Back-angle elastic and inelastic scattering of α particles from the even Ni isotopes

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Angular distributions for the elastic and inelastic scattering of α particles from the even Ni isotopes from 12.5 to 177.5° in the energy range from 18–27 MeV are reported. The β_2 coupling strengths to the first excited 2^+ state in each isotope are extracted from the data and are compared to similar results obtained at higher energy. The lack of any backward enhancement in the cross sections, in contrast to results reported for lighter nuclei, is explained on the basis of the level densities in the compound system.

[NUCLEAR REACTIONS $^{58,60,62,64}Ni(\alpha,\alpha')$, $E=18$–27 MeV; measured $\sigma(E;\theta)$; deduced optical-model parameters. Enriched targets. Coupled-channel analysis, resolution 200 keV, $\theta=12.5$–177.5°, $\Delta\theta=2.5°$.]

I. INTRODUCTION

Measurements of elastic α-scattering cross sections for target nuclei ranging from ^{10}B up to the Ca isotopes at a variety of bombarding energies have established large differences in the cross sections at backward angles for different isotopes,[1-8] e.g. the $\alpha+^{40}Ca$ elastic scattering cross sections at bombarding energies between 18 and 30 MeV show a strong over-all rise in the cross sections from 90 to 180° in striking contrast to the angular distributions of $\alpha+^{44}Ca$ scattering which show a regular over-all decrease of the cross sections with angle.[2] It has been further shown that the backward anomaly is also present in the inelastic cross sections[9] and in particular, a very strong backward enhancement is seen in the inelastic scattering to excited 0^+ states in ^{40}Ca. The α-particle scattering cross sections recently reported from nuclei with $Z>20$ (i.e., Te, V, Cr, Mn, Fe) also show no strong backward anomalies.

To investigate the question of whether the back-angle enhancement exists for target nuclei heavier than calcium, we have measured elastic and inelastic scattering angular distributions for the even Ni isotopes ($A=58$, 60, 62, and 64) for the angular range from 12.5 to 177.5° at laboratory bombarding energies of 18, 21, 24.1, and 27 MeV. This is the energy range for which the largest back-angle enhancement was observed for the Ca isotopes. It was believed that the Ni isotopes were most appropriate for this study because of similarities in shell structure. In addition, the (α, n) Q values, which were related to the phenomena of backward enhanced cross sections, are similar to those for the Ca isotopes.[10] As a by-product information on β_2, the coupling parameter to the first excited 2^+ state, was obtained from the inelastic scattering data.

There have been many other measurements of $\alpha+$Ni scattering at various energies and angular ranges.[11-16] In recent work, α elastic and inelastic cross sections at $E_\alpha=104$ MeV were measured by Rebel *et al.*[17] for all even Ni isotopes at forward angles and, in particular, β_2 values were extracted. Backward-angle elastic and inelastic cross sections were measured by Sewell *et al.*[18] for $\alpha+^{58}Ni$ in the energy range from 15–30 MeV.

The emphasis of the present work was to search for any possible back-angle anomaly in the same energy range where they have been observed for other isotopes and to investigate the energy dependence of β_2 by comparison with the work at 104 MeV reported in Ref. 17.

II. EXPERIMENT

Angular distributions were measured at 18-, 21-, 24.1-, and 27-MeV α bombarding energy for the angular range from 12.5–177.5° in 2.5° steps. The Munich large scattering chamber[19] and a multidetector array employing eight Si surface-barrier detectors was used. The targets were enriched self-supporting Ni foils each approximately 600–1200 $\mu g/cm^2$ thick. The α-particle beam was obtained from the Munich MP tandem accelerator with an intensity of 400–600 nA on target during the various runs. A typical particle spectrum is shown in Fig. 1. Each spectrum was

