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CRYSTAL BLOCKING IN HEAVY ION REACTIONS

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ABSTRACT

The crystal blocking technique, used to measure very short lifetimes (10^{-18} sec), was developed during the 1960's primarily in connection with the study of the channeling effect. Early blocking lifetime measurements involved light ion resonance reactions yielding typical lifetime values down to the order of 10^{-17} sec. Recently, studies of heavy-ion induced fission and fusion have extended the technique into the 10^{-18} to 10^{-19} sec scale. In this work measurements of fusion for ^{160}Ge and deep inelastic reactions for $^{28}\text{Si} + \text{Ge}$ are presented for bombarding energies around 8 MeV/nucleon. Also measurements of the projectile fragmentation of 44 MeV/nucleon $^{40}\text{Ar} + \text{Ge}$ are discussed. In all reactions studied the presence of particle evaporation is the dominant mechanism that determines the reaction times of about 10^{-18} sec extracted with the blocking technique.

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P.B

I. Introduction

The crystal blocking technique offers the unique possibility of a direct measurement of reaction times for cases where the decaying products are charged nuclei. This technique has been used primarily in the past to study light-ion induced resonance reactions [1,2], although some measurements exist for heavy-ion induced fission reactions [3,4]. In all these measurements the time sensitivity has been above the 10^{-18} sec scale primarily due to small recoil velocities. Recently, a measurement of the evaporation residues of the $^{160} + ^{12}\text{C}$ (diamond) fusion reaction [5] has been reported, and the time limit has been lowered to about 4×10^{-19} sec since for this reaction highly excited ^{28}Si compound nuclei are formed with high recoil velocities (~ 0.1 the speed of light). The conclusion of the work presented in [5] is that the process of equilibrium decay has been observed through the time delay introduced by the sequential emission of light particles, and that the blocking technique gives fundamental information in heavy-ion reaction mechanisms down to very short time scales. In this report three more systems are reviewed with the aim of achieving a better understanding of the reaction mechanisms between heavy-ions. The reactions discussed are: 103 and 120 MeV $^{160} + \text{Ge}$ [6], 220 MeV $^{28}\text{Si} + \text{Ge}$ [6] and 1760 MeV $^{40}\text{Ar} + \text{Ge}$ [7]. The different experimental methods utilized in this measurements will be given in Section II, the results of the elastic scattering of $^{160} + \text{Ge}$ (needed to establish a "zero time" calibration curve) together with data on alpha particle emission will be given in Section III. Results of the deep inelastic studies of $^{28}\text{Si} + \text{Ge}$ will be presented in Section IV., and extensive results of the study on projectile fragmentation of $^{40}\text{Ar} + \text{Ge}$ will be given in Section V.

II.) Experimental methods

All of the measurements discussed here were done with one Ge crystal (natural isotopic composition) $10\mu\text{m}$ thick and of an area of about 5 cm^2 . For each reaction a different beam spot of 1 to 2 mm in diameter was used with typical doses of $\sim 50\text{ }\mu\text{C}$. For this reason radiation damage effects were negligible. The crystal was mounted in a high precision goniometer and the $\langle 110 \rangle$ axis aligned to the beam by conventional channeling techniques. The ^{16}O and ^{28}Si measurements were done at the HHIRF using beams from the tandem and the cyclotron and the ^{40}Ar experiment was performed at the GANIL cyclotron facility in Caen, France. One unique feature of these measurements is the use of a two dimensional position sensitive ΔE , E detector systems that allows the extraction of blocking patterns as a function of the Z and E of the nuclear reaction fragment. For the experiments done at HHIRF the detector system consisted of a position sensitive gas proportional wire for the horizontal direction, a ΔE (ionization chamber) and a $500\text{ }\mu\text{m}$ (900 mm^2 area) solid state E detector. The vertical position is determined by measuring the drift time of the electrons to the proportional wire. For the experiment performed at GANIL some changes to the detection systems were necessary because of the increase of about a factor of 10 in the kinetic energy of the detected fragments. The ΔE element was replaced by a $300\text{ }\mu\text{m}$ (600 mm^2) solid state detector and the E element used was a $5000\text{ }\mu\text{m}$ thick (600 mm^2 area) solid state detector. For the vertical position a second gas proportional wire was placed in front of the horizontal wire and separated by 2.5 cm of insulating material. Both proportional detector shared the same gas volume composed of CH_4 flowing at a constant pressure of 50 torr.

