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NEAR SURFACE YIELD ENHANCEMENT IN NARROW ACCEPTANCE 180° ELASTIC SCATTERING FOR He IONS IN NON-CRYSTALLINE AND POLY-CRYSTALLINE SOLIDS

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Observations of an unusual near surface ($0 \leqslant x \lesssim 700$ A) yield enhancement in the energy distribution of elastically scattered He ions from amorphous and polycrystalline materials is reported. The integrated excess yield for small ($\theta_{1/2} = 0.2°$) versus large ($\theta_{1/2} = 4.5°$) acceptance angle at 180° scattering is typically 20% for He energies in the range $0.2 \leqslant E \leqslant 2.5$ MeV. Maximum peak to normal yield ratios have been observed as high as 60–70%. Materials in which the effect has been observed include amorphous germanium, the glassy metal alloy $Nb_{40}Ni_{60}$, fine grain polycrystalline Au, Pt, Mo, and Cu and also in single crystals of Si and Au continuously rotated during data collection to simulate a random lattice. The excess yields are largest for materials of atomic number above $Z = 40$ and decreases rapidly for elements below this value. The angular width and depth dependence of this effect suggest that it is sensitive to multiple scattering and also implies that the particle, upon scattering, must retrace its inward path within a cone of $\lesssim 0.2°$ from depths comparable to or less than a few hundred A.

In the process of studying uni-axial double alignment channeling in single crystals we have observed, for a variety of amorphous and poly-crystalline materials, an unusual enhancement in the near surface energy distribution of ions elastically backscattered within approximately ±0.25° of the 180° direction. The experimental geometry is depicted in fig. 1. An incident beam of He^+ is collimated to less than 0.01° half angle and directed onto the specimen through a set of movable annular detectors. A small (7 mm^2) planar detector ($\Delta\theta_{1/2} = 0.04°$) could also be positioned in the beam line to measure angular scans about the 180° scattering direction when the annular detectors are rotated out of the way. The 90° detector is used for generating comparative narrow angle ($\Delta\theta_{1/2} = 0.1°$) spectra not associated with the exact backward angle direction.

Comparison of the backscattered spectra observed

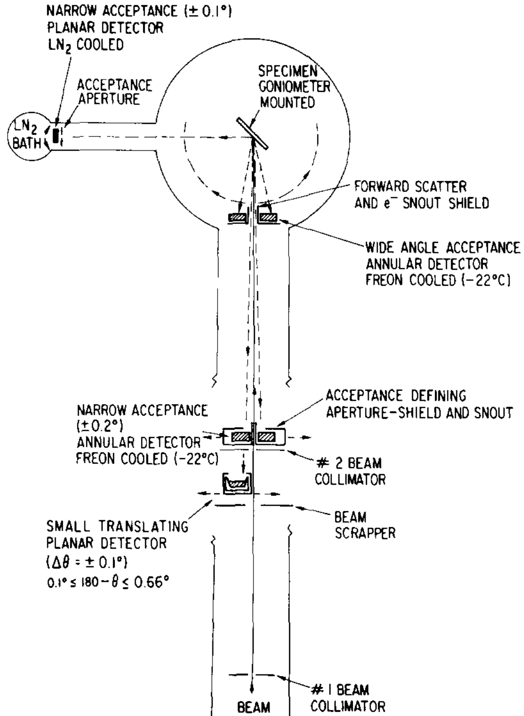

Fig. 1. Schematic diagram of experimental setup showing the beam configuration with respect to collimators and detectors.