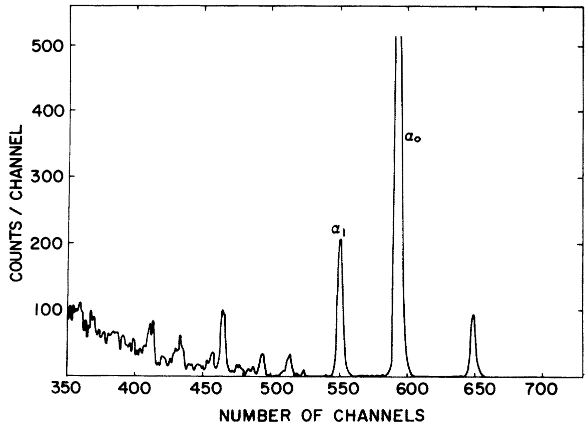

FIG. 1. Particle spectrum for $\alpha + {}^{60}Ni$ scattering at 85° (lab) and at E_α (lab) = 21 MeV. Only the elastic scattering (α_0) and the inelastic scattering to the 2^+ state at 1.33 MeV (α_1) are of interest in this paper. The energy resolution of about 200 keV is due to the relatively thick target used in these measurements (see text).

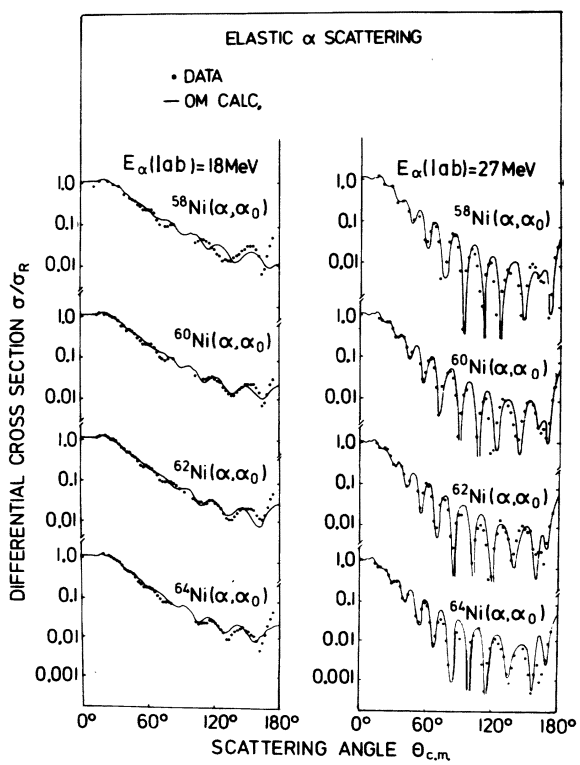

FIG. 2. Experimental and calculated angular distributions for the elastic scattering of α particles from the even nickel isotopes at bombarding energies of 18 and 27 MeV. The solid curves are calculated from a four-parameter optical model with $V = 41.4$ MeV, $W = 8.4$ MeV, $r_0 = 1.65$ fm, and $a = 0.52$ fm.

analyzed with a separate analog-to-digital converter (ADC) interfaced to the Munich PDP-8/PDP-10 computer system and dead-time corrections were made by measuring the charge accumulated for each ADC only during the time which that ADC was alive. The relative solid angles of each detector were determined by measuring the α-particle cross section at forward angles from a thin Au foil at 12 MeV. At this energy the forward-angle scattering is pure Rutherford scattering. The absolute normalization of the various α + Ni cross sections was obtained by comparing the forward-angle scattering at $E_\alpha = 12$ MeV to calculations of Rutherford scattering. The absolute normalization is accurate to about ± 8%.

III. ANALYSIS

The elastic scattering angular distributions are shown in Figs. 2 and 3. The inelastic scattering angular distributions to the lowest 2^+ state are shown in Figs. 4 and 5. Due to the target thickness only the ground state and first excited 2^+ state were completely resolved.

