Single Crystals and Short-Lived Particles

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(Received 27 May 1975)

Particles produced at high energies are channeled into narrow forward cones. This channeling is tight enough so that particles produced in an aligned single crystal have a non-negligible chance of interacting with downstream nuclei. The interaction probability including lattice vibrations is estimated. "Super multiple scattering" in single crystals is considered and shown to make this technique less suitable for charged particles. Applications are suggested including the possibility of charmed-particle—interaction experiments.

The discovery of the ψ meson, coupled with an increased interest in the charm hypothesis, has stimulated interest in the detection of short-lived particles. A ψ meson with a momentum of several hundred GeV/c may travel 1 interatomic spacing before it decays. It is predicted that charmed particles may have lifetimes of 10 to 100 fsec (10^{-14} to 10^{-13} sec) with mean path lengths on the order of 1 mm.[1] In an amorphous material a short path length gives little chance for an interaction. In single crystals, however, there are directions along atomic rows in which the nuclear density is appreciably higher, roughly a factor of 10 000. Can this property of single crystals be used to study the interactions of short-lived particles? This article presents a schematic development of some of the possibilities.[2]

With incident particles of several hundred GeV, particle-production distributions on nuclei are highly channeled in the forward direction. Some processes, such as the Primakoff effect,[3] can lead to production cones with angular distributions on the order of 0.01 mrad. The half angle subtended by a nucleus an atomic spacing away from a production point is

$$\theta_p = r/a \,, \tag{1}$$

where r is the nuclear radius and a is the interatomic spacing. For germanium this angle is 0.023 mrad. This suggests that if the incident particle beam is carefully aligned along an atomic row, secondary particles from a production site might proceed along the row and interact with a nearby downstream nucleus with non-negligible probability. A particularly favorable situation could occur if the produced particle interacted to give a second particle with a signature that could not be produced in the production process.

Because of the sharply peaked forward distribution, the Primakoff effect is one of the most favorable cases for production channeling. The most probable angle for pseudoscalar mesons photoproduced via the Primakoff effect is

$$\theta_p = \tfrac{1}{2}(m/E)^2 \,, \tag{2}$$

where m is the mass of the meson and E is the incident energy. θ_p is 0.01 mrad at 30 GeV for the π^0. The Primakoff effect could be employed to study π^0 scattering using photoproduced π^0's. The incident γ-ray beam would be oriented along a crystal axis. The production-channeled neutral pions would move down the nuclear row and sometimes collide with nearby nuclei and interact. The amount of interaction relative to photoproduction would be scaled down by the relative interaction probability of the π^0. The actual scattering distribution will be convoluted with the photoproduction cross section to take into account the angular distribution of the incident π^0 beam. Since the Primakoff peak is sharp, this will introduce relatively little broadening of the scattered distribution. The photoproduction portion can be stripped out by subtracting out data from a nonaligned run with the crystal. This technique will give a direct measurement of the π^0 interaction distribution using a true, highly collimated π^0 beam. Somewhat similar techniques could be used to study charmed-particle or ψ interactions. At present energies the ψ photoproduction angular distribution is too wide,[4] in part reflecting the massiveness of the ψ. This type of experiment is more sophisticated than another approach: The measurement of production distributions as additional layers of matter are added to the production nucleus by increasing the atomic number.[5] Essentially this gives only the total cross section.

For production channeling, both the angular divergence and alignment of the production beam must be on the order of 0.01 mrad to hold the secondary particle on a nuclear row. Some neutral beams at high-energy accelerators can operate at ± 0.03 mrad. Crystals for x-ray work can be aligned to 0.005 mrad without great difficulty. In coherent-bremsstrahlung experiments,[6] crystals have been aligned to 0.01 mrad.[7] Good bremsstrahlung crystals have rms mosaic angles of 0.05 to 0.1 mrad. With substances such as germanium, it may be possible to do even better. Goniometer vibrations have been held below 0.1 mrad. Note that appreciable temperature rises are common when particle beams are targeted. Cross sections for radiation-induced defects are high. This defect-production effect, although troublesome, has not precluded coherent-bremsstrahlung experiments.

