THE ISOLATED RESONANCE METHOD FOR INVESTIGATING ORIENTATION EFFECTS AND ELECTRON ENERGY LOSSES OF HYPERCHANNELED PARTICLES

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The isolated resonance of the nuclear reaction on impurity interstitials was used to investigate orientation effects. The method is shown to provide the best energy resolution in comparison with other methods. The $^{13}C(p,\gamma)^{14}N$ reaction resonance at a proton energy of 1.7476 MeV was used to investigate the proton flux distribution in the (0001) plane channel of the single-crystal solution Re-0.4 at.%^{13}C. Some special features of the γ-quantum yield of the reaction in relation to energy have been established. Electron energy losses of hyperchanneled protons were measured. It is demonstrated that the γ-quantum yield of the channeled proton-excited reaction is dependent on the amplitude of thermal vibrations of carbon atoms.

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1. INTRODUCTION

The basic facts about orientation effects at channeling of hydrogen and helium ions were obtained from the analysis of angular and energy distributions of particles scattered by the nuclei of crystal atoms [1]. In the narrow energy range, in the near-surface region of the crystal, at depths of up to ~ 6 wavelengths of particle trajectory oscillations, the scattering spectrum shows a fine structure. Therefore, in studies of a channeled particle flux in this region, stringent requirements are imposed on the energy resolution of the method. The two factors, namely, straggling (discrete statistical character of electron energy loss fluctuations in the medium) at the crystal in/out parts of the scattered particle trajectory and the energy resolution of the spectrometer, substantially restrict the experimental possibilities of the scattering method. This leads to the smoothing of spectra, blurring of their structure and, as a consequence, to ambiguities in the analysis of results [2].

To investigate the orientation effects, we offer an approach based on the use of isolated resonances of excitation functions of the reactions on the impurity interstitial and substitution atoms, which occupy certain positions in the crystal.

2. METHOD

The property of many nuclear reactions is the presence of one or more peaks (resonances) in the plot showing the radiation yield (e.g., (p,γ) reaction) versus particle energy. These resonances are measured experimentally by varying the energy through its small increments with simultaneous measurement of the reaction yield for each energy value. At $E_0 > E_{res}$, the particle loses its energy in the target until the energy attains the resonance value at the depth "x" in the "δx" element, where the reaction takes place.

If the reaction is excited by channeled particles, the resonance radiation yield depends not only on the atom concentration in the "δx". In this case, the yield is also dependent on many other factors: the flux distribution in the channel, the arrangement of atoms, on which the reaction is excited, electron energy losses of channeled particles, the energy straggling, the crystallographic direction, etc.

The resolution of the elastic scattering method, without regard for both the geometry responsible for the solid acceptance angle of the detector and the target surface roughness, is given by the expression

$$(\Delta E_{bs})^2 = (\delta E_{bm})^2 + (\delta E_{spc})^2 + (\delta E_{in})^2 + (\delta E_{out})^2 , \quad (1)$$

where δE_{bm} is the beam energy straggling at entry into the crystal, δE_{spc} is the spectrometer resolution, δE_{in}, δE_{out} denote the straggling before and after particle scattering in the target, respectively.

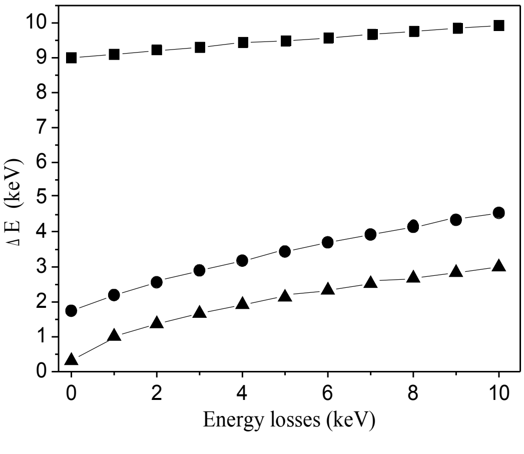

Fig. 1. *Energy resolution of the backscattering method as a function of energy losses for the surface-barrier detector (), magnetic spectrometer (), and the method of resonant nuclear reaction $^{15}N(p,\alpha\gamma)^{12}C$ ()*