III). Results for the $^{16}\text{O} + \text{Ge}$ system.

In order to successfully utilize the crystal blocking technique to measure nuclear reaction times it is necessary to establish a zero time calibration curve and the primary purpose of the $^{16}\text{O} + \text{Ge}$ experiment was to measure in detail the elastic scattering at different energies and angles to achieve such calibration. Figure 1 shows the two dimensional blocking pattern resulting from the elastic scattering of 103 MeV ^{16}O ions (extracted from the HHIRF tandem accelerator) incident on the Ge crystal placed in a random direction respect to the beam. The $\langle 110 \rangle$ axis was aligned to the detector placed at the scattering angle of 22.3° . The typical crystallographic structure of the $\langle 110 \rangle$ axis can be seen, where also the major 110, 100 and 111 planes are observed. It is important to point out that the reduction of the yield seen in the center of the pattern, indicated by the intersection of the planes, can be directly related to the lifetime of the reaction. For very short lifetimes (like in the elastic process) the reaction products originate on a crystal lattice site and hence they are blocked by the lattice atoms yielding a minimum. For longer lifetimes, the reaction products are displaced towards the center of the channel thus increasing the yield along the channel direction. This effect can be studied in a more quantitative way by integrating the blocking pattern in the azimuthal direction around the crystal axis. The resulting blocking angular distribution for the data of figure 1 is shown in figure 2(a) (open triangles). The solid curves drawn in figure are the result of standard calculations of the blocking angular distribution using the multistring statistical approximation [4,5]. In this calculation in addition dechanneling effects due to finite crystal thickness have been considered using the diffusion equation as described by Gemmell [8] and also thermal vibrations are included with a vibration amplitude (μ) of .085 Å [8].

The thin solid line in figure 2(a) shows the result of such calculation and the fact that it does not fit the data is because effects of experimental angular resolution and static crystal imperfection have not been included. The measured experimental resolution is 0.05° and after folding a gaussian resolution function the agreement to the data is clearly improved. Nevertheless still was found not to be sufficient to account completely for the angular distribution of figure 2(a). By increasing in addition the vibration amplitude up to $0.13 \text{ \AA}$ a perfect fit to the data can be achieved (thick solid line). This increase can be justified by the assumption that is the manifestation of crystal imperfections although could reflect other unknown theoretical effects, however for the present case it can be taken as an empirical way of calibrating the prompt lifetime distribution. In order to check the consistency of this procedure another elastic scattering blocking angular distribution was measured using a beam of $120 \text{ MeV } ^{160}\text{O}$ ions extracted from the Oak Ridge cyclotron. The same crystal was used in a different beam spot of about 2 mm diameter. The results for the elastic scattering at a lab. angle of 10° are shown (solid circles) in figure 2(b). The calculation (solid line) is in excellent agreement with the data using the same value of $0.13 \text{ \AA}$ for the vibration amplitude as in figure 2(a) together with the measured experimental resolution of 0.06° .

