Observation of a long-lived nuclear quasimolecule in the ^{20}Ne + Ge system

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Bombardment of a Ge single crystal by 102-MeV ^{20}Ne ions reveals a nearly complete disappearance of the blocking minima for values $\theta = 58–52°$ of the emission angle of the heavy products of the inelastic interaction. The corresponding reaction time is approximately 10^{-17} s.

Kienle[1] has shown that in heavy-nucleus collisions such as U + U a certain fraction of the events involve the production of a double nuclear system with a lifetime of about 6×10^{-20} s, which is substantially longer than the collision time. The crystal blocking effect during the bombardment of a diamond single crystal with ^{16}O ions has been used[2] to measure the time delay in the production of the products of the inelastic interaction. Gomez del Campo *et al.*[2] attribute the delay which they found, $\tau \sim 10^{-18}$ s, primarily to the scale time for a secondary decay of the excited product.

The kinetic energy of the recoil nuclei in elastic scattering is given as a function of the emission angle in the laboratory coordinate system by

$$E_{\mathrm{el}} = \frac{4\gamma E_i}{(1+\gamma)^2}\cos^2\theta , \tag{1}$$

where $\gamma = A_i/A_T$ is the ratio of the mass numbers of the ion and the target nucleus, and E_i is the energy of the ion in the laboratory system. For inelastic scattering the energy is lower than E_{el} and may decrease to the lower kinematic limit $E_{\mathrm{min}} = E_{\mathrm{el}}/4$. Correspondingly, there is an upper limit on the extent to which the reaction can be inelastic, $\Delta E_{\mathrm{max}}(\theta)$, which depends on the angle:

$$\Delta E_{\mathrm{max}} = \frac{E_i}{1+\gamma}\cos^2\theta , \tag{2}$$

where ΔE is the excitation energy of the products. At angles greater than or approximately equal to the Rutherford angle, $\theta \gtrsim \theta_R$, the recoil nuclei of elastic and quasielastic interaction are predominant. At $\theta < \theta_R$ the degree of inelasticity increases with decreasing θ. There is accordingly the possibility of experimentally determining the reaction time as a function of the degree of inelasticity. Experimentally, we observe a blocking effect as the emission angle of the recoil nuclei, θ, with respect to the beam is changed. As a reference point we use the blocking minimum in the angular region corresponding to the elastic and quasielastic interactions.

In the present experiments a thick single crystal of natural germanium is bombarded by 102-MeV ^{20}Ne ions accelerated on the U-300 cyclotron of the JINR. The angular resolution of the experiment, ± 0.3°, is achieved by limiting the beam to a diameter of 1 mm. At an ion intensity of 10^{10} s^{-1} the crystal remains at room temperature. The recoil nuclei are detected by a glass track detector 120 mm from the target in the angular interval 50–75°. The threshold for the detection of Ge nuclei by this detector is 5 MeV. The thickness of the working layer of the target is about 0.5 mg/cm^2 (along the normal) and corresponds to an energy loss of about 3–4 MeV for the incident ions. Nuclei with $Z < 15$ do not produce visualizable tracks in the glass, so target-like products of the elastic and moderately inelastic interactions are singled out from the large variety of particles produced in the nuclear interaction ^{20}Ne + Ge. The deep inelastic heavy products corresponding to processes involving a complete dissipation of kinetic energy are emitted at angles $< 45°$ from the beam and do not strike the detector. The fission cross section of the compound nucleus is estimated from experimental data to be much smaller than the cross section for the production of the observable recoil nuclei. The beam is directed onto the target along a direction which does not coincide with a crystallographic direction. The blocking minima associated with the crystallographic ⟨111⟩ axis and with the (100) planes making various angles with the beam can be measured for each angle θ at which the recoil nuclei are observed by changing the orientation of the crystal. These measurements are important for extracting detailed information on the reaction time.

Figure 1 shows some of the results of an inspection of the blocking minima. These results correspond to a fixed ion dose, so that the erosion of the blocking minima due to radiation damage to the crystal is constant (and not very great). In the region of quasielastic interactions, $\theta > 62°$, we observe both axial and planar blocking features, fairly well defined. The angular widths of the minima given here have been corrected for the angular resolution of the experiment. As θ is reduced in the interval $58° > \theta > 52°$, the blocking media gradually disappear, and a characteristic structure

