choice, the resulting values of $\tilde{\beta}_0$, $\tilde{\beta}_1$, and $\tilde{\beta}_2$ are given in Table I. Comparing the results of Table I we see that correlation corrections substantially improve the uncorrelated shell-model values. However, also note that while the calculated total matrix element can agree very well with experiment, the individual parameters can still differ by a factor of 2. Thus, I conclude that microscopic calculations of just the total muon capture rates can be incomplete, and that an evaluation of the reduced isotensor and isoscalar matrix elements should also be made.

[1]B. Goulard and H. Primakoff, Phys. Rev. C **10**, 2034 (1974).

[2]A term in $(N-Z)/2Z$ also appears in the energy-weighted expression of Ref. 1.

[3]H. Primakoff, Rev. Mod. Phys. **31**, 802 (1959).

[4]J. C. Sens, Phys. Rev. **113**, 679 (1959).

[5]Note that if I had defined β_0 and β_2 in terms of the unsubtracted operators $\langle \theta_0 \rangle$ and $\langle \theta_2 \rangle$, the value of β_2 would be changed by $-A|\langle||\theta_z||\rangle|^2/3$, making it very large and negative, and similarly, β_0 would be changed by $[-A/3 + 4T_z (T_z + 1)/3A]|\langle||\theta_z||\rangle|^2$.

[6]The factor-of-2 discrepancy in the total $\langle \theta_- \theta_+ \rangle$ has also been obtained in other calculations; see, for example J. R. Luyten, H. Rood, and H. Tolhoek, Nucl. Phys. **41**, 236 (1963); J. Joseph, F. Ledoyen, and B. Goulard, Phys. Rev. C **6**, 1742 (1972).

[7]A. M. Lane and A. Z. Mekjian, Phys. Rev. C **8**, 1981 (1973).

[8]A. Z. Mekjian and W. M. MacDonald, to be published.

[9]G. E. Brown and M. Bolsterli, Phys. Rev. Lett. **3**, 472 (1959).

Ionization Loss of Channeled 1.35-GeV/c Protons and Pions

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The channeling effect has been observed to reduce the ionization energy loss by about a factor of 3 for 1.35-GeV/c protons and π^+ traversing a 0.67-mm germanium crystal.

As part of an experimental program to investigate the channeling effect for high-energy particles in crystals, we have measured the ionization-loss spectra of several charged particles under channeling conditions. Considering the interest this subject has generated at lower energies during the past decade,[1] we have chosen to present some of our preliminary data in this brief note. Also theoretical simplifications afforded in the limit of high velocities clarify certain concepts applicable to the channeling energy-loss effect.

Secondary beams of 1.35-GeV/c protons, π^+, and π^- were obtained from the CERN 30-GeV proton synchrotron. After passing through a collimation system (described below), the beam was transmitted through a 0.67-mm-thick germanium single crystal. This specimen was prepared to serve simultaneously as a channeling medium and a solid-state ionization detector. The former requirement was satisfied by the crystal having a low mosaic spread (< 0.1 mrad) with a major axis direction oriented along the beam direction, and the latter by utilizing high-purity n-type germanium material (impurity concentration $\sim 3 \times 10^{10}$ atoms/cm^3) with a suitable shallow boron-implanted layer (2000 Å, front contact) and a thin aluminum back contact (300 Å), thereby forming an "intrinsic" germanium ionization detector. The sample was mounted in a goniometer and cooled in vacuum to around 100°K in order to obtain acceptable energy resolution [$\lesssim 10$ keV full width at half-maximum (FWHM)] for the measurements. A bias voltage of 15 V totally depleted the sample.

The entire mechanical layout of the experiment

is illustrated in Fig. 1 of Ref. 2. This system, without the solid-state-detector capability, has been used recently[2] to demonstrate the high-energy channeling effect on a similar beam.

The incident beam was collimated roughly by anticoincidence counters in front of the sample. The selected component of the beam thus obtained contained a range of angles of incidence of ~ 50 mrad[2]. The goniometer served only to place the ⟨110⟩ crystal-axis direction within this range.