Reaction products of the $^{160}\text{O} + \text{Ge}$ reaction were identified for $Z=9$ to $Z=2$ using the $E - \Delta E$ section of the detector system and separated blocking angular distribution where analyzed. The analysis of the blocking angular distribution for the reaction products from $Z=6$ to $Z=9$ indicate no measurable lifetime effect down to $\sim 3 \times 10^{-19} \text{ sec}$ and confirm the idea that these nuclei are produced as a result of direct (fast) processes. However, detailed analysis of the emitted alpha particles shows significant time-delay effects. Figure 3(a) shows an energy spectrum of alpha particles emitted at 22° , from the $120\text{MeV } ^{160}\text{O} + \text{Ge}$

reaction, taken with a solid state counter telescope of elements $E=2000 \mu\text{m}$ and $DE=300 \mu\text{m}$. The solid line, normalized to the data at the maximum, is the result of a Monte Carlo calculation done with the computer code LILITA [9] assuming that the alphas are emitted from the complete fusion of $^{16}\text{O} + \text{Ge}$ and shows that nearly 50% of the alpha particles can be accounted for by a compound nucleus process. Figure 3(b) shows the blocking angular distribution for the same reaction at 22.3° except that a gate on the energy spectrum below 20 MeV has been applied to assure that most of the alphas are from compound nucleus emission. Under the assumption of complete fusion the recoil velocity of the compound nucleus is determined and hence the decay time (for multiple particle emission) can be extracted using the blocking angular distribution of figure 3(b). This resulting time is 1×10^{-17} sec (solid line) which agrees well with the value of 2×10^{-17} sec predicted by Monte Carlo calculations (LILITA) for the multiparticle compound nucleus decay process. The dashed curve in figure 3(b) corresponds to an alpha-particle emission time of 3×10^{-18} sec and corresponds to the lower time limit for this experiment.

IV). Results for the $^{28}\text{Si} + \text{Ge}$ reaction.

The $^{28}\text{Si} + \text{Ge}$ reaction was used to study de-excitation times for deep inelastic collisions (DIC). Usually for DIC reactions the only reference to time concerns the primary reaction time, which is the time needed for formation and separation of the dinuclear complex after large amounts of energy dissipation and mass exchange have occurred. Although considerable time delays are expected most experimental and theoretical estimates predict values $\tau < 10^{-20}$ sec [10] i.e., too fast to be measured directly. Nevertheless the blocking technique will be sensitive to the secondary time, which reflects the time delay introduced by the emission (in equilibrium or not) of light particles coming from the primary fragments, and is in this regard that the blocking measurements can provide unique information for the DIC process.

The $^{28}\text{Si} + \text{Ge}$ reaction was studied by bombarding the same Ge crystal used previously with a 220 MeV ^{28}Si beam extracted from the HHIRF tandem. The detector was placed at an angle of 16.2° respect to the beam, and energy spectra and blocking angular distributions were obtained for reaction products of $Z=16$ to $Z=6$. The analysis of the energy spectra showed large energy dissipation (Q values from -70 to -100 MeV) typical of DIC reactions in this mass range. Also small quasielastic components were present for the $Z = 12$ and 13 fragments. The elastic scattering blocking angular distribution could be fitted with a known resolution of $.06^\circ$ and an amplitude $\mu = 0.15 \text{ \AA}$ (15% larger than for ^{16}O). From the analysis of the blocking angular distributions perpendicular recoil distances D_p were extracted and range from $.51^\circ \text{ \AA}$ for $Z=16$ to $.139 \text{ \AA}$ for $Z=6$. The recoil distance is related to the lifetime (τ) by: $D_p = V_r \tau \sin(\theta_r)$ where V_r is the magnitude of the recoil velocity and θ_r its angle respect to the crystal axis. For a compound nucleus reaction V_r is the compound nucleus velocity and θ_r is the laboratory angle θ_{lab} (the detector is always aligned to the axis) therefore the determination of τ is straight forward, however for two body primary reactions like DIC or fragmentation there is an uncertainty on V_r and θ_r . In general $\theta_r = \theta_{lab} - \theta_p$ where θ_p is the center of mass angle of the primary reaction. For DIC reactions details of the primary angles are not too important because the primary fragments have large amounts of internal excitation and hence the final angular distribution is entirely governed by the recoil introduced by the emission of light particles. Also what is needed to compute τ is $\overline{\sin(\theta_r)}$ which in this case is $\overline{\sin(\theta_{lab})}$ due to the fact that θ_p is symmetric respect to the beam direction. The magnitude of V_r has to be determined from a detailed analysis of the energy spectra taking into consideration the effects of particle emission (for similar analysis see Ref. [10] and [11]). For the present case the magnitude of V_r decreased from $0.113 c$ for $Z = 16$ to $0.09 c$ for $Z = 6$. With the values of V_r and θ_r just discussed the resulting τ can be deter-

