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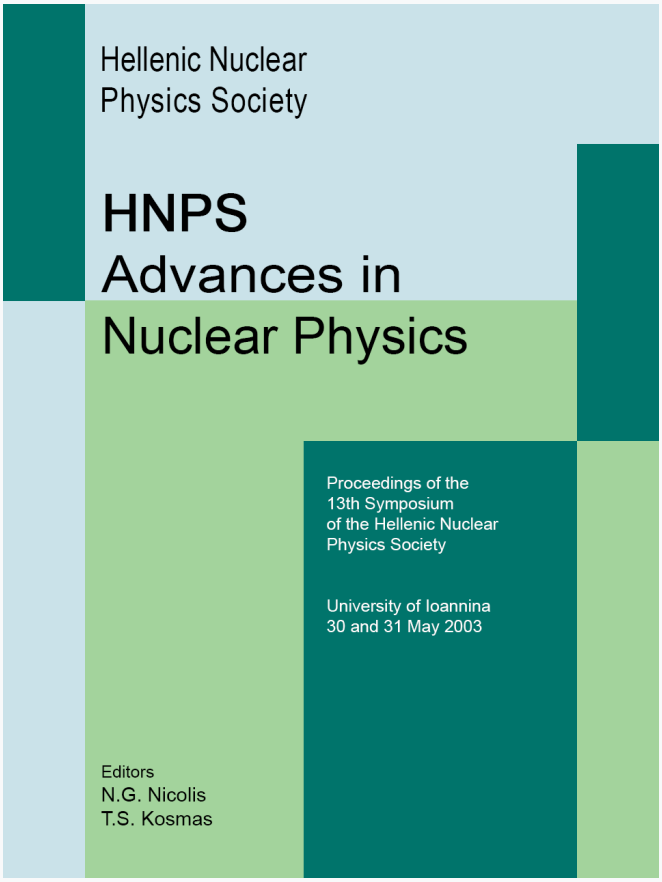

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Measurements of energy loss of charged particles traveling in crystalline materials along the channeling direction

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Abstract

A method for determining the energy loss and mean dechanneling distance of light charged particles traveling along a low index axis of a crystal in the backscattering geometry, is presented. The method is based on nuclear resonance reactions which act as a marker for the range in the backscattering spectra. Computer simulations based on the assumption of an exponential rate of dechanneling of the incoming particles in the crystalline material, are in good agreement with measured spectra. The results of applying this method to protons and alphas in crystals of Si, SiO_2, SiC and MgO are discussed and possible improvements are indicated.

Introduction

As observed from the early 1960's [1, 2], the energy loss of charged particles channeled along a low index axis of a crystal, is only a fraction of the corresponding one in a random direction of incidence. This was explained by Lindhard [3] by means of the channeled particles traveling in a region of low charge density and thus suffering only a portion of the normal energy loss. According to this theoretical treatment, a value of 0.5 is expected for α, the ratio of energy loss for channeled versus randomly incident particles. Most of the experiments carried out in the past in the transmission geometry for a variety

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of crystals, reported values for α ranging between 0.3 and 0.7 [4, 7]. In these experiments, the energy loss of the "best channeled" particles is determined by measuring the final energy of the transmitted ions through thin crystals. This method, however, is based on the preparation of homogeneous self-supported thin crystals and cannot easily be used in material analysis, where thick crystals are studied mainly in the backscattering geometry. In addition, the values of α determined in transmission experiments are expected to be lower than those determined in backscattering geometry, since the latter represent the average of the ratios between highly and poorly channeled particles, while accurate knowledge of α, for different crystals is important for both basic physics studies as well as rapidly growing applications.