A set of three two-dimensional position-sensitive drift chambers was situated both in front of and behind the sample, at suitable distances, to determine for each event the detailed angles of incidence and emergence of the particles. The charge created in the depletion layer of the sample was collected and amplified by standard techniques and then processed in coincidence with the signals from the position-sensitive detectors. Discrimination between protons and π^+ was effected by the time-of-flight method.

Figure 1 shows the yield of 1.35-GeV/c π^+ scattered through angles smaller than 0.35 mrad as a function of the angle of incidence to the ⟨110⟩ crystal direction. A clear channeling-transmission peak is observed. This particular angular scan was made in such a way as to avoid any complications due to the nearby planar effects. These planar effects were demonstrated in an earlier note.[2] A very similar behavior is shown by 1.35-GeV/c protons.

Figures 2(a) and 2(b) show the germanium-detector pulse-height spectra for 1.35-GeV/c protons and π^+, respectively. In the figures, the pulse height has been converted to energy deposited in the depletion depth from a calibration ob-
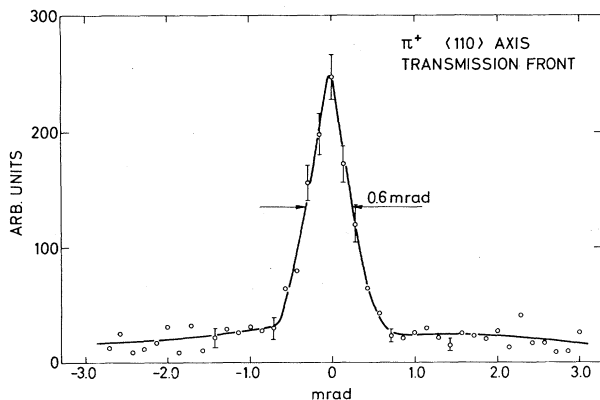
tained by exposing the detector to ^{57}Co and ^{137}Cs γ-ray sources.

The open circles correspond to the energy-loss spectra of particles whose angles of incidence lie far from any major axis or planar directions (random beam). The filled circles show the spectra obtained for channeled particles whose incident angle to the ⟨110⟩ axis is aligned within 0.9 mrad and whose scattering angle is less than 0.35 mrad. These axial-channeled particles clearly show a reduced energy loss as compared with the random beam. Similar results are obtained for the {111} planes and they will be presented in a future publication.

Analysis of the experimental results is somewhat complicated by the fact that all of the energy lost by the incident particle in traversing the germanium detector is not contained and converted into collectable charge in the depletion region. A "head-on" collision between a 1.35-GeV/c pion and an electron, for example, results in 89-MeV recoil electrons, which easily escape from the
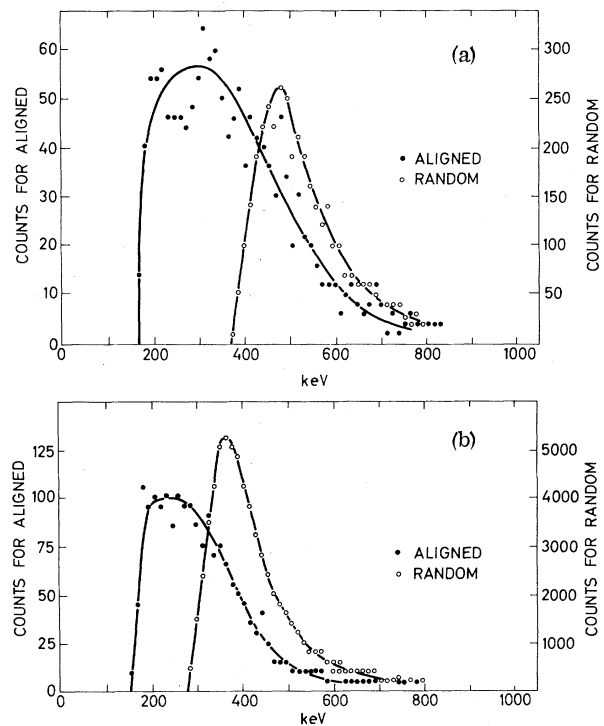

FIG. 2. (a), (b) Pulse-height spectra from germanium detector for 1.35-GeV/c protons and π^+, respectively. Closed circles, spectrum from particles within 0.9 mrad of ⟨110⟩ axis direction. Open circles, spectrum from incident angles not including any major axial or planar directions. All curves have been drawn only to guide the eye.

