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ROLE OF SURFACE VIBRATIONS IN THE REACTION $^{36}Ar+^{208}Pb$ FOR INTERMEDIATE-ENERGY LOSSES

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Abstract: The double-differential cross section $d^2\sigma/d\Omega\, dE$ for pure inelastic events has been calculated for the reaction $^{36}Ar+^{208}Pb$ at 390 MeV. We do not find evidence for pronounced structures in the energy range $E \gtrsim 30$ MeV which can be attributed to simple multiple excitation of high-lying surface modes.

1. Introduction

A rich variety of vibrations has been revealed through study of the nuclear response with light-ion reactions [cf. e.g. ref. [1]) and references therein]. More recently, these studies have also been pursued making use of heavy-ion projectiles [cf. e.g. refs. [2-5]) and references therein]. The excitation of surface modes has been found to play an important role in the damping of energy and angular momenta observed in heavy-ion collisions [cf. e.g. refs. [6-8]) and references therein]. Because of the complexity of these processes, only in the quasielastic regime is it expected that individual states can give a signal in the double-differential cross section as a function of scattering angle and energy.

During the last few years, structures in the region of intermediate energy losses, and extending to rather high excitation energies, have been reported for a variety of reactions [9-19]). Some of them have been identified with the pick-up and successive evaporation of a nucleon leading back to the entrance-channel mass partition [20-22]). A number of these structures seem, however, to be associated with states of the target nucleus, displaying energies which are independent of the projectile and widths of the order of few MeV. At certain angles, peaks in the cross sections with properties similar to those of known giant resonances have also been observed.

In the present paper we analyze the reaction $^{36}Ar+^{208}Pb$ at a bombarding energy of 390 MeV, making use of the surface excitation model of ref. [6]). Inelastic channels including those associated with the excitation of both low-lying collective states and high-lying giant resonances are explicitly included in the calculations. The effect of particle-transfer processes is taken into account in terms of a microscopically calculated [23]) absorptive potential which depopulates the inelastic channels along the trajectory.

In sect. 2 the model used in the calculations is briefly reviewed. In sect. 3 the analysis of $^{16}O+^{208}Pb$ and $^{36}Ar+^{208}Pb$ data is presented; the first is used here to check the ability of the model to reproduce the structures associated with the excitation of giant resonances in grazing collisions. The conclusions are collected in sect. 4.

2. The model

The coherent surface excitation model of heavy-ion reactions has been discussed in detail in a series of papers [cf. e.g. ref. [6]) and references therein]. In what follows we thus only summarize the main points relevant to the present investigation.

The relative motion of the two ions is described in terms of classical trajectories. The other degrees of freedom taken explicitly into account are the surface vibrations associated with each of the fragments. This is because the short-range nature of the nuclear interaction makes it important to follow the evolution of the nuclear surfaces throughout the collision. The effects of the nuclear forces are described in terms of a surface–surface interaction which determines the relative motion and provides the main mechanism for the excitation of the surface modes. The surface–surface interaction is rather well known empirically from the analysis of elastic scattering data. Very similar potentials have been obtained within the proximity approximation and through double-folding calculations. The electrostatic interaction between the ions is taken to be the point Coulomb field plus the monopole–multipole term which is responsible for Coulomb excitation.

In heavy-ion reactions particle transfer plays also a very important role in the damping of energy and angular momentum. In the surface excitation model this is treated as a statistical incoherent process which takes place while the surfaces are in contact [cf. ref. [24])]. Reactions where either exchange of particles or particle transfer followed by evaporation takes place contribute to the cross section associated with the entrance-channel mass partition. Treating particle transfer as a depopulation mechanism through an imaginary potential one can estimate the absolute cross section in the inelastic channel. In this approach, which we follow throughout, particle transfer does not affect the trajectory of relative motion [cf. e.g. ref. [25])].