Conventional channeling experiments[8] also utilize single crystals. In conventional channeling a charged particle moving between and nearly parallel to two atomic planes experiences a series of coherent Rutherford scatterings soft enough to retain the particle between the plane. Channeling experiments have now been performed at CERN[9] and are underway at Brookhaven National Laboratory[10] in the GeV range where the critical angle for channeling is in the neighborhood of 1 mrad. Production channeling is in some ways more closely related to blocking, the conjugate effect to channeling. In blocking, outgoing charged particles are forced away from nuclear rows by Rutherford scattering. Blocking is used to determine nuclear lifetimes in the attosecond to femtosecond range (10^{-18} to 10^{-15} sec). Temmer has suggested that blocking could be used to study particle lifetimes with widths in the MeV range.[11]

Lattice vibrations are a serious complication in the production-channeling process. Zero-point vibrations are

$$x_{00} = \langle x^2 \rangle^{1/2} = 3\hbar^2/4kM\Theta_D , \tag{3}$$

where M is the mass of the atom, k is Boltzmann's constant, and Θ_D is the Debye temperature.[12] Lattice vibrations can be minimized by choosing a stiff crystal with a large atomic mass. Perhaps the most useful material with a small zero-point vibration is tungsten ($x_{00} = 0.027$ Å); for germanium $x_{00} = 0.042$ Å. Lattice vibrations are proportional to the square root of the temperature. They are roughly twice the zero-point vibrations alone at room temperature. Calculations by Gilbert and Robinson[13] show that near-neighbor correlations are small—less than 12% for niobium.

The lattice vibrations alter the probability of interaction with the nearby nuclear neighbors. The nucleus may be anywhere in a disk encompassed by the magnitude of the vibrations. It is possible for a particle that travels sufficiently far to interact with one of many of the nuclei down a crystal row. To find the total probability of interaction, it is necessary to sum over the probability for all the nearby nuclei along the row.

The nature of the interaction probability is illustrated schematically in Fig. 1. The particle produced at the production nucleus is channeled by the production process in a cone with half angle θ_c. To simplify the calculation the production process is assumed to populate uniformly the production cone. Likewise the nucleus is presumed to have uniform probability of being at any point on the lattice vibration disk. At a critical distance z_c along the crystal row (typically several thousand angstroms) the production cone

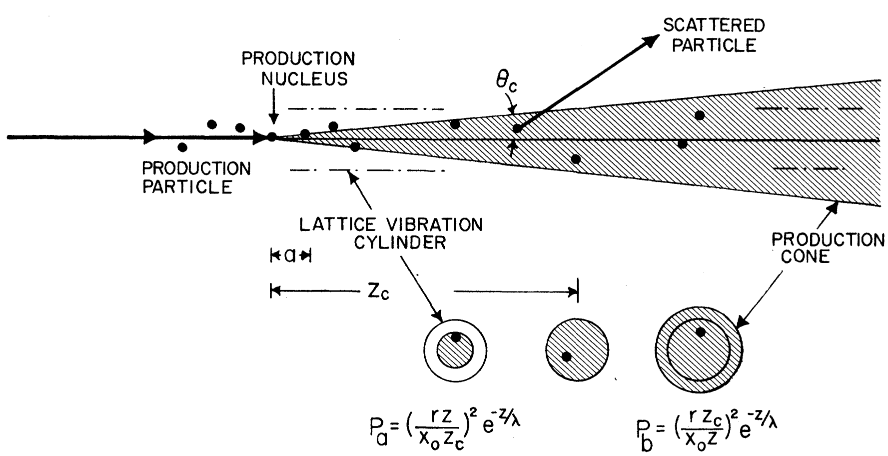

FIG. 1. Production-channeling geometry including the effect of lattice vibrations.

just covers the lattice vibration disk. This occurs when $z_c = x_0/\theta_c$. The relative interaction probabilities for atoms before and after z_c are given in Fig. 1, including the effect of particle decay. The total interaction probability relative to the production probability is obtained by summing over all the atoms beyond the production nucleus. For infinite lifetimes this gives

$$P = \tfrac{4}{3} r^2/x_0\theta_c a \ . \tag{4}$$

This assumes that the interacting nucleus is totally opaque to the interacting particle. Figures 2(a) and 2(b) show the fractional differential and integral probability as a function of z. Figure 2(c) illustrates the relative probability as a function of mean path length λ.

The relative probability of production channeling increases with increasing nuclear cross section (πr^2) and decreases with larger lattice vibrations, atomic spacing, and production-channeling angle. On the assumption that $\theta_c = 0.01$ mrad, the interaction probability relative to production for germanium is 0.4% and for tungsten, 1.0%.

Secondary interactions also occur in amorphous targets. The path length to accumulate equivalent probabilities in germanium is 0.4 mm and in tungsten is 0.5 mm. The amorphous length is 235 times longer for germanium and 470 times longer for tungsten than the single-crystal path length to accumulate 80% probability. Because the production cone includes low-nuclear-density regions when $z > z_c$, this is substantially less than the factor of 10 000 that an argument based on nuclear density along a lattice row would indicate. To minimize the amorphous secondary interaction background, either the produced particle must be short lived or the target must be very thin.

