collisions[5] except that the rise and decay of the curve are more rapid as functions of energy, and the maximum occurs at a lower energy.

When the results of the present measurements of cross sections and relative intensities are correlated with the data of Lipeles, Swift, Longmire, and Weinreb, it is seen that inelastic channels of the $He^{+}+Ar$ system which lead to excited Ar I and He I may result as often as those which lead to excited Ar II. A more thorough study of all these processes is required for the development of adequate experimental data which will lead to a better understanding of the theory of low-energy collision processes.

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CHANNELING AND COHERENT BREMSSTRAHLUNG EFFECTS FOR RELATIVISTIC POSITRONS AND ELECTRONS*

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Channeling of positrons in silicon single crystals has been observed in transmission and scattering measurements for incident energies from 16 to 28 MeV. In addition, the forward bremsstrahlung intensity has been established as a new observable of the channeling phenomenon. Enhancement of the low-energy portion of the bremsstrahlung spectrum ($E_\gamma < 1$ MeV) has been observed with both positron and electron beams incident along the crystal axes; this enhancement is attributed to coherence effects in bremsstrahlung production.

The phenomenon of channeling of energetic particles in crystals has been the subject of extensive investigation.[1] The effect has been observed for positive ions, positrons, and electrons, but in no case in the literature have the particles been extremely relativistic. For positrons this is mainly the result of the extreme difficulty not only of producing a high-energy beam, but of focusing it to the very small angular divergence necessary to explore the channeling effect. This Letter reports on our efforts to overcome these difficulties, and our success in establishing certain qualitative features of relativistic positron- (and electron-) crystal collision processes as a function of crystal orientation. Namely, we have observed channeling of 16- to 28-MeV positrons in silicon, and also have shown that bremsstrahlung intensity is correlated with the channeling phenomenon. Other effects of crystal orientation have been observed that probably reflect coherent bremsstrahlung production. Results for electrons are also presented for comparison with the positron data; orientation dependences were observed for electrons, although they are not clearly identifiable with normal channeling.

Monoenergetic ($\Delta E/E \leq 1\%$) positron and electron beams were obtained from the Livermore electron linear accelerator. The particles impinged upon thin (5- to 53-μm) silicon crystals mounted on a goniometer capable of sweeping the crystal through a two-dimensional angular range in 0.04-mrad steps. Measurements were performed to yield intensities of particles and photons as a function of the angle between the incident beam and either the $\langle 111 \rangle$ or $\langle 110 \rangle$ crystallographic direction. A plastic scintillator allowed separate observation of forward-transmitted particles, and of particles scattered into the angular ranges 0.5 to 0.6 and 0.9 to 1.0 deg with respect to the incident beam. A thin-walled transmission ionization chamber filled to 0.5 atm of xenon gas was used to observe the forward bremsstrahlung. In the bremsstrahlung measurements, a magnet which followed the crystal target swept transmitted particles away from the detector. The maximum angular divergence of the beam was determined by the use of suitable collimation systems. For particle observations, the beam collimation consisted of two $\frac{1}{8}$-in.-diam aluminum collimators placed 20 ft apart, with no focusing elements between them. For the bremsstrahlung observations, $\frac{3}{8}$-in.-diam carbon collimators were employed. The $\frac{3}{8}$-in. system provided a maximum beam divergence of 3 mrad, of the same order as the expected critical angle for channeling. Careful tuning of quadrupole magnets in the beam transport system appeared to result in beam divergences considerably smaller than this value, since the positron-transmission measurements performed with either set of collimators yielded essentially the same channel widths.

Curves representative of the main features of the data are shown in the illustrations, where the various measured intensities are plotted as a function of θ, the crystal angle. In all cases in the data for positrons, channeling produces a narrow structure in the curves, centered about $\theta=0$. This is illustrated in Fig. 1(a) for scattered 20-MeV positrons (scattering into the angular range 0.9 to 1.0 deg with respect to the beam), for the ⟨110⟩ direction of a 53-μm crystal. Figure 1(b) represents the same measurement for electrons, and a similar though much less prominent narrow structure appears. Both curves show other, broader structure. Curves for forward-transmitted particles (not shown) have shapes that are complementary to those in Fig. 1, as expected. Although the data presented here are for directional channeling only, planar channeling was observed clearly for all the crystals. Figures 2 and 3 show the forward (±0.1 deg) bremsstrahlung intensity from 28-MeV positrons and electrons, respectively, for the ⟨111⟩ direction of a 42-μm crystal. The curve for positrons shows the narrow channeling structure referred to above.