The low-lying vibrations and damped giant resonances are treated as harmonic modes. The average occupation number $\langle N_i(\rho)\rangle$ for each mode i excited in a collision with impact parameter ρ is given by

$$\langle N_i(\rho)\rangle = E_i(\rho)/\hbar\omega_i\,, \tag{1}$$

where $E_i(\rho)$ is the excitation energy associated with the mode. The probability distribution for having a number n_i of phonons is

$$P_{n_i}(\rho)=\frac{\langle N_i(\rho)\rangle^{n_i}}{n_i!}\,\mathrm{e}^{-\langle N_i(\rho)\rangle}\,, \tag{2}$$

and the probability for an energy loss E at that impact parameter is

$$P(\rho, E)=\sum_{\{n_i\}}\delta\left(E-\sum_i n_i\hbar\omega_i\right)\prod_i P_{n_i}(\rho)\,. \tag{3}$$

The double-differential cross section can now be written as

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}E\,\mathrm{d}\Omega}=\sum_\rho\frac{\rho|\mathrm{d}\rho/\mathrm{d}\theta|}{2\pi\sin\theta\,\mathrm{d}E}\,P(\rho, E)\,T(\rho)\,, \tag{4}$$

where the sum extends over all impact parameters that feed the chosen scattering angle $\theta(\rho)$, and where

$$T(\rho)=\exp\left\{\frac{2}{\hbar}\int_{-\infty}^{\infty}W_t(r)\,\mathrm{d}t\right\} \tag{5}$$

is a coefficient describing the probability that the system has to remain in the intial mass partition. The function $W_t(r)$ is the imaginary part of the ion–ion potential due to mass transfer.

3. Analysis of the reaction ^{36}Ar+^{208}Pb

It has been suggested that the structures observed in the reaction ^{208}Pb(^{36}Ar, ^{36}Ar) are associated with the excitation of states of ^{208}Pb. In order to assess the validity of this interpretation it is important to use in the analysis of the data a good description of the lead spectrum. In table 1 we show the response functions used for both projectile and target; it was constructed by making use of empirical information and of microscopic calculations based on the random-phase approximation formalism [28,31]).

Recently, the inelastic process ^{208}Pb(^{16}O, ^{16}O)^{208}Pb* has been studied [5]) at a bombarding energy of 400 MeV in the laboratory system. At grazing angles ($\theta\leq 12°$) the low-lying states and some of the giant resonances have been clearly identified. The analysis of this data thus provides us with a convenient opportunity to test the soundness of the response function chosen for ^{208}Pb. Making use of the folding potential of ref. [26]) and adjusting the strength of an imaginary potential of the same geometry the main features of the excitation function can indeed be reproduced, as shown in fig. 1 [cf. fig. 3 of ref. [5])]. The structure found experimentally between ~20 and ~45 MeV excitation energy has been attributed to pick-up processes followed by evaporation [cf. fig. 4 of ref. [5])].

There is no conclusive empirical determination of the imaginary potential for the ^{36}Ar+^{208}Pb case. For this reason, and in order to reduce the uncertainties of the analysis as much as possible, we have calculated the function W_t making use of the microscopic formalism of ref. [23]). In these calculations all one-particle transfer

TABLE 1

Spectra of ^{36}Ar and ^{208}Pb used in the calculations

Nucleus	$\hbar\omega$ [MeV]	λ^{π}	% EWSR	Γ [MeV]
^{36}Ar	5.1	2^+	20	
	17.4	2^+	80	2.0
	5.0	3^-	25	
	29.3	3^-	50	4.0
	17.8	4^+	25	3.0
	39.7	4^+	50	6.0
	8.1	5^-	12	
	30.0	5^-	50	8.0
^{208}Pb	13.6	0^+	100	2.0
	4.1	2^+	16	
	10.8	2^+	82	2.7
	2.6	3^-	17	
	17.0	3^-	80	5.0
	4.3	4^+	6	
	10.9	4^+	23	2.5
	24.0	4^+	71	7.0
	3.3	5^-	4	
	20.0	5^-	40	9.0

The energy, spin, parity and percentage of the energy-weighted sum rule for each mode is given. The last column collects the spreading widths used for the different giant resonances.