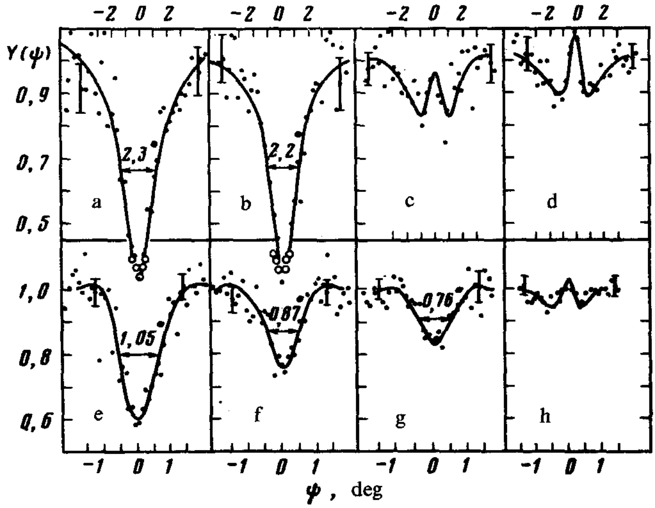

FIG. 1. Profiles of ⟨111⟩ axial blocking minima (a–d) and of (110) planar blocking minima (e–h) of a Ge single crystal. The directions along which the recoil nuclei are detected make the following angles with the beam: a—66°; b—59°; c—54°; d—52°; e—74°; f—68°; g—63°; h—57.5°.

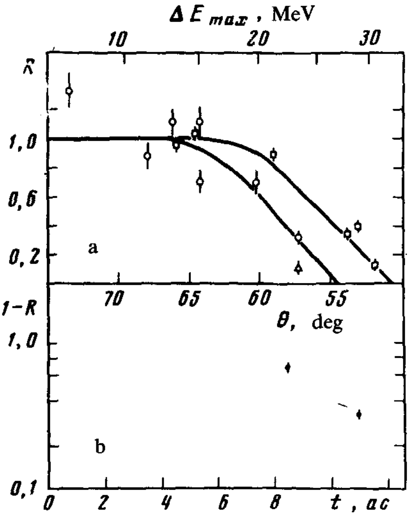

FIG. 2. a: Relative intensity of the crystal blocking effect, R. □—$\langle 111 \rangle$ crystallographic axis; ○—$(0\bar{1}1)$ plane; △—$(\bar{1}01)$ plane. b: Value of $1 - R$ for $\theta = 57.5°$ versus the time t.

with a maximum appears. This new structure demonstrates a large displacement of the radiating object from an angle of the crystal lattice.

As a measure of the effect of the lifetime on the blocking minimum we adopt the parameter $R = \Omega_\tau / \Omega_0$, where Ω is the total volume of the axial shadow or the area of the planar shadow. The subscript 0 specifies the reference blocking minimum. The parameter R represents the fraction of nuclei that have decayed in a time shorter than $t = r_c / v_\perp$, where r_c is the cutoff parameter of the atomic potential of the axis or plane, and $v_\perp$ is the normal component of the velocity of the decaying nucleus. Figure 2a shows the measured values of R (corrected for the change in the angular width of the minimum due to the change in the energy of the nuclei) versus the scattering angle θ or the degree of inelasticity of the process, $\Delta E_{\max}$. We see that the fraction of nuclei that decay rapidly decreases with increaseing $\Delta E_{\max}$. In integral form, the results in Fig. 2a characterize the reaction time.

Some information about the temporal distribution of reaction events can be extracted. Assuming $r_c = a_{TF}$ for the planar case and $r_c + 6a_{TF}$ for the axial case, we find the fraction of nuclei that have not decayed in the time $r_c / v_\perp$, $1 - R$, to be 1.5 $\sin^{-1} \alpha ac$ and 9.2 $\sin^{-1} \theta ac$ in the planar and axial cases, respectively. Using the measured values of R at $\theta = 57.5°$ for the $\langle 111 \rangle$ axis and the $(0\bar{1}1)$ and $(\bar{1}01)$ planes, which make angles $\alpha = 10.5°$ and 48° with the beam, we find the integral temporal distribution of events at three points as a function of time t which is shown in Fig. 2b. In the case of an exponential decay we would have a distribution $1 - R(t) = e^{-t/\tau}$. The points in Fig. 2b do not conform to an exponential function and are described by an integral of a temporal distribution with a peak at $t \gtrsim 9$ ac.

In summary, we have observed a time delay of about 10^{-17} s for the emission of target-like products in the inelastic interaction of ^{20}Ne and Ge nuclei. This time is much longer than the rotation period ($T \approx 4 \times 10^{-21}$ s) of a double nuclear system with an angular momentum of about $l_{\max} = 49\hbar$. We can therefore say that we have observed a long-lived nuclear quasimolecule ^{20}Ne + Ge. There is apparently no other explanation for the observed time delay of the events—neither in terms of the time of a secondary decay of an excited product[2] nor in terms of the fission time of a compound nucleus. Interestingly, this observation corresponds to moderately inelastic reactions, so that the long lifetime of the quasimolecule does not lead to a complete dissipation of the kinetic energy of the relative motion of the nuclei. It probably takes the form of periodic oscillations or a rotation.

[1] P. Kienle, Report D7-83-644, International School-Seminar on Heavy-Ion Physics, Dubna, 1983, p. 216.

[2] J. Gomez del Campo *et al.*, Phys. Rev. Lett. **51**, 451 (1983).

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