The elastic scattering angular distributions for all energies and all isotopes show a regular decrease in a diffractionlike pattern with angle. None of the isotopes studied shows a backward increase

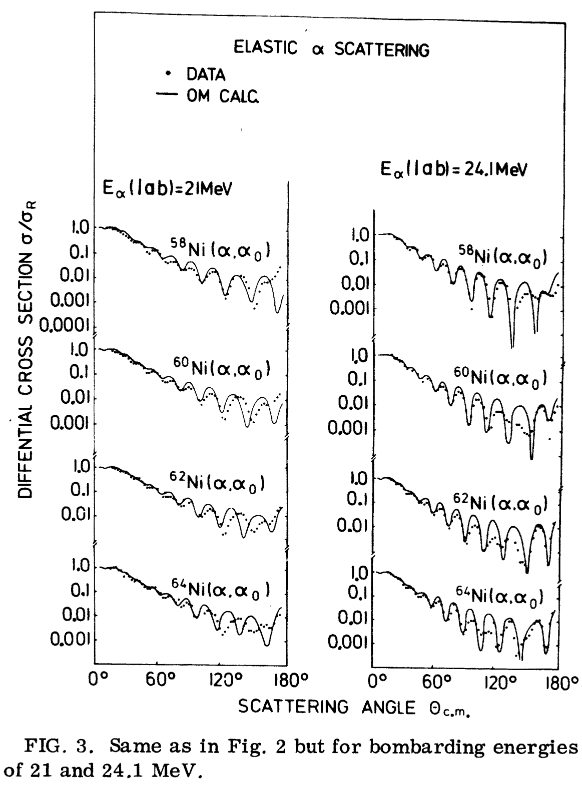

FIG. 3. Same as in Fig. 2 but for bombarding energies of 21 and 24.1 MeV.

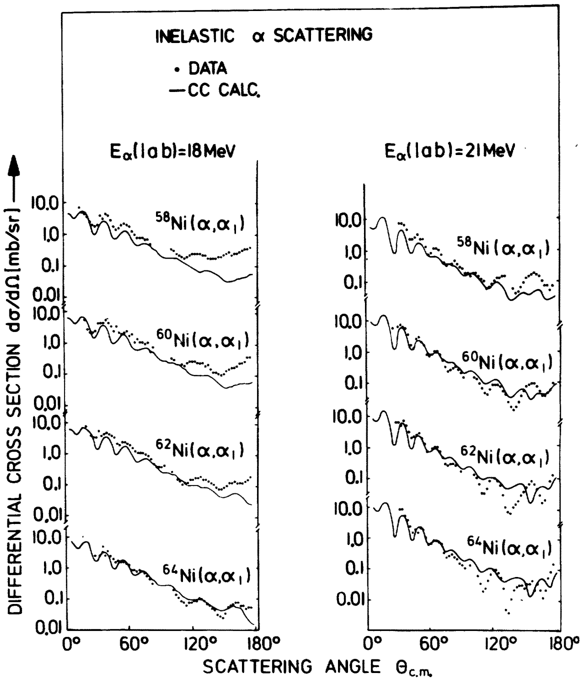

FIG. 4. Experimental and calculated angular distributions for the inelastic α scattering to the first excited state (2^+) in the even nickel isotopes at bombarding energies of 18 and 21 MeV. The solid curves represent coupled-channel calculations. A 0^+-2^+ vibrational coupling scheme was used along with the parameters listed in Table I. The corresponding results for the elastic scattering are shown in Figs. 6 and 7.