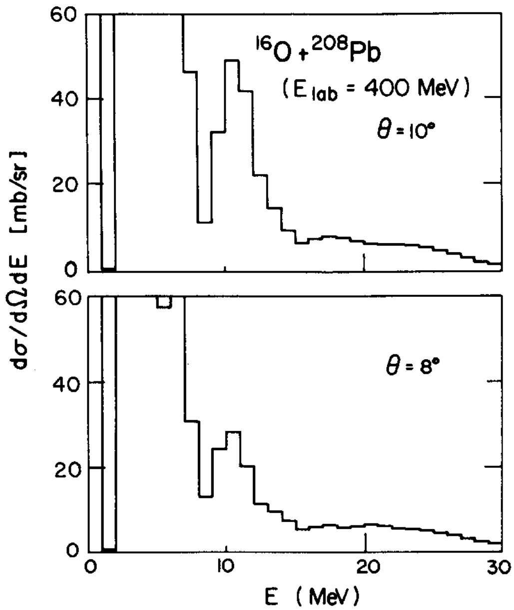

Fig. 1. Double-differential cross section $d^2\sigma/d\Omega\, dE$ as a function of the excitation energy for the collision of ^{16}O with ^{208}Pb at 400 MeV. The results of the model are shown for two angles close to the grazing angle.

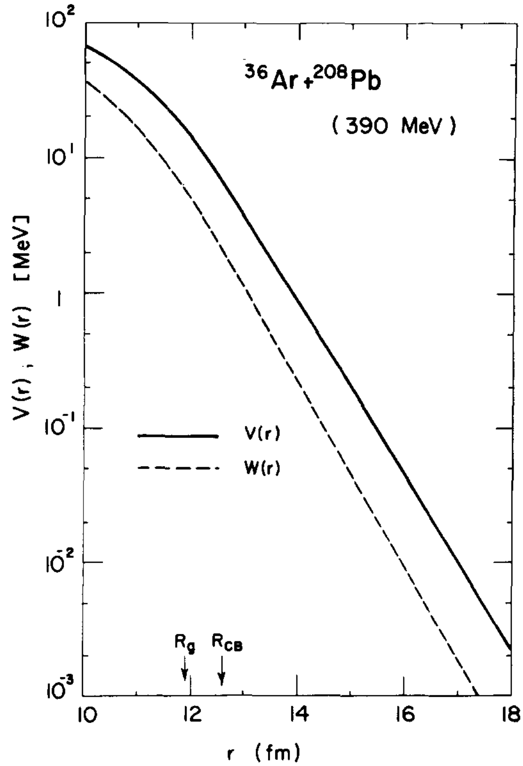

Fig. 2. Optical-model potentials used for the reaction of ^{36}Ar on ^{208}Pb. The solid curve corresponds to the real part of the potential and was taken from ref. [26]). The dashed curve displays the imaginary part arising from particle transfer. It was calculated by making use of the model of ref. [23]). Indicated with arrows are the grazing distance R_g and the radius of the Coulomb barrier R_{CB}.

processes with Q-value larger than -20 MeV have been included (~250 channels). The energies of the single-particle transitions entering in the calculation are obtained making use of a Saxon–Woods potential with standard parameters [for more details cf. ref. [23])]. In the ^{36}Ar+^{208}Pb system the absorption seems to be dominated by neutron-transfer reactions. The real and imaginary parts of the ion–ion potential used in the analysis of this reaction are shown in fig. 2.

For an impact parameter close to grazing ($\rho \sim 9$ fm), the average number of phonons associated with the low-lying and giant resonances are displayed in fig. 3 as a function of time. A sequence of shapes corresponding to this trajectory is shown in fig. 4. As expected [cf. also ref. [6])] the low-lying modes are the most strongly excited. This is a consequence of the large collectivity and relatively low energy of these modes. The probability of multiple excitation of giant resonances is small. In fact, typical values of $\langle N \rangle$ for these high-lying states are 0.1–0.3. This results from the adiabatic cut-off associated with these states at the bombarding energies under consideration [cf. also ref. [23])].