FIG. 1. Typical angular spectrum of the yield of small-angle (< 0.35 mrad) scattering events for angles of incidence including the axial ⟨110⟩ direction.

sample without creating the collectable charge characteristic of that energy loss since the range of such electrons is about 50 mm in germanium.

Cursory perusal of electron range-energy curves and kinematical energy-recoil-angle relations suggests that on the average, for our detector geometry, recoil electrons with energies in excess of ~ 500 keV escape without contributing significantly to the pulse heights recorded in Figs. 2(a) and 2(b). The data therefore represent restricted energy-loss spectra.[3] The restricted energy-loss rate $(-dE/dx_{rest})$ due to ionization by the random beam may be suitably described by the formula

$$\left(-\frac{dE}{dx_{rest}}\right)=\frac{2\pi e^4 Z_2 N}{m_e v^2}\left\{2\ln\frac{2m_e v^2\gamma^2}{I}-2\frac{v^2}{c^2}+\left[\ln\frac{T_0}{2m_e v^2\gamma^2}-\frac{T_0}{2m_e c^2\gamma^2}+\frac{v^2}{c^2}\right]\right\},\qquad(1)$$

where the term in square brackets represents a modification of the normal energy deposited, due to a lack of contribution from energy transfers greater than T_0. The mean energy loss for the case of random incidence is given by Eq. (1) with

$$T_0 = 2m_e v^2\gamma^2 \qquad (2)$$

which is the maximum energy transfer in a "head-on" collision. In the above two formulas v and c are the velocities of the incident particle and light, respectively, m_e is the electron rest mass, and γ is the relativistic factor $(1-v^2/c^2)^{-1/2}$. Z_2 and N are the atomic number and concentration of atoms in the target. I is the well-known mean excitation energy of target atoms. Formula (1), apart from some algebraic manipulations, corresponds to Eq. (88) in Ref. 3 without contribution from shell effects or Cherenkov radiation loss.

Table I gives the theoretical mean energy loss ΔE_{rand} for the random beam. The value for protons is simply determined by Eqs. (1) and (2) and the germanium-sample thickness. For pions, the density effect is expected to be important at this energy. A reduction of 5% from the value predicted by Eqs. (1) and (2) has been assumed.[4] ΔE_{det} indicates the experimentally determined mean energy deposited in the detector by the random beam. ΔE_{rest} is the restricted energy loss

from Eq. (1) with a value of $T_0 = 400$ keV assumed for both protons and pions and the density-effect correction for pions included. The agreement between ΔE_{detec} and ΔE_{rest} is quite good and suggests that the random energy-loss part of the experiment gives totally reasonable results. Experimental errors in the values for ΔE_{det} are of order 1%. We have also obtained qualitative, though not totally quantitative, agreement with the Landau-Vavilov energy-loss straggling distributions for the random beam. Because of the difference between $T_0 = 400$ keV and $2m_e v^2\gamma^2$, this is not very surprising.

Quantitative analysis of the energy-loss spectra for the channeled particles is a more delicate matter. There exists at this time no accurate formula analogous to Eq. (1) for predicted energy losses of channeled particles. Needless to say, predicting the detailed distribution of losses is an even more complicated task. Nevertheless it seems possible to draw several conclusions based upon the data and considerations of channeling and energy-loss concepts.

It is well known[5] that at high particle velocities, contributions to energy loss in the nonchanneled situation come roughly equally from distant resonant excitation of host atoms and the more violent close-encounter collisions with the atomic electrons. Classical paths associated with channeled particles of low transverse energy are restricted to regions of rather low electron density. There are three important consequences of these considerations. First, one expects for well-channeled particles a reduction in energy-loss rate by approximately a factor of 2 in comparison with random penetration due to a lack of contribution from the close collisions. Second, one may expect the fluctuations in energy loss for the best-channeled particles to be considerably reduced in comparison with the random beam, since for the latter it is relatively infrequent but large energy transfers by close collisions that essentially de-

TABLE I. Energy losses for 1.35-GeV/c particles.