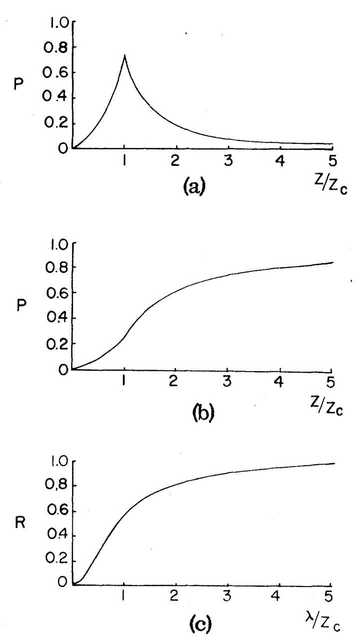

FIG. 2. (a), (b) Fractional differential and cumulative probability of production channeling as a function of z. (c) The fraction of infinite lifetime probability accumulated as a function of mean path length.

Another complication for production channeling with charged particles is a problem similar to dechanneling in conventional channeling experiments. For a particle moving in the column containing the nuclei and defined by the magnitude of the lattice vibrations there will be increased multiple scattering. The super ion density in the column is

$$N_s = (af/x_0)^2 N \ , \tag{5}$$

where N is the amorphous ion density and f is a factor close to 1 that depends on the crystal geometry. The "super–multiple-scattering" angle is proportional to the square root of the ion density or

$$\theta_m{}^s = (af/x_0)\theta_m \ , \tag{6}$$

where θ_m is the amorphous multiple scattering angle. A 100-GeV charged particle moving a distance of $4z_c$ along a nuclear row in germanium will have $\theta_m{}^s = 0.4$ mrad, sufficient to destroy the production-channeling effect. This applies to both incident and outgoing charged particles. The presence of super multiple scattering suggests that production channeling will be limited to neutral particles or very short-lived charged particles.

In summary, production channeling appears difficult but not demonstrably impossible. Extremely good crystals, good alignment, and good beams will be required. Higher production energies will increase the channeling. Charged particles do not appear to be suitable. Neutral short-lived particles with mean path lengths on the order of several thousand angstroms seem to be the most favorable candidates for use in demonstrations of production channeling.

I would like to thank B. Gittelman for supplying information on π^0 photoproduction. G. W. Temmer and W. M. Gibson gave helpful advice on conventional channeling. T. L. Gilbert and J. E. Robinson kindly reviewed the question of near-neighbor coherence in solids.

*Operated by Universities Research Association Inc. under contract with the U. S. Energy Research and Development Administration.

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Observation of Autoionizing Transitions in Helium Using the $(e, 2e)$ Technique*

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(Received 5 May 1975)

Resonance ionization from the $(2s2p)\ ^1P$ and $(2p^2)\ ^1D$ levels of helium has been observed in an $(e,2e)$ experiment, in which the kinematics of all electrons is fully determined, at incident energies of 200 and 400 eV and a scattering angle of 10°. The results show that as the angle of emission approaches the direction $-\vec{Q}$, where $\vec{Q}$ is the momentum transfer to the helium atom, the resonance profile becomes more symmetric and the resonance cross section increases sharply.

The autoionization of helium excited by electron impact has been studied in recent years by measuring the spectra either of the scattered electrons[1] or of the emitted cascade or decay electrons.[2] Since the interference between the direct-ionization amplitude and the resonance or autoionization amplitude depends on the momenta of the scattered electrons, the more recent work has concentrated on observing the resonance profiles as a function of the angle of either the scattered or emitted electron. However, such experiments always involve integration over the momenta of the undetected electrons. On the other hand in an $(e,2e)$ experiment, where the two outgoing electrons are detected in coincidence, the kinematics of the electrons is completely determined. This means that information can be obtained on the resonance[3] and the direct cross sections as a function of the momentum $\vec{k}'$ of the emitted (or decay) electron for known values of the momentum transfer $\vec{Q}=\vec{k}_0-\vec{k}$, where $\vec{k}_0$ and $\vec{k}$ are the momenta of the incident and scattered electron, respectively.

One additional major advantage of the $(e,2e)$ technique for studying autoionizing states is that it provides information which can be compared directly with scattering theory without incurring any ambiguities from normalization of the experimental data. In this respect it is very similar to the electron-photon angular-correlation experiments of Eminyan *et al.*[4] and Arriola *et al.*[5] These experiments showed that when a scattered electron leaving an atom in an excited state is detected in coincidence with the cascade photon, fine details of electron-atom collision can be investigated. In particular it is possible to determine the ratios of excitation amplitudes leading to the various magnetic substates of the intermediate excited level, as well as to determine their relative phases.

This is also true for an $(e,2e)$ autoionization experiment if there is no direct contribution to the cross section. For instance, with neglect of the direct contribution and interference between