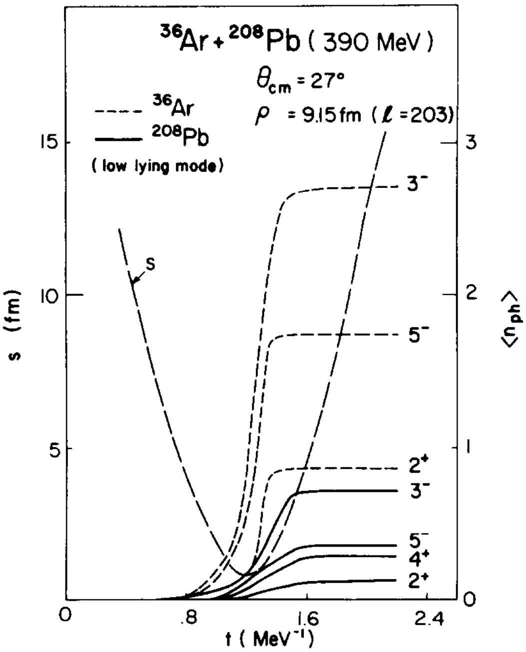

Fig. 3. Average number $\langle n_{\text{ph}} \rangle$ of low-lying collective phonons excited in the collision of ^{36}Ar on ^{208}Pb as a function of time. The trajectory corresponds to an impact parameter $\rho = 9.15$ fm leading to a scattering angle $\theta_{\text{c.m.}} = 27°$; also displayed is the distances s between the surfaces of the two interacting ions.

Trajectories with smaller values of the distance of closest approach could in principle have a better chance of exciting the giant resonances. However, the probabilities $T(\rho)$ for these trajectories to remain in the inelastic channel are vanishingly small. We note that not even in deep-inelastic processes do any of the modes normally acquire a large number of phonons [cf. e.g. table 1 ref. [27])]. If this were the case, rather extreme deformations may arise, putting into question the validity of the model.

The inelastic spectra associated with the reaction under discussion are compared with the data in fig. 5 for angles close to grazing. A conspicuous feature of these results is that most of the cross section is associated with events where a variety of

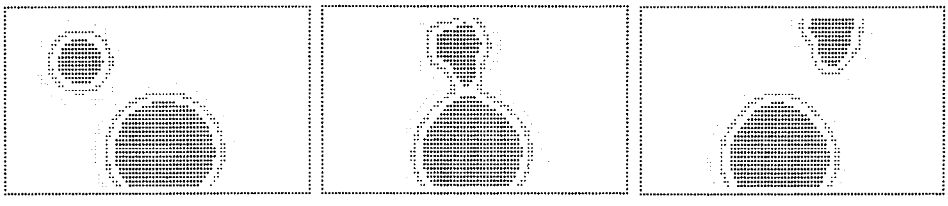

Fig. 4. Density profiles for ^{36}Ar and ^{208}Pb along the trajectory with impact parameter $\rho = 9.15$ fm (cf. fig. 3). The sequence of shapes corresponds, from left to right, to the times $t/\hbar = 0.8$, 1.2 and 1.6 MeV^{-1}.