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in the two annular silicon surface barrier detectors represents a direct measure of the difference associated with wide angle ($\Delta\theta_{1/2} = 4.6^\circ$) versus narrow angle ($\Delta\theta_{1/2} = 0.2^\circ$) acceptance. Such a comparison is shown in fig. 2 for 1.6 MeV He^+ scattered from fine grain poly-crystalline platinum. The spectra were normalized to match in the region beyond 800 Å. This normalization procedure will be discussed further below. An energy to depth conversion was made using standard calculations and current stopping power data. The depth resolution is typically 100 Å. It is observed from fig. 2 that the narrow angle spectrum has a substantial yield enhancement in the first 700 Å from the surface. This excess yield appears to rise to a maximum just behind the surface (at $\lesssim 100$ Å) then decreases in a regular way to the normal yield at about 700 Å deep. A similar yield enhancement in near surface energy distributions of backscattered ions is often seen for specific incident beam directions near planar or axial channels in single crystals. These so called compensation wings are associated with scattering from atom rows or planes when the incident angles are such that the ions encounter increased atom densities. The excess yield associated with these scattering events are compensated for by the large reductions in yield along channeling directions. If a crystal is rotated, in the single alignment configuration, to average over all possible directions during data collection the net effect of compensation and channeling is a normal thick target Rutherford type spectrum. The data in fig. 2 were taken from a specimen composed of fine polycrystalline grains which should result in a spectrum that is essentially the same as a rotating single crystal spectrum. In fact spectra similar to those in fig. 2 were also obtained from rotating single crystal measurements. However, because the narrow angle 180° configuration represent a *double alignment* channeling situation whenever the beam impinges on a channeling direction (i.e. the particle experiences channeling going in and blocking coming out of the crystal) there is some remote possibility that total compensation may not occur. It is not obvious why this should occur, however, we can determine whether such an artifact is significant by repeating the experiment on amorphous materials.

Figs. 3 and 4 show the results of such an experiment performed on amorphous germanium. Fig. 3 is a standard single alignment backscattering spectrum taken from a specimen that had a surface made amorphous by bombardment along a non-channeling direction with a combination implant of phosphorus at 35 and 75 keV. Standard channeling measurements were made with 0.8 MeV He ions along ⟨100⟩ in the substrate crystal region and in the 5° tilted rotating specimen mode. In fig. 3 are the results of such measurements for the usual wide angle acceptance at 160° back angle. These results confirm that an amorphous germanium layer 1800 Å thick had been formed by the phosphorus bombardment. The yield

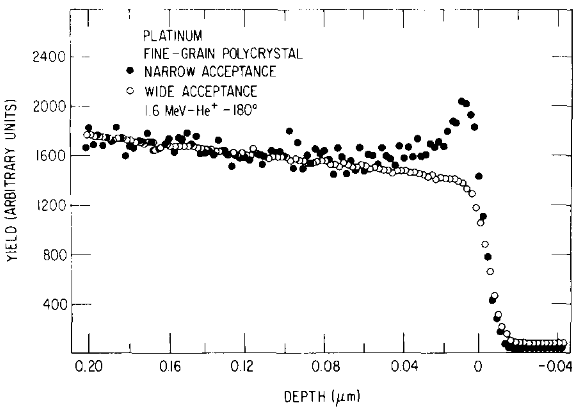

Fig. 2. Comparison of 180° scattering yields, as a function of depth, observed in the wide and narrow acceptance angle annular detectors for 1.6 MeV He ions on platinum.

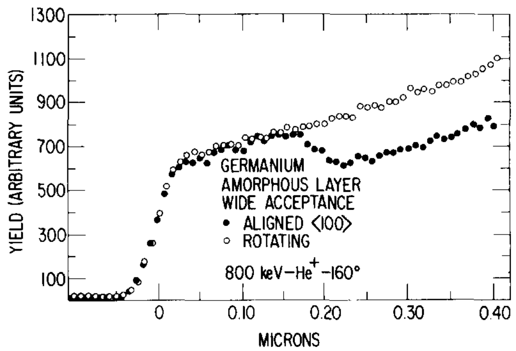

Fig. 3. Comparison of single alignment channeling yield (i.e. wide acceptance) with rotating reference spectrum for 800 keV He ions on germanium. Data demonstrates the existence of an amorphous layer produced by ion bombardment.