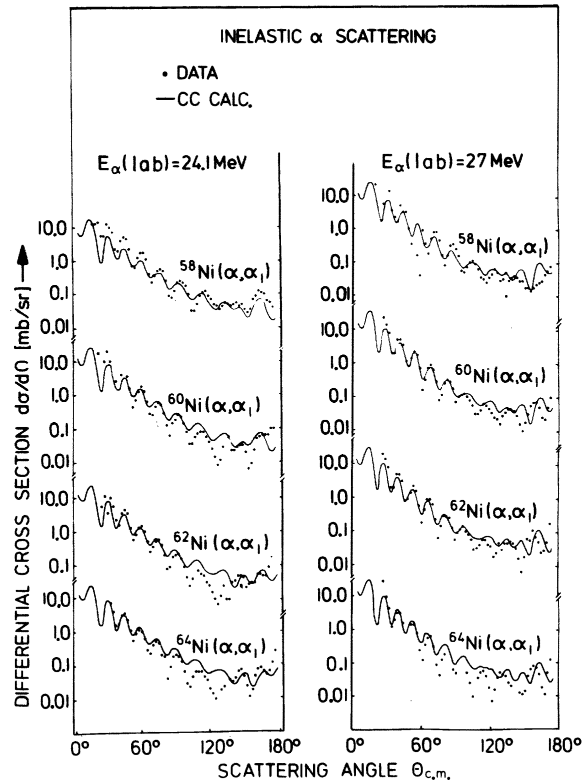

FIG. 5. Same as in Fig. 4 but for bombarding energies of 24.1 and 27 MeV.

of the cross section comparable to the anomalous cases observed for other target nuclei, e.g. in the Ca region. The inelastic cross sections show a similar falloff with angle and exhibit no backward enhancement. It should also be noted that the Blair phase rule[20] is accurately obeyed for angles less than 90°.

The initial analysis of the elastic scattering cross sections was in terms of a simple four-parameter optical model with a nuclear potential of the form

$$U(r) = (V + iW)f(r) ,$$

where

$$f(r) = \left\{1 + \exp\left[\frac{(r - r_0 A^{1/3})}{a}\right]\right\}^{-1} . \quad (1)$$

Although many acceptable parameter sets were found which fitted well isolated or selected groups of angular distributions, the best set to fit all data was for $V = 41.4$ MeV, $W = 8.4$ MeV, $r_0 = 1.65$ fm, and $a = 0.52$ fm. This set of parameters is capable of fitting the angular distributions at all energies and for all isotopes and yields excellent agreement between calculation and experiment. The optical-model fits are shown in Figs. 2 and 3. Of particular interest to the present study is the fact that no l-dependent absorption[18,21-23] or Regge-pole parametrization[1,24,25] is necessary to adequately describe the data, in contrast to results reported for lighter target nuclei as ^{40}Ca (Refs. 21 and 23) and ^{16}O (Ref. 26).

The inelastic cross sections were fitted using the Karlsruhe version[27] of the coupled-channel code Jupitor[28,29] of Tamura. A simple 0^+-2^+ vibrational coupling scheme was assumed. The optical-model parameters were initially chosen to be the same as those given above with the exception that W was reduced by about 10% to account

TABLE I. Parameter values for the optical model and for the coupling strength β_2 as used in the coupled-channel calculations.

	V (MeV)	W (MeV)	r_0 (fm)	a (fm)	β_2
^{58}Ni	41.5	7.8	1.60	0.60	0.15
^{60}Ni	41.5	7.8	1.60	0.60	0.17
^{62}Ni	41.5	7.8	1.60	0.60	0.16
^{64}Ni	41.5	7.8	1.60	0.60	0.16

for the coupling to the 2^+ state. The β_2 coupling strengths were taken from the work of Rebel *et al.*[17] This parameter set yielded the right order of magnitude cross sections but the phase of the theoretical oscillations in the back-angle cross sections was incorrect. The parameter set was then adjusted by increasing the diffuseness parameter to yield good agreement with all isotopes at all energies. The final parameter set is given in Table I and the final fits to the inelastic cross sections are shown in Figs. 4 and 5. Because of the strong coupling between the 2^+ and 0^+ (g.s.), the fits to the elastic scattering cross sections are affected by the coupling. The coupled-channel fits to the elastic cross sections are shown in Figs. 6 and 7. Again no additional assumptions such as l-dependent absorption are necessary to adequately describe the inelastic scattering in contrast to the case of inelastic α scattering from ^{40}Ca recently reported.[30]

IV. RESULTS

The elastic and inelastic scattering of α particles from the even Ni isotopes in the energy range from 18–27 MeV can be readily described with a simple optical model in the case of elastic scattering and in terms of a coupled-channel calculation assuming a vibrational coupling for the case of inelastic scattering to the first 2^+ state. Furthermore, the coupling strengths necessary to fit the data reported here are identical to those reported by Rebel *et al.*[17] to describe the inelastic scattering at 104 MeV. Apparently the β_2 coupling strengths have no variation with energy as indeed would be expected if they represent the mean square deformation of the nucleus due to zero-point vibrations.