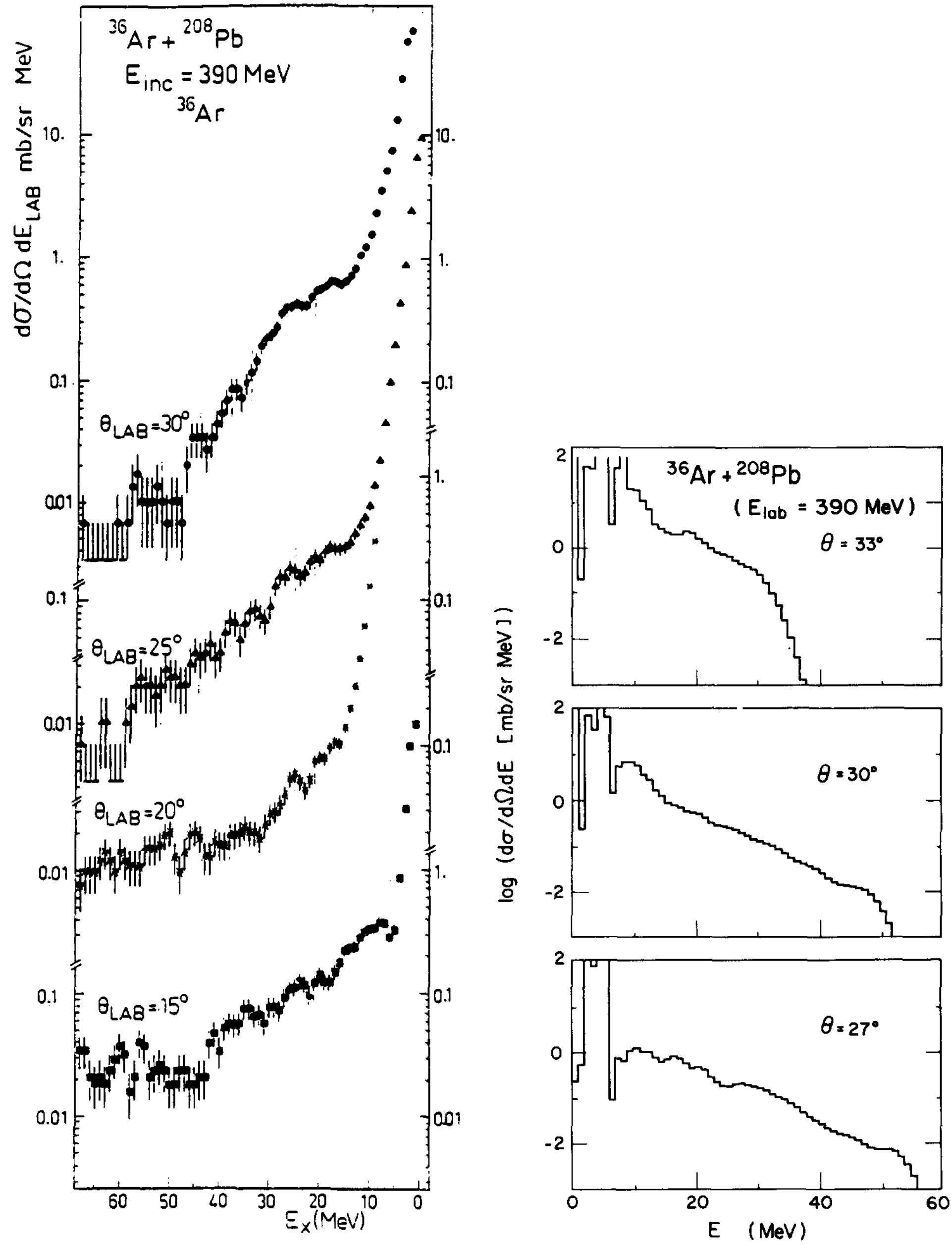

Fig. 5. Double-differential inelastic cross sections as a function of excitation energy for the reaction $^{36}Ar+^{208}Pb$ (390 MeV) and for three angles smaller than the grazing angle. In these histograms events leading to projectile excitation larger than 12 MeV have been excluded. To the right, an experimental figure corresponding to similar scattering angles is adapted from ref. [16]).

different modes is excited. One should note, however, that energy losses of the order, although somewhat smaller, than those observed experimentally are obtained, and that the calculated cross sections have the right order of magnitude.

4. Conclusion

The inelastic processes associated with the reaction $^{36}Ar + ^{208}Pb$ up to intermediate energy loss have been calculated. The low-lying modes of both target and projectile are moderately excited, while giant resonances are excited with probabilities corresponding to average number of phonons $\langle N \rangle < 1$. Thus, we do not find signs of structures in the double-differential cross sections which can easily be attributed to simple, multiple excitation of a single high-lying mode. Exchange of particles and transfer processes, followed by evaporation, also lead to the entrance-channel mass partition. It is an open question whether such processes can produce the observed structures in the $^{36}Ar + ^{208}Pb$ excitation function.

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