Following the pioneer works of refs [8-11], a new technique has been developed recently [12], which can be applied "in situ", to simple and more complicated crystals, without any special preparation of the target. It is based on the use of Channeling/RBS and nuclear resonance reactions, which act as a marker for the determination of range of the beam particles in the target material. In order to fit the recorded spectra, a computer simulation program has been developed, based on reaction cross sections and on the assumption of an exponential rate of dechanneling of the incoming particles in the crystalline material. The results are compared to measured spectra in the cases of low energy protons and alphas incident on crystals of Si, SiO_2, SiC and MgO [12,15].

Experimental Procedure

The experiments were performed using the 5.5 MV Tandem Accelerator at N.C.S.R. 'Demokritos', Athens, Greece and the 3 MV TANDETRON Accelerator at Forschungszentrum, Rossendorf, Dresden, Germany. Protons and alphas were accelerated to energies 1.7-2.5 and 3.0-3.5 MeV, respectively and were led to high accuracy goniometer chambers. The detection system consisted of a single Si surface barrier detector placed at an angle 160^0 and 170^0, respectively in the two laboratories. Before the measurements, a polar and an angular scan had to be performed in order to align the beam to the axis of the crystal.

Spectra of backscattered protons or alphas were then taken in random and aligned angles of incidence in the energy ranges where the beam particles exhibit resonances with the target material. In the case of protons on Si, SiO_2 and SiC, the $^{28}Si(p,p)^{28}Si$ reaction was

used, which exhibits two sharp resonances at proton energies 1.67 and 2.09 MeV, as well as the $^{12}C(p,p)^{12}C$ with a strong resonance at 1.75 MeV. In the case of alphas on SiO_2 and MgO, the $^{16}O(\alpha,\alpha)^{16}O$ reaction was used, which exhibits two sharp resonances at lab energies 3.04 and 3.37 MeV. The compound elastic process interferes with the Rutherford scattering process, producing the constructive maxima or destructive minima observed in the spectra of the backscattered beam particles. As an example, experimental spectra for protons on Si and SiC as well as alphas on SiO_2 are shown in Figs. 1a, b, c, respectively, for both random and channeling directions. It is seen that, depending on the beam energy, the resonance peaks appear clearly when they are excited close to the surface of the crystalline target or they are smeared out when they are excited deeply into the crystal. It is also seen that the interference maxima and minima of the resonance peaks in the aligned spectra are shifted to the inside of the crystal due to the lower energy loss. Thus the resonance peaks can play the role of a good marker for the range in the simulations of the spectra.