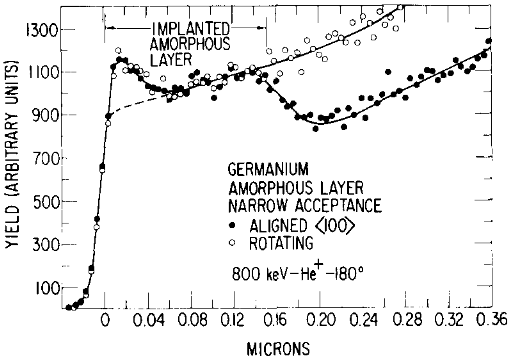

Fig. 4. Comparison of narrow angle channeling yield with rotating reference spectrum for 800 keV He ions on germanium. Data demonstrates the existence of the enhanced near-surface yield for amorphous material.

beyond 1800 Å is from dechanneling of the beam after it passed through the amorphous layer. Disordered layers produced by heavy ion bombardment, as were done here, are known to be of high quality amorphous character. Fig. 4 shows a comparison similar to that in fig. 3 where now a channeled and rotating reference spectrum under narrow acceptance angle are being compared. The yield anomaly is seen to exist for both spectra of fig. 4. It is important to note that the scaling factor used to bring the channeled spectrum amorphous yield into coincidence with the rotating reference amorphous yield is the same in figs. 3 and 4. This is significant because it demonstrates that the anomalous feature in fig. 4 is indeed an enhancement in the yield from the near surface region rather than the zone behind the feature being a depleted region of the energy distribution. It is seen that the enhancement again extends from near the surface to about 700 Å there being a regular decrease with depth from the peak value which occurs in the vicinity of the surface at a depth of $\lesssim 150$ Å.

To further test the non-crystalline nature of the effect, measurements were made on a specimen of amorphous $Nb_{40}Ni_{60}$. This glassy material was prepared by a totally different method than the amorphous germanium. The binary alloy was prepared by levitation melting and splat cooling in order to achieve the totally disordered state. The specimens examined in this experiment were obtained from a batch that was observed to be in the glassy state by transmission electron microscopy. The published reports of these observations show that the material was amorphous at the level of second nearest neighbors for temperatures below 600°C [1]. These same reports also demonstrated that ion bombardment does not alter the amorphous condition but rather will convert any crystalline character achieved by heating above 600°C to the amorphous condition. We feel that this system represents a very stable well defined material on which to test the non-crystalline character of the effect we are observing. Measurements made in narrow angle compared to wide angle acceptance confirmed the presence of the near surface enhancement for scattering from both the nickel and the nobium atoms as observed in the double edged spectrum of the binary alloy [2]. We must conclude therefore that this effect is not associated with artifacts attributable to unbalanced compensation averaging in randomized poly-crystalline double alignment channeling. An explanation must therefore be obtained from some other property of ion scattering or post-collision interactions.

In order to achieve a better understanding of the effect being observed we have made some systematic observations on aspects such as the angular extent over which the effect exists with respect to the 180° direction, its energy dependence, and the target atomic number dependence. Fig. 5 shows the results obtained from scanning the small silicon planar detector about an angle $0.11° \pm 0.04° \leqslant 180° - \theta \leqslant 0.55° \pm 0.04°$ with respect to the 180° scattering direction. Analysis of these results showed that an effective half width of $\lesssim 0.2°$ is in effect for 1 MeV He ions on platinum. The energy dependence was examined for $0.2 \leqslant E \leqslant 2.5$ MeV and it was observed that the intensity of the effect had a broad maximum in the range 400–800 keV but was still very pronounced over the full energy range studied. It was also observed that the persistence depth of the effect increased with increasing energy (500 Å at 0.8 MeV and 700 Å at 2.5 MeV). In examining the dependence on the target atomic number it was observed that the excess near surface yields were largest for materials of atomic number above $Z = 40$ and decreased rapidly for elements below this value. Careful analysis of the spectra are required to establish the existence of the effect in silicon and aluminum whereas the enhanced yields were very pronounced in Cu, Nb, Mo, Pt, and

