Gamma-Ray Emission in Crystal Blocking Experiments

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Gamma-ray emission from the recoil particle can have a large effect on the blocking dip observed in crystal blocking experiments. We demonstrate this effect experimentally, and give a theoretical description based on standard channeling theory that is in good agreement with the measurement. We discuss the implications for lifetime measurements using the crystal blocking technique.

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The crystal blocking technique [1] is well established as a method for the determination of short nuclear lifetimes in the range 10^{-18} to 10^{-16} s. The effect was initially used for the measurement of lifetimes in nuclear fission and in proton-induced reactions [1] but more recently has been applied to heavy-ion collisions [2–5]. In these latter collisions, the detected ion for which the blocking effect is measured can also be excited. In this Letter we demonstrate that gamma-ray emission by the blocked ion leads to a lifetime-dependent change in the blocking dip. This effect is large and may severely limit the application of the method to heavy-ion collisions. Such an effect has been inferred from observations by Karamyan [6,7] on the effect of secondary particle emission on blocking measurements, but has not been explicitly demonstrated hitherto.

The blocking effect and its application to lifetime measurement may be described briefly as follows: A compound nucleus formed from a crystal atom and an incident ion recoils from a lattice site and decays by particle emission. Reaction products are observed in the direction of a major axis of the crystal. If the recoil distance traveled before decay is small (compared to the thermal vibration amplitude) the channeling effect [8] prevents ("blocks") the reaction products from being emitted parallel to the axis. This leads to the formation of a "blocking dip" in the angular distribution in the neighborhood of the axial direction. If the recoil distance is large, the reaction products are no longer blocked, and the mean recoil distance, and hence the lifetime, may be determined from the amount by which the blocking dip is then filled.

In this paper we report on the perturbation of the blocking effect by gamma radiation emitted from the recoiling nucleus. In this case the filling in of the dip results from the transverse momentum imparted to the nucleus during its deexcitation. This deexcitation can occur both inside and outside the crystal; it turns out that the contribution to the filling in from these two cases can be similar and so the effect is not easily applied to measure the lifetime of the decaying state. However, the effect may be large. Below, we give experimental results for a case of known lifetime, and present an analysis which is somewhat simplified but allows the main features of the effect to be explained.

A beam of 31.2-MeV ^{12}C ions was scattered from a 1.3-μm-thick silicon crystal. Elastically and inelastically scattered ^{12}C ions were detected in a two-dimensional position-sensitive E-ΔE detector telescope placed at 30° in the laboratory, at a distance of 1.2 m from the target. The ⟨110⟩ axis of the crystal was aligned in the direction of the detector and the beam entered the crystal far from any major axis or plane. The detector subtended an angle of approximately 1°, large enough for the entire blocking dip to fall within the detector area. The energy E, energy loss in the detector ΔE, and the x and y position of the ion striking the detector were recorded event by event, allowing the construction of the blocking dip in the x-y plane. The two-dimensional dips thus recorded were azimuthally averaged about the center of the dip to produce normalized blocking-dip plots of yield as a function of the angle from the axial direction.

Blocking dips were obtained for the elastically scattered carbon, and for inelastic scattering to either the 1.78-MeV state in ^{28}Si (with ^{12}C in the ground state) or the 4.43-MeV ($\tau = 61$ fs) [9] state of ^{12}C (with the ^{28}Si in the ground state). The dips are shown in Figs. 1 and 2. The dips for the elastic and 1.78-MeV (Si*) inelastic carbon ions are similar and are consistent with calculations based on dechanneling models with no lifetime effect. The effect of the difference in ion energy ($E = 27.8$ MeV for ^{12}C elastic and $E = 26.0$ MeV for ^{28}Si excited) is not expected to be large. However, the inelastic (4.43 MeV) dip has a much greater minimum yield and has been almost completely filled in; we ascribe the difference to the effect of the emission of the 4.43-MeV gamma ray. We note as a preliminary to our analysis that emission at 90° of such a gamma ray from a recoiling 23.6-MeV ^{12}C ion will result in a deviation of the ion by 0.34°; the measured half-angle of the elastic blocking dip is 0.21°.