mined and they are given as a function of the Z of the secondary fragment on figure 4(a). Figure 4(b) shows the differential cross section (points) measured at 16.2° together with the results of a Monte Carlo calculation (histograms) which assumes that the primary Z distribution is a gaussian centered at $Z = 16$ with a standard deviation $\sigma_Z = 2$. The main conclusion to be drawn from the extracted times given in figure 4(a) is that for all Z fragment the time delay is large and this result can be interpreted only as due to a multiparticle emission process of the excited primary fragments. It is also interesting to note that these times are comparable in magnitude with those of the $^{16}\text{O} + ^{12}\text{C}$ reaction [5] although the Z dependence is different since τ decreases with Z in this case opposite to what was observed in reference [5].

V.) Results for the $^{40}\text{Ar} + \text{Ge}$ reaction.

The $^{40}\text{Ar} + \text{Ge}$ measurements were carried out in order to achieve a better understanding of the reaction mechanism in peripheral collision between heavy ions in the intermediate energy domain of 20-100 MeV/nucleon. As was demonstrated in the previous sections the crystal blocking technique is sensitive to the internal excitation energy given to the primary fragments during the collision since it determines the time delay introduced by the multiparticle decay process.

The experiment done at the GANIL facility using an ^{40}Ar beam of 1.76 GeV consisted in measuring the two dimensional blocking patterns at four laboratory angles, 3.5° , 5.3° , 8° and 11.8° . After each measurement, a run at 3.5° was repeated to study possible effects of radiation damage. After a total accumulated dose of 500 μC no damage was evident within the experimental resolution. Fragments of $Z > 9$ were analyzed and show the typical kinematic characteristics of projectile fragmentation products [12,13]. The resulting two dimensional blocking pattern obtained for all reaction products of $Z > 9$ emitted at a laboratory angle of 5.3° and along the $\langle 110 \rangle$ axial direction is shown in figure (5),

where the typical $\langle 110 \rangle$ structure can be seen. This pattern is as good as the one given in figure (1) inspite of the fact that the angular span of the pattern has been reduced by about a factor of 3 (the channeling angle of 1.76 GeV ^{40}Ar on $\langle 110 \rangle$ Ge is about $.08^\circ$).

Integrating the two dimensional blocking pattern in the azimuthal direction around the crystal axis the blocking angular distributions are obtained. In figure (6) a blocking distribution obtained at 3.5° is shown for fragments of $Z = 18$ which is the Z of the beam. However the energy spectra is dominated by events which are not elastic scattering and in principle some time delay could be present in this distribution. The calculation similar to that described in Section III for a value of the thermal amplitude of $.085 \text{ \AA}$ is shown by the long-short line in figure (6) and as can be seen does not fit the data. To properly account for the blocking distribution, two additional effects, crystal imperfections and experimental resolution, must be included. As discussed in the calculation shown in figure (1) the data on figure (6) has been fitted by using the measured angular resolution of $.04^\circ$ and a vibration amplitude of $.18 \text{ \AA}$ which represents a 38% increase respect to the value needed to fit the 160 elastic scattering (see figure (1)). The dashed curve shown in figure (6) is for the value $\mu = 0.18 \text{ \AA}$, but without including the corrections due to experimental resolution. The solid curve shows the best fit to the data under the assumption of prompt reaction (the value of $\tau = 5 \times 10^{-19} \text{ sec}$ shown in the figure corresponds to an estimate of the recoil distance $D_p = 0.1 \text{ \AA}$ and a recoil velocity $V_r = 0.3 \text{ c}$). Results for other blocking angular distributions for fragments of $Z = 16, 14, 13$ and 12 at 3.5° are shown in figure (7). The calculations are also given for prompt components using the same parameters as those of figure (6) and as can be seen the good agreement is indicative of a good "zero time" calibration curve. Then time delay effects, if present, can be extracted at larger angles since, for a given lifetime, the recoil distance D_p increases as $\text{SIN}(\theta_{lab})$.