According to the classical theory of Lindhard[2] the critical angle ψ_c for the channeling of nonrelativistic particles is given by

$$\psi_c \approx (2Z_1Z_2e^2/Ed)^{1/2},$$

where Z_1 and Z_2 are the atomic numbers of the projectile and target, respectively, e is the electronic charge, d is the distance between atoms in a lattice row, and E is the projectile energy. For relativistic particles E is replaced by $\frac{1}{2}pv$, where p is the relativistic momentum of the particle and v is its velocity. For our particle beams $\frac{1}{2}pv \sim \frac{1}{2}E$. Our measured half-widths at half-minima for the positron channeling dips were, for both particle and bremsstrahlung data, about 40% smaller than the values obtained from the relativistic equation (e.g., about 2 mrad for 20-MeV positrons). The energy dependence of the measured widths was in accordance with the theoretical prediction.

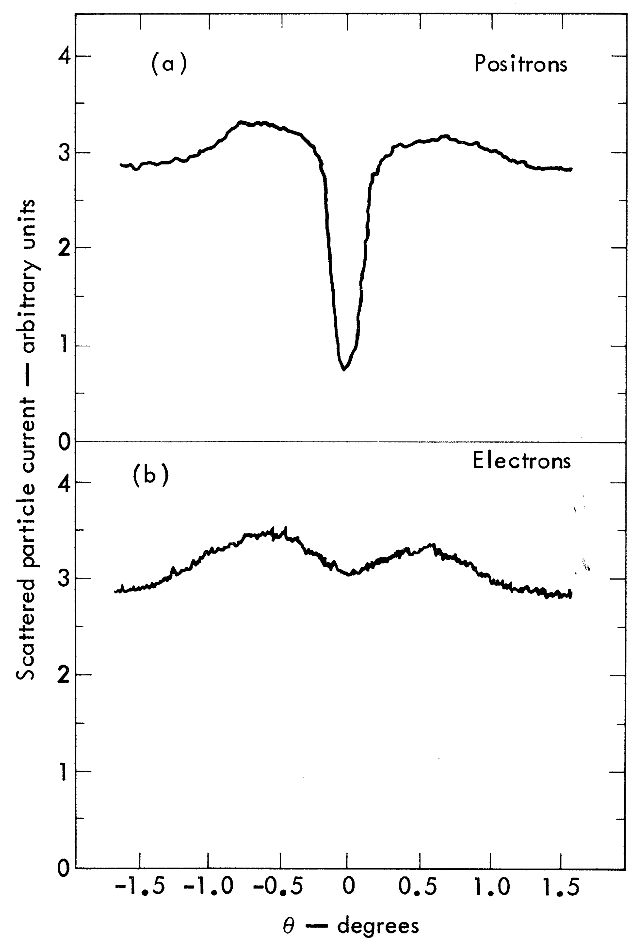

FIG. 1. Scattering of 20-MeV (a) positrons and (b) electrons into an angular range 0.9 to 1.0 deg with respect to the beam. Data are for a 42-μm silicon crystal, and θ is the angle between the ⟨111⟩ crystallographic direction and the beam axis. Curves are normalized to equal off-channel values. Our best scattering data, for the ⟨111⟩ direction of a 19-μm silicon crystal, showed a channeling minimum that was $\sim\frac{1}{6}$ the off-channel value.