In order to bring out the salient physical features of the effect we present an analysis based on a schematic model; a more detailed analysis will be presented elsewhere. The basic physical situation is the following. A recoil ion decays in flight, either inside or outside the crystal. If ions

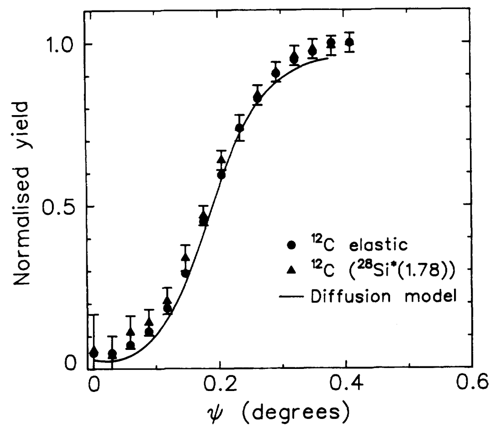

FIG. 1. Blocking dips from elastically scattered 31.2-MeV ^{12}C ions and inelastically scattered ions (1.78-MeV state in ^{28}Si) in a 1.3-μm silicon crystal. Errors for the elastic scattering case are smaller than the points. The solid line is a diffusion model calculation of the dip for elastically scattered ^{12}C ions.

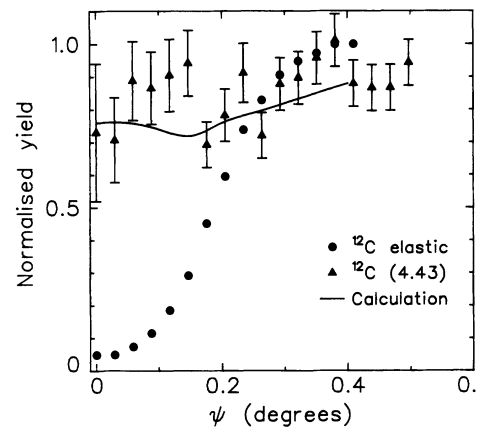

FIG. 2. Blocking dips from elastically scattered 31.2-MeV ^{12}C ions (as in Fig. 1) and inelastically scattered ions (4.43-MeV state in ^{12}C) in a 1.3-μm silicon crystal. The calculation is discussed in the text.

decay between the crystal and the detector, the recoil from the emission of gamma rays leads to a spread in angle about the initial direction; this results in a smearing of the blocking distribution by a convolution of the blocking dip with the angular distribution resulting from the recoil. If the ions decay inside the crystal, the transverse energy distribution [1,8] of the ions is changed and the resulting blocking distribution is modified; this may be viewed as a type of dechanneling. The final blocking distribution observed at the detector is the sum of these two components.

In our simplified model, we assume that the emission of gamma rays is isotropic, and we work within the continuum model of channeling [8]. We assume that the initial distribution in transverse energy $E_\perp$ of the blocked ions is given by a sharp-cutoff model,

$$\Pi_0(E_\perp)=\begin{cases}0, & E_\perp < E_{\perp c},\\ 1, & E_\perp \geq E_{\perp c},\end{cases} \tag{1}$$

where $E_{\perp c} \approx E\psi_{1/2}^2$ is the blocking angle. The yield in the absence of decay is

$$\chi_0(\psi)=\int_0^\infty T(E_\perp,\psi)\Pi_0(E_\perp)dE_\perp\,, \tag{2}$$

where $T(E_\perp,\psi)$, the transmission function, describes the transmission through the crystal surface and is given by [10]

$$T(E_\perp,\psi)=\frac{1}{A(E_\perp)}\int\delta(E_\perp-U(\mathbf{r})-E\psi^2)d\mathbf{r} \tag{3}$$

and ψ is the angle from the axial direction. In addition, we ignore other dechanneling effects such as the effect of thermal vibrations and scattering from electrons.

The blocked ions of mass M and kinetic energy T in the laboratory (crystal) frame move at small angles to some axial direction in the crystal. After emission of the gamma ray of energy E_γ the path of an ion deviates by some angle θ determined by the recoil momentum; this is determined by the energy and the direction of emission of the gamma ray. For isotropically emitted gamma rays, and small angles of deflection, the distribution of θ is given by

$$n(\theta)d\theta=\frac{1}{\theta_m}\frac{\theta d\theta}{(\theta_m^2+\theta^2)^{1/2}}\,, \tag{4}$$

where the maximum angle of deviation θ_m is given by

$$\theta_m^2=E_\gamma^2/2Mc^2T\,. \tag{5}$$

The yield of the ions around the crystal direction is then

$$\chi(\psi)=(1-F)\chi_1(\psi)+F\chi_2(\psi)\,, \tag{6}$$

where χ_1 and χ_2 are, respectively, the blocking dips for ions decaying inside or outside the crystal and F is the fraction of ions decaying outside the crystal, given by

$$F=(v\tau/t)[1-\exp(-t/v\tau)]\,, \tag{7}$$

where τ is the mean life of the excited ion, v its speed, and t the crystal thickness measured along the direction of motion.