Fig. 1 shows the resolving power of scattering methods versus energy losses, as ~ 0.5 MeV protons penetrate deep into the target. The straggling depends on the depth, at which the particle is scattered in the crystal. As it is seen from Fig. 1, in the parts of the proton trajectory before δE_{in} and after δE_{out} scattering in the near-surface zone of the crystal the contribution to the resolving power from straggling is insignificant if a semiconductor-detector spectrometer is used. The measurements of scattered proton energy with the use of a cooled Si - detector (curve ()) give the worst resolution. This is due to the fact that the semiconductor-detector spectrometer for the protons of this energy has $\delta E_{spc} \sim 9$ keV [3]. The use of the magnetic analyzer for the spectrometry of scattered particles [4], as it follows from Fig. 1 (), substantially improves the energy resolution. Here the straggling does give a certain contribution to the energy resolution. But in the given case, the magnetic analyzer acts as a differential instrument; besides, its scattered-particle acceptance solid angle is considerably smaller than that of the semiconductor-detector spectrometer.

The dependence of the resolving power of the isolated resonance method on the depth, at which the reaction occurs, is defined by the expression

$$(\Delta E_{nr})^2 = (\delta E_{bm})^2 + \Gamma_{res}^2 + (\delta E_D)^2 + (\delta E_{in})^2 , \qquad (2)$$

where δE_{bm} is the beam energy straggling at entry into the crystal, Γ_{res} is the natural line width of resonance, δE_D is the Doppler broadening the natural line with Γ_{res} of the resonance, δE_{in} is the energy straggling of particles at entry into the crystal. The resonance can be selected to have $\Gamma_{res} > \delta E_D$.

As it follows from Eq. (1), the resolution depends on channeled particle straggling over the part of the trajectory up to the reaction excitation, and is independent of the spectrometer resolution. This enables one to obtain a much better depth resolution by the isolated resonance method rather than by the scattering method.

The two methods are equally dependent on δE_{bm}. Stringent requirements are imposed on the technical capabilities of the accelerator.

3. RESULTS AND DISCUSSION

The program developed to simulate the channeled particle flux as well as the experimental data on the location of carbon atoms in the single-crystal solution Re-0.4 at.%^{13}C were used to investigate the evolution of proton trajectories in the plane channel (0001) by the isolated resonance method. The nuclear reaction ^{13}C(p,γ)^{14}N, which shows a strong isolated resonance at a proton energy of 1.7476 MeV, Γ_{res} = 135 eV, was used to determine the localization of carbon atoms. It has been established [5] that carbon in rhenium occupies octahedral interstitial sites. In crystals with the hexagonal close-packed lattice (rhenium being among them), the plane of octahedral interstitial sites lies just at the center between the (0001) planes.

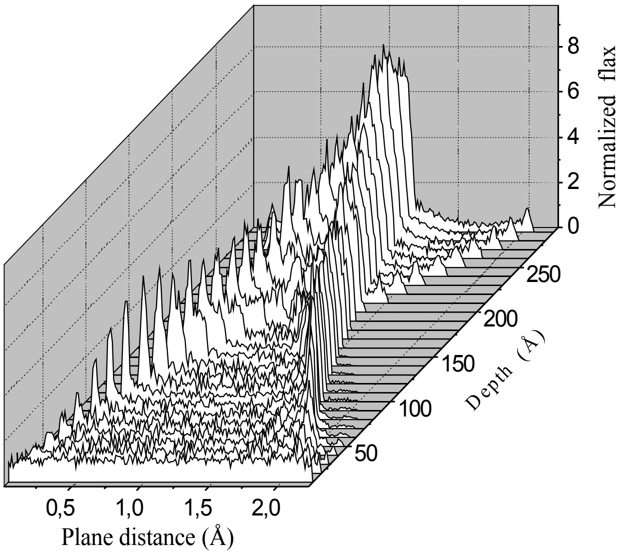

Fig. 2. *Channeled proton flux distribution in the transverse plane along the (0001) channel,* $E_0 = 1.7476$ *MeV,* $\varphi_{in} = 0^{\circ}$

Fig. 2 shows some special features of the dynamic distribution of the proton flux in the (0001) channel up to the first bundle of trajectories for a variety of depth values. As a result of a series of soft correlated collisions with the atoms of the planes, protons having a large amplitude of trajectories give rise to the peaks along the edges of the flux distribution. As the depth grows, the peaks approach the center of the channel and form the maximum in the region of the first bundle of trajectories. As it is obvious from Fig. 1, in the middle of the channel, up to the maximum, the flux of hyperchanneled protons is uniform in the transverse plane, and is close to a constant value, irrespective of the depth value.