The electron particle data do not agree with expectations based on earlier electron-channeling work done at lower energies.[3] In all cases in our work (both in scattering and transmission measurements, for all targets and for all beam

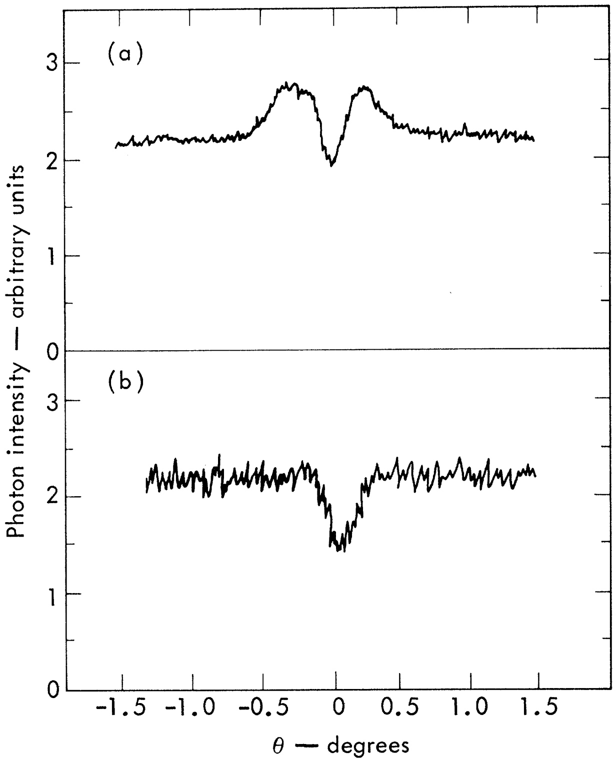

FIG. 2. (a) Foward (±0.1 deg) bremsstrahlung detected by the ionization chamber, for 28-MeV positrons incident on a 53-μm silicon crystal. θ is the angle between the beam axis and the ⟨110⟩ crystallographic direction. (b) Similar data, but with a $\frac{1}{2}$-in. lead absorber between the crystal and the detector. Curves are normalized to equal off-channel values.

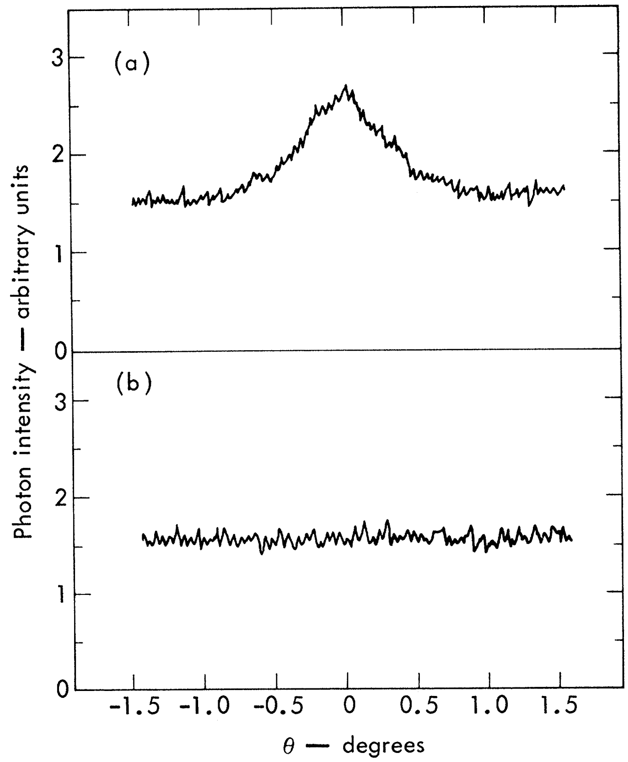

FIG. 3. (a) Forward (±0.1 deg) bremsstrahlung detected by the ionization chamber, for 28-MeV electrons incident on a 53-μm silicon crystal. θ is the angle between the beam axis and the ⟨110⟩ crystallographic direction. (b) Similar data but with a $\frac{1}{2}$-in. lead absorber between the crystal and the detector. Curves are normalized to equal off-channel values.

energies) the electron data showed a broad structure like that for positrons, and a narrow structure centered about 0° that was broader and much less prominent than for positrons. Predictions based on the earlier work would lead one to expect, for the case shown in Fig. 1(b), roughly the inverse of the curve shown for positrons.