The lack of any anomaly for the α+Ni scattering as described in this paper in contrast to the scattering from some lighter-target nuclei is discussed next. We like to emphasize at this point that several explanations for the back-angle anomalies as described in the Introduction have been offered. None of these models, however, can explain all aspects of this phenomenon; thus leaving uncertainty in its understanding. A detailed discussion on the various models suggested and on their consequences was recently given at the Marburg Conference[1] and we like to refer to the proceedings of this conference for a portrayal of the present state of back-angle anomalies in α-particle scattering. In the following we like to interpret the lack of any observed backward en-

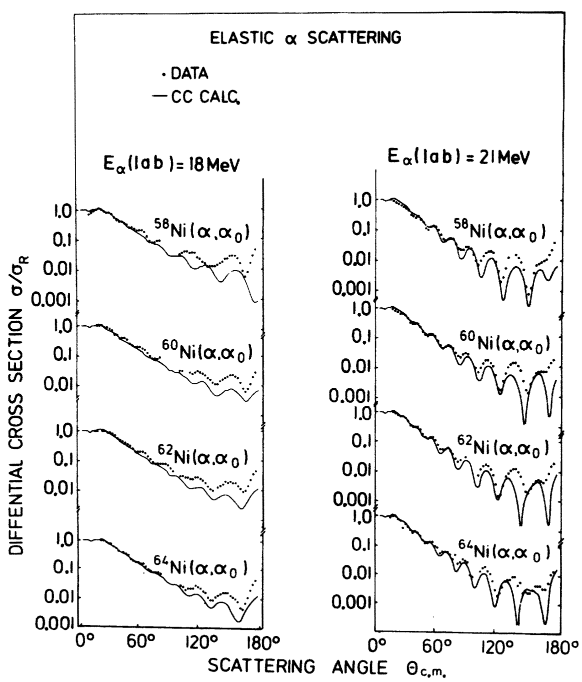

FIG. 6. Comparison of the elastic α scattering from the even nickel isotopes with coupled-channel calculations at bombarding energies of 18 and 21 MeV. The solid curves are calculated using a 0^+-2^+ coupling scheme along with the parameters listed in Table I. The corresponding results for the inelastic scattering are shown in Figs. 4 and 5.

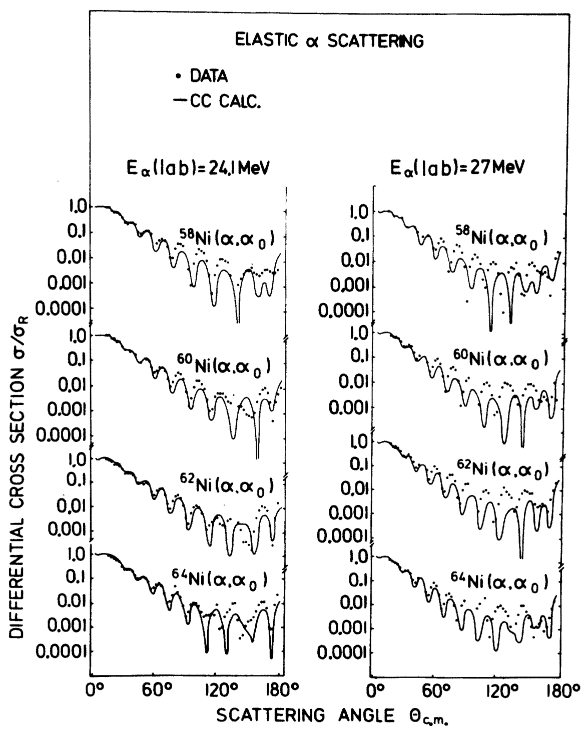

FIG. 7. Same as in Fig. 6 but for bombarding energies of 24.1 and 27 MeV.