To extract lifetimes from the data, it is more convenient to define the blocked yield as the integral over angle of the dip in the blocking angular distributions. The evolution of these blocked yields as a function of θ_{lab} is shown in Fig. 8 for fragments of various Z . For all fragments a clear reduction of the area (a filling-in of the dip) with increasing angle is seen. This is an indication of a time delay effect. The curves in Fig. 8 are predictions of the calculations described above for three different lifetimes (τ). The blocked yield was calculated for the associated recoil distance normal to the channel (D_p) given by: $D_p = \overline{V_r \tau \sin(\theta_r)}$ where $\overline{V_r}$ is the average velocity of the primary fragment and θ_r its angle relative to the crystal axis. The average $\overline{\sin(\theta_r)}$ was calculated using the angular distribution given by the fast fragmentation model [14] as a weighting factor with a width parameter $\sigma_0 = 89$ MeV/c consistent with current systematics [12,13]. The error introduced in the determination of τ due to the uncertainty in $\overline{V_r}$ is negligible. The average $\overline{\sin(\theta_r)}$ deduced from the calculated fragmentation angular distributions results in a lifetime roughly 20% shorter than that obtained assuming 0° emission of the primary fragments. In Fig. 8, the reduction at small angles, when Z decreases, of the calculated area for $\tau = 2$ and 3×10^{-18} sec is related to the increasing width for smaller Z of the assumed primary angular distribution.

The solid lines in Fig. 8 show the prediction for a decay time of 5×10^{-19} sec, a value representing the limit of sensitivity of the present experiment. For this short lifetime, the decrease with angle of the average kinetic energy [13] results in a predicted increase of the blocked yield. This contrast with the experimental observation of a 30% reduction of the blocked yield from 3.5° to 11.8° . Curves corresponding to decay times of 2×10^{-18} sec (dashed lines) and 3×10^{-18} sec (short-dashed lines) are also shown. For all fragments these curves bracket the data and within the precision of the experiment there is no

evident Z dependence on the decay time. For each fragment an average lifetime has been obtained by a least square fit to the data. The resulting lifetimes are shown in Fig. 9.

The measured lifetimes are compared in Fig. 9 to the predictions of a simple abrasion-ablation model [13,15]. In this model it is assumed that in the collision the overlap region between the projectile and target is sheared away and that the abraded projectile almost preserves its initial direction and velocity carrying away a small amount of excitation energy. This energy is given by the surface energy difference between the deformed abraded nucleus and a spherical nucleus of the same volume. The calculated excitation energies increase linearly with the number of nucleons abraded from the projectile to reach 50 MeV for a fragment of mass 20. This excitation energy is then dissipated by nucleon evaporation (ablation stage) giving rise to the time delay observed in the production of the secondary fragment. The decay times of the primary fragments were calculated with the code LILITA [9] with a primary mass distribution obtained from the abrasion model. For a given mass the Z distribution was obtained using the Q ground-ground systematics [16] where the cross section is given by $\exp(Q_{gg}/T)$, where Q_{gg} is the ground state Q value of the equivalent two body reaction and T is taken as 2 MeV. The calculated lifetimes depend primarily on the distribution of excitation energies and to a much lesser degree on the assumed primary nuclide distribution. The abrasion model predicts for $Z > 15$ excitation energies which are too small to lead to particle evaporation, and therefore to produce sufficient secondary delay times it was necessary to increase the input excitation energies by about 10 MeV. The result of such calculation which describes well the data are shown by the histogram in Fig. 9. For comparison,