Fig. 3 shows the calculated (—, - - -) and measured () functions of the ^{13}C(p,γ)^{14}N reaction excitation at proton channeling along the (0001) plane up to the first bundle of trajectories. The same figure shows the excitation function for random protons ( ). As expected, a sharp increase in the γ-quantum yield is observed at the resonance energy, irrespective of the beam momentum orientation relative to the crystal. The increase in the reaction yield for random protons attains saturation and further remains unchanged irrespective of energy. The excitation function for channeled protons has a plateau, ~ 400 eV in width (shown by the arrow in the figure). The γ-quantum yield in this region stays close to a constant value, and substantially exceeds the yield from random protons. The hyperchanneled proton flux at the center of the channel, where valence electrons are found (Fig. 1), gives the main contribution to the reaction excitation function in the plateau part. An insignificant contribution to the excitation function comes from dechanneled protons. The increased yield observed in the plateau region as compared to the yield for random protons is accounted for by a decrease in the electron energy losses of hyperchanneled protons on valence electrons. The estimates give the ratio $(dE/dx)_{(0001)} / (dE/dx)_{random}$ to be 0.64. The greatest γ-quantum yield is realized in the region of the first bundle of proton trajectories.

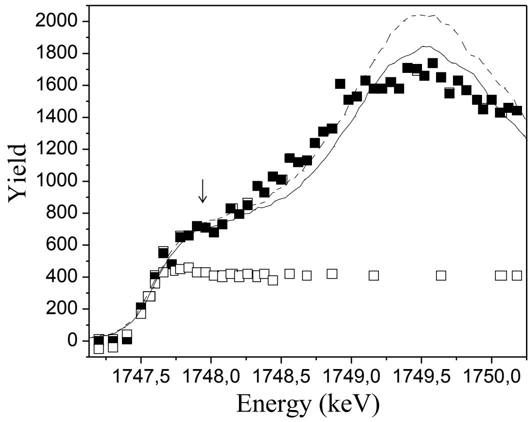

Fig. 3. *$^{13}C(p,\gamma)^{14}N$ reaction yield vs proton energy*

The simulation program used here takes into account the thermal vibrations of impurity atoms in the transverse plane of the (0001) channel in the harmonic approximation. Numerical calculations have pointed (Fig. 3) to the existing dependence of the reaction yield at the maximum of the excitation function on the r.m.s. amplitude of thermal vibrations of ^{13}C atoms. As the amplitude of ^{13}C vibrations grows the γ-quantum yield drops. The best agreement between the measured data and the calculations was obtained at the thermal vibration amplitude equal to 0.102 Å.

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МЕТОД ИЗОЛИРОВАННОГО РЕЗОНАНСА И ЭЛЕКТРОННЫЕ ТОРМОЗНЫЕ ПОТЕРИ ЭНЕРГИИ ГИПЕРКАНАЛИРОВАННЫХ ЧАСТИЦ

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Изолированный резонанс ядерной реакции на примесных атомах внедрения использован для изучения ориентационных эффектов. Показано, что этот метод позволяет получить лучшее энергетическое разрешение по сравнению с другими методами. Резонанс реакции $^{13}C(p,\gamma)^{14}N$, при энергии протонов 1,7476 МэВ, использовался для исследования распределения потока протонов в плоскостном канале (0001) монокристаллического раствора Re-0,4 ат.%^{13}C. Установлены особенности выхода γ-квантов реакции в зависимости от энергии. Измерены электронные потери энергии гиперканалированных протонов. Показано, что выход γ-квантов реакции, возбуждаемой каналированными протонами, зависит от амплитуды тепловых колебаний атомов углерода.

МЕТОД ІЗОЛЬОВАНОГО РЕЗОНАНСУ ТА ЕЛЕКТРОННІ ГАЛЬМОВІ ВТРАТИ ЕНЕРГІЇ ГІПЕРКАНАЛЬОВАНИХ ЧАСТИНОК

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Ізольований резонанс ядерної реакції на впроваджених атомах домішок використано для вивчення орієнтаційних ефектів. Показано, що цей метод дозволяє одержати краще енергетичне розрізнення у порівнянні з іншими методами. Резонанс реакції $^{13}C(p,\gamma)^{14}N$, при енергії протонів 1,7476 МеВ, використовувався для дослідження розподілу потоку протонів у площинному каналі (0001) монокристалічного розчину Re-0,4 ат.%^{13}C. Встановлено особливості виходу γ-квантів реакції в залежності від енергії. Виміряно електронні втрати енергії гіперканальованих протонів. Показано, що вихід γ-квантів реакції, що збуджується канальованими протонами, залежить від амплітуди теплових коливань атомів вуглецю.