Particle	ΔE_{rand} [a]	ΔE_{rest} [b]	ΔE_{det} [c]	$\Delta E_{leading\ edge}$ [d]
Protons	579	539	538	180 keV
π^+	537	423	421	180 keV
π^-	537	423	424	

[a] Theoretical random energy loss with density effect included for pions.

[b] Theoretical restricted energy loss with $T_0 = 400$ keV and density effect included for pions.

[c] Experimental mean energy deposited in detector.

[d] Leading edge of channeled energy-loss distribution.

termine the energy-loss straggling distribution and cause the large difference between the most probable and the mean loss. Finally, corrections due to electrons leaving the detector are not necessary, and the energy deposited is equal to the energy loss for the well-channeled part. The width of the channeled spectra for both protons and π^+ is most likely dominated by the transverse energy distribution. We therefore tentatively identify the low-energy edge of the spectra as the energy loss for low-transverse-energy-channeled particles. The numerical results are indicated in Table I under $\Delta E_{\text{leading edge}}$.

Well-channeled particles in the $\{111\}$ planes have an energy loss similar to that in the $\langle 110 \rangle$ axial case. This suggest that our values for the best-channeled axial loss should be considered as a highest lower bound, for it is likely that diffusion of transverse energies by multiple scattering on electrons allows virtually none of the classical paths traversing only the regions of lowest electron density to survive the thickness of the crystal. Measurements on thinner crystals should remedy this situation.

At this point a short discussion of the theoretical implications of these new results is called for. Experimentally it is now verified that the strong reduction in stopping power is a general property of positive channeled particles over a considerably extended velocity region. The physical arguments used in the preceding discussion are characteristic of the state of the theory which is only of use for qualitative prediction. Comprehensive prediction presents a serious challenge. While detailed comment on the matter would be out of place here a few brief remarks relating the present data to the problem follow.

The simple description of the stopping problem for penetration in a random target, contained in Eq. (1), relies heavily on translational invariance with respect to the path of the incident particle. As a result of this invariance, various Fourier components of the incident particle's field contribute incoherently to the stopping. Application of Bethe's sum rule and dipole expansions of matrix elements are responsible for the dependence of Eq. (1) on the average electron concentration NZ_2 and the dipole oscillator distribution (contained in the definition of I), respectively. We may anticipate that the transition to a description involving the path dependence in an inhomogeneous atomic system will be complicated by the need for further accurate information about the medium. Indeed in this case there will be additional contributions from interference between different wavelength components of the penetrating particles' field. A generalization of the methods applied to random stopping may be developed[6] based upon further sum rules and expansion techniques. These methods suggest, respectively, that for the inhomogeneous problem a knowledge of the ground-state charge-density function and complicated generalization of dipole oscillator strengths is necessary. The essential point is that for high velocities, i.e., $v\gamma \gg v_0 Z_2$ ($v_0 = e^2/\hbar$), the ionization loss becomes independent of the latter quantity and numerical calculations predicting path-dependent energy loss become feasible. Aside from the measurements reported here, there appear to be no experimental data satisfying the above criterion.

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[1]For an extended review, see D. S. Gemmell, Rev. Mod. Phys. 46, 129 (1974).

[2]O. Fich, J. A. Golovchenko, K. O. Nielsen, E. Uggerhøj, G. Charpak, and F. Sauli, Phys. Lett. 57B, 90 (1975).

[3]U. Fano, Annu. Rev. Nucl. Sci. 13, 1 (1963).

[4]W. H. Barkas and M. J. Berger, in Studies in Penetration of Charged Particles in Matter (National Academy of Sciences-National Research Council, Washington, D. C. 1964), Chap. 7.

[5]J. Lindhard, K. Dan. Vidensk. Selsk., Mat.-Fys. Medd. 34, No. 14 (1965) [see Eq. (3.15) and the discussion preceding it].

[6]J. A. Golovchenko, BNL Report No. 20261; J. A. Golovchenko and H. Esbensen, to be published.