The contribution χ_2 is simply a convolution. It is assumed that the total distance over which ions decay is comparable with the crystal thickness and much less than the detector-to-crystal distance. The yield $\chi_2(\psi)$ may then be written as

$$\chi_2(\psi)=\int_0^{2\pi}\frac{d\phi}{2\pi}\int\int_0^\infty d\psi' d\psi''\chi_0(\psi')n(\psi'')\delta(\psi^2-\psi'^2-\psi''^2+2\psi''\psi'\cos\phi)\,. \tag{8}$$

We now consider the contribution χ_1. Suppose that an ion has initially a transverse energy $E_\perp$. The ion emits a gamma ray when at some point $\mathbf{r}$ in the plane transverse to the axis and the transverse energy is changed to $E'_\perp$ because of the recoil imparted to it. Under the usual statistical assumptions of the continuum model [8] of axial channeling, an ion of transverse energy $E_\perp$ is found with uniform probability in the normalized area $A(E_\perp)$ accessible to it. The probability density for a transition from $E_\perp$ to $E'_\perp$ as a result of the emission may then be written

$$P_E(E_\perp,E'_\perp)=\int_0^{2\pi}\frac{d\phi}{2\pi}\int_0^\infty d\theta^2\int_{E'_\perp\geq U(\mathbf{r})}d\mathbf{r}\,p_0(E_\perp,\mathbf{r})n(\theta^2)\delta(E'_\perp-E_\perp-E\theta^2+2E\psi\theta\cos\phi)\,, \tag{9}$$

where $E_\perp=E\psi^2+U(\mathbf{r})$ and the probability density $p_0(E_\perp,\mathbf{r})$ for finding an ion of transverse energy $E_\perp$ at $\mathbf{r}$ in the transverse plane is given by

$$p_0(E_\perp,\mathbf{r})=\begin{cases}1/A(E_\perp), & E_\perp\geq U(\mathbf{r}),\\ 0, & E_\perp<U(\mathbf{r})\,.\end{cases} \tag{10}$$

This density has the symmetry property [11],

$$A(E_\perp)P_E(E_\perp,E'_\perp)=A(E'_\perp)P_E(E'_\perp,E_\perp)\,. \tag{11}$$

In general, this transition density can only be obtained numerically. However, we can obtain a useful approximation as follows: Over most of the accessible area, $U(\mathbf{r})\ll E_\perp$, so that we may assume $U(\mathbf{r})=0$. We then obtain

$$P_E(E_\perp,E'_\perp)=\mathcal{A}(E_\perp,E'_\perp)\frac{1}{2\pi E_m^{1/2}}I(E_\perp,E'_\perp,E_m)\,, \tag{12}$$

where

$$\mathcal{A}(E_\perp,E'_\perp)=\begin{cases}A(E'_\perp)/A(E_\perp), & E'_\perp<E_\perp,\\ 1, & E'_\perp\geq E_\perp\,.\end{cases} \tag{13}$$

The function $I(E_\perp,E'_\perp,E_m)$ is symmetrical in $E_\perp$ and $E'_\perp$, and can be written in terms of elliptical integrals of the first kind; the rather lengthy expression is omitted here.

The transverse energy distribution after decay is then

$$\Pi_1(E_\perp)=\int_0^\infty P_E(E'_\perp,E_\perp)\Pi_0(E'_\perp)dE'_\perp\,. \tag{14}$$

With these approximations, $\Pi_1(E_\perp)$ was evaluated numerically and the dip $\chi_1(\psi)$ obtained after transmission through the crystal surface.

The results of this calculation are shown in Fig. 1 and agree well with the experimental points. The effect of multiple scattering has been ignored, but, because the calculated yield is so close to unity, it is not expected to change the results significantly.

The large yield at small angles in the dip for the 4.43-MeV inelastically excited ions in Fig. 2 can thus be understood in terms of the recoil imparted to the ions by the emitted gamma photons. This effect has hitherto been ignored in the analysis of heavy-ion blocking experiments, but its importance must not be underestimated as it can mimic a reaction lifetime. In certain experiments, the detected fragment may have had considerable excitation leading to a cascade of emitted gamma rays. While the energy of these gamma rays may well be considerably less than the 4.43-MeV photon responsible for our large yield, the summed effect of a large number can be important. Any measured blocking dip may thus be dominated by the recoils resulting from this cascade. We conclude therefore that great care must be taken in the analysis of blocking experiments to exclude the effect of gamma-ray-induced deblocking.

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