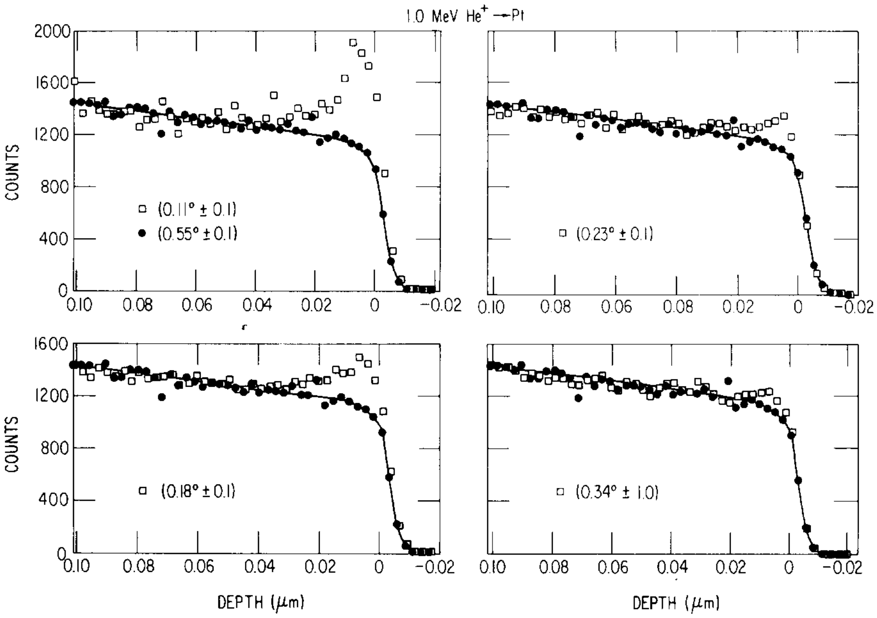

Fig. 5. Spectra taken with small planar detector for various angles (as indicated) with respect to the 180° direction. Black filled circles represent normal reference spectrum taken at 0.55° and open squares are spectra taken at various angular positions showing relative intensity of the enhanced near surface yield for 1 MeV He^+ on fine grain poly-crystalline platinum.

Au. These results strongly suggest that the process involved is sensitive to multiple scattering and also imply that the particle, upon scattering, must retrace its inward path within a cone of $\lesssim 0.25°$ from depths comparable to a few hundred Å or less. It is very unlikely that a nuclear resonance or nuclear size effect was involved since a 200 keV helium ion cannot sufficiently penetrate the coulomb barrier of platinum to give such a large magnitude effect as was observed at that energy.

It is possible to conceive of a number of mechanisms that might account for this effect however we are not able to demonstrate their validity at this time. In as much as the particle is confined to a cone of $\lesssim 0.2°$ about the 180° direction one finds that the ion is passing through the zone of its incoming path within a radius of less than 1 Å from the original trajectory over the first 100 Å of its path reveisal. This means the exiting ion is in a position to interact with the various electronic disturbances it generated on the way in. An 800 keV helium ion having a velocity of 6.4×10^8 cm s^{-1} will travel 100 Å in 1.6×10^{-15} s. These time intervals are on the same scale as the lifetime of the electronic disturbances produced during its inward penetration over a similar 100 Å distance. If the ion is exposed to potentials on the order of 15–20 eV it could experience steering forces similar in magnitude, but of different origin, as those known to exist in channeling situations. The electronic wake field that trails a penetrating ion might be involved in such a process, however the low effective mass of a plasmon wake argues against the probability that it could effectively deflect an ion as heavy as helium. In addition we observed that the effect was very weak in aluminum which is a material that is supposed to have a very well defined plasmon wake. This leads one to consider other possibilities such as bound or semi-bound states of the ion along its exiting path occurring through transient molecular formation and dissociation with the ion–electron pairs formed during penetration. The ion velocities involved in these observations are quite fast and tend to argue against such a possibility. Alternatively, since we are observing an energy distribution it is conceivable that abrupt reductions in stopping power after the 180°-like collisions might account for the effect. Since equilibration stripping distances are on the order of 20 Å, this effect would be confined to the very near surface. Also, if changes in stopping power were involved, one would expect to see a general reduction in the yield of particles at lower energy through simple conservation of particle arguments. Such particle conservation effects may not be observable in the angular scan measurements since the effective solid angle associated with the observed enhancement is very small compared to the overall solid angle from which the excess particles could be steered. Another mechanism that needs to be tested is the possibility that, within the narrow cone of $\sim\pm 0.25°$, particles that backscatter to 180° do not experience true randomization of azimuthal angle but rather retrace their multiple scattering paths followed on the way in [3]. Other experiments and theoretical calculations will have to be performed to test these ideas.

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