The bremsstrahlung data for both positrons and electrons show several interesting features. The upper curves in Figs. 2 and 3 correspond to unfiltered bremsstrahlung detected by the ionization chamber. The positron data show the characteristic channeling dip; this was expected since bremsstrahlung production is a small-impact-parameter phenomenon. In addition, curves for both positrons and electrons show a broad structure rising above the off-channel values. When a $\frac{1}{16}$-in. lead absorber was placed between the target and the ionization chamber the broad structure was essentially eliminated, indicating that it results from low-energy photons ($E_\gamma \lesssim 1$ MeV). This observation of low-energy broad structure also has been made by Godlove and co-workers[4] at the U. S. Naval Research Laboratory. The narrow channeling dip for positrons is still seen with a $\frac{1}{2}$-in. lead absorber, as shown in Fig. 2(b); the high-energy portion of the bremsstrahlung spectrum is thus clearly influenced by the channeling phenomenon. For a given bombarding energy and crystal, the broad structure associated with low-energy photons is similar in width to the broad structure seen in the particle-scattering measurements. This, together with the absence of residual broad structure in the curves for filtered bremsstrahlung, suggests that these effects are related. In the case of particle data for positrons, however, one could be observing the "shoulders" that normally are seen in channeling measurements and that are attributed to an increased probability for small-impact-parameter events. The shoulders are more prominent and narrower for higher incident particle energies, consistent with this interpretation. However, this type of interaction normally would not be expected to result in preferential production of low-energy bremsstrahlung photons. The appearance of the low-energy bremsstrahlung structure in the region of alignment of the beam with the periodic structure of the crystal suggests the possibility of coherent bremsstrahlung effects. Such an enhancement of the low-energy part of the photon spectrum was predicted by Dyson and Überall,[6] and discussed in more detail by Überall.[6] A relativistic electron (or positron) of energy E interacts coherently with a low-energy bremsstrahlung photon of wavelength λ over a path length $L \approx \lambda(E/m_0c^2)^2$, and for an aligned particle the photon intensity is expected to be enhanced by a factor N, equal to the number of crystal atoms contained in the coherence length L. If d is the lattice spacing, then $N = L/d$. Since matrix elements for bremsstrahlung production are small for impact parameters larger than the Thomas-Fermi screening radius a, these enhancement effects should occur for $\theta < a/L$. Accordingly, for incident particles in the energy range of our experiment, N becomes greater than unity for photon energies less than a few MeV, and enhancement should occur for $\theta < 30$ mrad. The effect should be about twice as strong for 28-MeV particles as for the 20-MeV case, and should occur in roughly half the angular range. Our low-energy photon observations are quite consistent with these predictions. These coherence effects occur in addition to any channeling effects, and it should be noted that the above predictions are for particle trajectories not influenced by the channeling mechanism.

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TUNABLE SPIN-FLIP LASER AND INFRARED SPECTROSCOPY

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We investigate the use of a tunable spin-flip Raman laser in infrared absorption spectroscopy. The Raman laser is tunable from 10.9 to 13.0 μm with linearity and resettability of tuning better than ~4 Å at ~12.0 μm. This limit is set by the present measurement capability. A study of the absorption spectrum of NH_3 in the 12.0-μm region shows that the spin-flip Raman laser is superior to a conventional grating spectrometer in attainable resolution.

The recent report of a tunable spin-flip Raman laser[1] in InSb is of considerable significance for infrared spectroscopy. The spin-flip Raman laser in InSb is continuously tunable from 10.9 to 13.0 μm[2] (when pumped at 10.6 μm) by varying the dc magnetic field. If sufficiently narrow and stable, such a source might be quite important in infrared spectroscopy. In this paper we report measurements of linearity and resettability of the spin-flip Raman-laser frequency which were made in order to evaluate its suitability for this purpose. At present, linearity and resettability are better than $1:3\times10^4$ corresponding to ~4 Å at ~12.0 μm, i.e., ~800 MHz at 830 cm^{-1}, and are limited by our measurement capability. The emission linewidth is estimated to be ≲0.03