^{28}Si (upper part) and from ^{27}Al (lower part). The summed elastic and inelastic data for ^{28}Si from Barrette *et al.* (Ref. 1) are shown as open squares connected by solid lines. The energy scale has not been corrected for energy loss in target. (See text for details.)

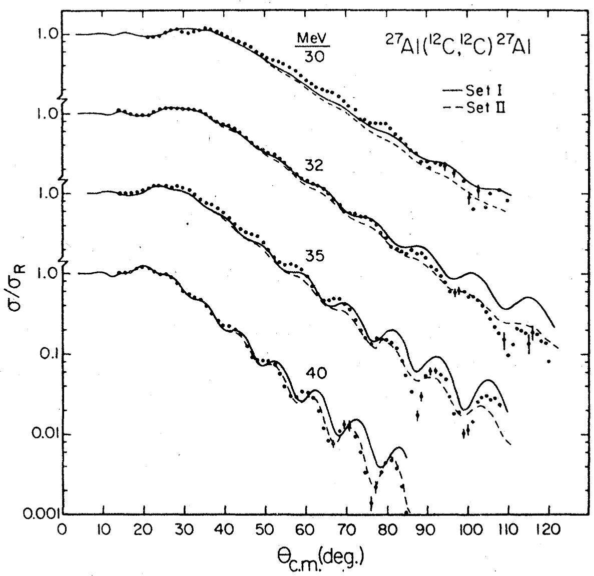

FIG. 2. Center of mass angular distributions of ^{12}C elastic scattering from ^{27}Al. The error bars are the statistical errors. The solid lines were calculated with the optical potential defined by parameter set I of Table I and the dashed lines with set II.

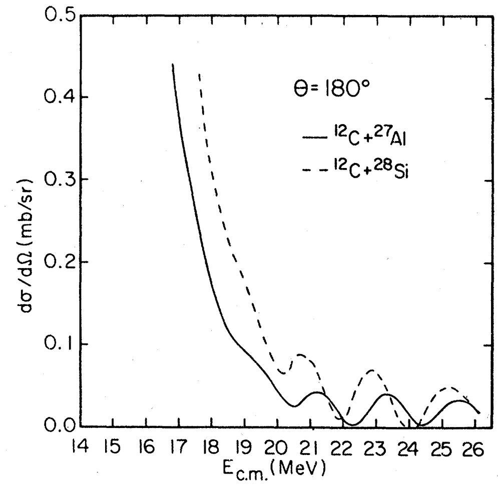

FIG. 3. Calculated excitation function for the elastic scattering of ^{12}C from ^{27}Al (solid line) and from ^{28}Si (dashed line) using the optical potential parameter sets of Table I.

tation function for $^{12}C + ^{28}Si$ calculated with the parameter set II of Ref. 13, also given in Table I. The magnitudes of the calculated cross sections are not sensitive to small changes in the optical model parameters. The two-calculated excitation functions have similar features in the energy range presented, viz., they both show the presence of structures with a width of ~1 MeV in the c.m. system. The calculated cross sections are about one order of magnitude smaller than the experimental values. Also, neither the position nor the widths of the structures correspond to experiment in either case. Thus, the data for $^{12}C + ^{27}Al$, like those for $^{12}C + ^{28}Si$, cannot be described by an energy independent optical model parameter set.

The observation that the $^{12}C + ^{27}Al$ cross section at 180° is down by a factor of 3 with respect to that for $^{12}C + ^{28}Si$ shows that the effect which is responsible for the gross structure is inhibited in the $^{27}Al + ^{12}C$ case. However, if the structure is due to resonances then the reduction in the cross section could result from the target spin of the ^{27}Al nucleus. For an isolated resonance formed via a single l value, the spin of $\frac{5}{2}$ of the ^{27}Al nucleus would lead to a reduction of the cross section by a factor of 6 due to the statistical spin factor $\{(2I_1+1)(2I_2+1)\}^{-1}$, where I_1 and I_2 are the spins of the entrance channel nuclei. However, the reduction of the cross section for the $^{13}C + ^{28}Si$ scattering compared to that for $^{12}C + ^{28}Si$ could not be accounted for by the spin $\frac{1}{2}$ of the ^{13}C nucleus. Neither can the reduction of the cross section by a factor of 10 for $^{16}O + ^{29,30}Si$ scattering compared to that for $^{16}O + ^{28}Si$ be accounted for by the statistical spin factor.

In summary, the data presented show a gross structure at $E_{c.m.} = 19.5$ MeV in the 180° scattering of ^{12}C from ^{27}Al, and the angular distributions show oscillatory structure at forward and middle

TABLE I. Derived optical model potentials (parameters in units MeV and fm)

$$V(r) = \frac{-U}{1+\exp(r-R_R)/a_R} - \frac{iW}{1+\exp(r-R_I)/a_I} + V_C(r),$$

$$R_I = r_i(A_p^{1/3} + A_t^{1/3}) \quad (i = R, I).$$

Target	U	r_R	a_R	W	r_I	a_I	r_{Coul}
^{27}Al set I	27.49	1.30	0.45	7.55	1.23	0.26	1.31
set II	27.49	1.32	0.43	15.55	1.28	0.25	1.31
^{28}Si (Ref. 13)	26.96	1.318	0.457	7.95	1.211	0.19	1.31

angles in the energy region of the enhancement. Among the non-$4n$ systems investigated so far, $^{12}C+^{27}Al$ exhibits the strongest gross structure in the 180° scattering. The similarity of both the forward angle angular distributions and the backward angle excitation function for $^{12}C+^{27}Al$ and $^{12}C+^{28}Si$ strongly suggests that a common phenomenon is responsible for the anomalous scattering in both systems.

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