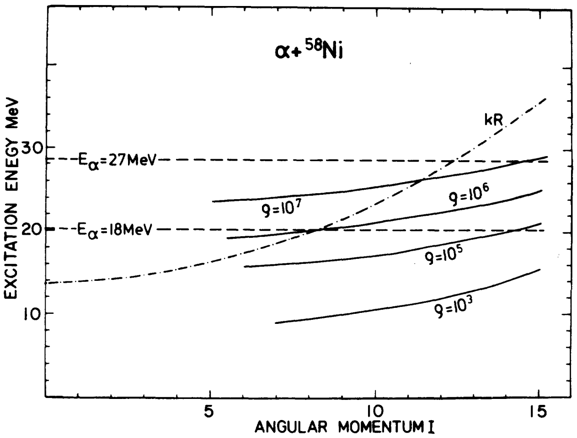

FIG. 8. Contour map of density of states in the $\alpha + {}^{58}$Ni compound system. The range of excitation energies covered by the data presented in this paper is indicated by the horizontal lines. It can be seen that the density of states with angular momenta I close to the grazing angular momentum of the entrance channel, indicated by the kR curve, is sufficiently large so that no angular momentum mismatch effects are expected (see text).

hancement for $\alpha + {}^{58,60,62,64}$Ni scattering in terms of one of these models, namely, the optical model with angular-momentum-dependent absorption.[10,22,23,30,31] Similar interpretations in terms of the other models are difficult and have not been done; thus from the following it can only be concluded that the experimental results presented in this paper can be understood in terms of the l-dependent absorption model, but it does not necessarily prove that this is the only possible explanation.

The lack of any observed backward enhancement in the cross sections for scattering from the Ni isotopes can be explained in terms of the optical model with angular-momentum-dependent absorption by considering the density of states of different angular momentum in the compound system. In Fig. 8 we have projected the density of states in the compound system formed from $\alpha + {}^{58}$Ni onto the E_x vs $I(I+1)$ plane, where E_x is the excitation energy of the compound system and I is the spin of the compound levels. The level densities were calculated from a standard Fermi-gas level-density formula.[32] Also shown for comparison in Fig. 8 is the value of kR which represents the angular momentum corresponding to a grazing collision. This value was calculated with

$$R = 1.4(A_1^{1/3} + A_2^{1/3})$$

and with

$$k = \frac{1}{\hbar}\left[2M(E_{\text{c.m.}} - E_C)\right]^{1/2},$$

where M is the reduced mass, $E_{\text{c.m.}}$ is the c.m. energy and E_C is the Coulomb barrier height (calculated with $r_0 = 1.4$ fm).

It is well known for composite particles such as α particles or heavy ions, that because of strong absorption only partial waves for grazing collision make strong contributions to the scattering (elastic and inelastic) cross sections. For the bombarding energy range considered in the present work, i.e., 18–27 MeV, corresponding to an excitation energy $E_x = 20.2$–28.6 MeV in the compound system, it is demonstrated in Fig. 8 that there are many states (10^6–10^7 per MeV) of high angular momentum in the compound system which can readily absorb the partial waves for grazing collision. The simple assumption of the optical model,[33] that $W(E_x, J)$ is a function of $\rho(E_x, J)$ where W is the absorptive potential of the optical model and $\rho(E_x, J)$ is the level density in the compound system, indicates that the absorptive potential is so large, even for the highest partial waves, that there is strong absorption and, therefore, no angular momentum dependence for W is required. Thus, no backward enhancement in the cross section for energies greater than $E = 18$ MeV is expected. Similar arguments of course apply for the other Ni isotopes. This is in strong contrast to the case of α scattering from the isotopes in the Ca region, where the density of states in the compound system is lower and the Q values for formation of the compound nucleus have a strong influence on the number of compound states available for a grazing collision.[34,31] We like to note that the slight increase of the cross sections at energies below 15 MeV as observed in Ref. 35 for α-Ni elastic scattering is most probably due to compound elastic scattering. On the basis of the present work we conclude that anomalous back-angle α scattering probably does not exist for nuclei above the Ca region.

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