increasing the excitation energy of the primary fragment by 30 MeV, would produce time delays that reach the 10^{-17} sec scale — incompatible with the measured delays — and would give too much particle evaporation producing negligible yields for secondary fragments of $Z > 15$.

In conclusion, the present observation of time delay effects show that secondary emission of light particles is an important process to be considered in the description of projectile fragments produced in intermediate-energy heavy-ion reactions. The measured decay times are consistent with a broad primary distribution of fragments with relatively low excitation energies (< 50 MeV).

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FIGURE CAPTIONS

- Fig. 1. Two-dimensional blocking pattern obtain for the elastic scattering of ^{16}O on Ge at $E(^{16}\text{O}) = 103$ MeV. The angles are measured along the reaction plane or perpendicular to the reaction plane. The $\langle 110 \rangle$ axis is centered at 22.3° .
- Fig. 2a Blocking angular distribution (triangles) obtain by azimuthal integration of the pattern given in Fig. 1. The value of $\mu = 0.035$ Å corresponds to the thermal vibration amplitude. However, a value of $\mu = 0.13$ Å is needed to fit the data together with a gaussian smearing of $\sigma = .05^\circ$ corresponding to the measured resolution.
- Fig. 2b Blocking angular distribution (circles) measured for the elastic scattering of 120 MeV $^{16}\text{O} + \text{Ge}$ at a laboratory angle of 10° . The solid curve is the theoretical prediction using the experimental resolution width $\sigma = .06^\circ$. The rest of the parameters of the calculation are the same as in Figure 2(a).
- Fig. 3a Energy spectra (points) of the alpha particles emitted in the $^{16}\text{O} + \text{Ge}$ reaction.
- Fig. 3b Blocking angular distribution measured for alpha particles below $E(\text{lab})$ 20 MeV for the 120 MeV $^{16}\text{O} + \text{Ge}$ reaction.
- Fig. 4a Results of the deexcitation times (τ) measured with the crystal blocking technique for the DIC products of 220 MeV $^{28}\text{Si} + \text{Ge}$.
- Fig. 4b Measured (points) and predicted (histograms) differential cross sections for DIC of the $^{28}\text{Si} + \text{Ge}$ system.
- Fig. 5 Two-dimensional blocking pattern obtain for all the projectile-like fragments of $Z > 9$ produced at $\theta_{\text{lab}} = 5.3^\circ$.

FIGURE CAPTIONS continued

- Fig. 6. Blocking angular distribution(data points) measured for the projectile-like fragments of Ar ions. The theoretical curves are explained in the text.
- Fig. 7. Blocking angular distributions (data points) measured for projectile-like fragments of S, Si, Al, and Mg at a laboratory angle of 3.5° . The energies, $\bar{E}$, corresponds to the centroid of the energy spectra. The solid curves are theoretical predictions for prompt reactions $\tau < 5 \times 10^{-19}$ sec.
- Fig. 8. Variation as a function of scattering angle of the blocked yield (area) obtained from the integral of the blocking angular distributions. The curves represent theoretical calculations or different decay times of the primary fragments.
- Fig. 9. Comparisons of the decay time extracted from the blocking measurements (solid points) with Monte-Carlo calculations (histograms) using an abrasion calculation with 15 to 50 MeV of internal excitation energy given to the primary fragments. The Z_{pLF} refers to the measured secondary fragments.

Fig. 1

Fig. 2

Fig. 3

220 MeV $^{28}\text{Si} + \text{Ge}$

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9