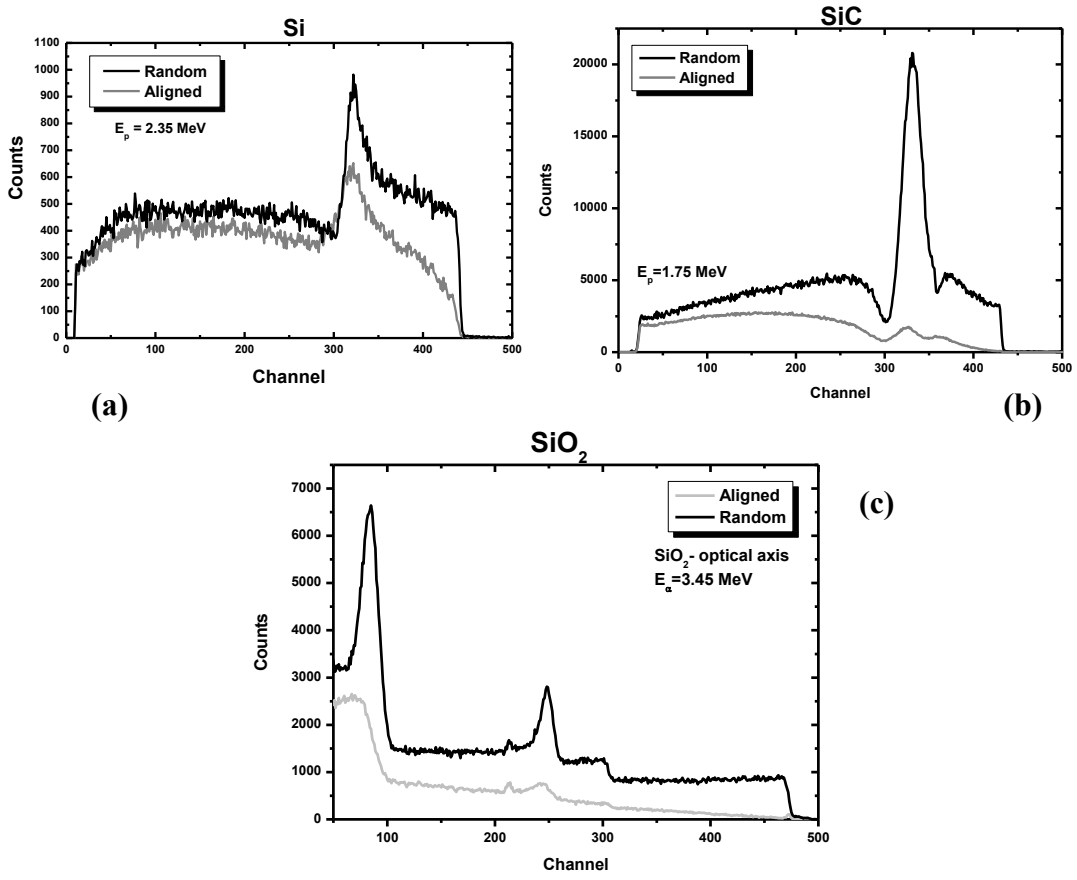


Fig. 1. *Experimental RBS/C spectra for protons on Si (a) and SiC (b) as well as alphas on SiO_2 (c), for both random and aligned modes, at energies where resonances are excited. In*

case (c), both resonances of $^{16}O(\alpha,\alpha)^{16}O$ are exhibited (around channels 70 and 250), while the weak peak between them is due to carbon build up during the experiment.

Data analysis

For the simulation of the energy spectra a program was written [12] which divides the target into slices, of typical thickness ~5μg/cm^2, and splits the beam into a channeled and a dechanneled component which is assumed to increase exponentially with depth x according to the expression $N(x)=N_o(1-e^{-x/\lambda})$. N_o is the number of beam particles initially in the channel at the surface of the target, N(x) is the number of dechanneled beam particles at a distance x inside the target and λ is the mean dechanneling length and is treated as a parameter. Then it follows the evolution of the two components of the beam through the slices inside the target. At each slice the aligned component loses energy at a rate of α times that of the random component, which is taken from Ziegler et al. [16]. The parameter α should lie in the range $0<\alpha<1$ and has to be determined by fitting the experimental data. The dechanneled part of the beam undergoes nuclear reactions governed by the reaction cross section at the specific energy with which the beam particles enter at each slice in the random direction. The number of particles backscattered to the detector direction are transported into the crystal assuming random energy loss and a simulated aligned spectrum is generated and compared to the experimental one. For the simulated spectra the accurate knowledge of the elastic cross sections for the reactions $^{28}Si(p,p)^{28}Si$, $^{12}C(p,p)^{12}C$, $^{16}O(p,p)^{16}O$, $^{16}O(\alpha,\alpha)^{16}O$, $^{28}Si(\alpha,\alpha)^{28}Si$ and $^{24}Mg(\alpha,\alpha)^{24}Mg$, which are excited in the various targets used in the present work, is mandatory. The excitation functions of these reactions for the energy range and the laboratory angle in consideration, were taken from the literature, or were extracted from the deconvolution of the corresponding random orientation experimental data [12]. An automatic search for the parameters α and λ is also carried out by using the MINUIT minimization code to yield the best fit to the experimental data. Simulations of channeled spectra in the cases of protons on Si and SiC as well as alphas on SiO_2 are shown in Figs. 2a, b and c, respectively, as solid lines. They are seen to be in good agreement with the experimental points even in the case of the two resonance structures for C and Si appearing in SiC.

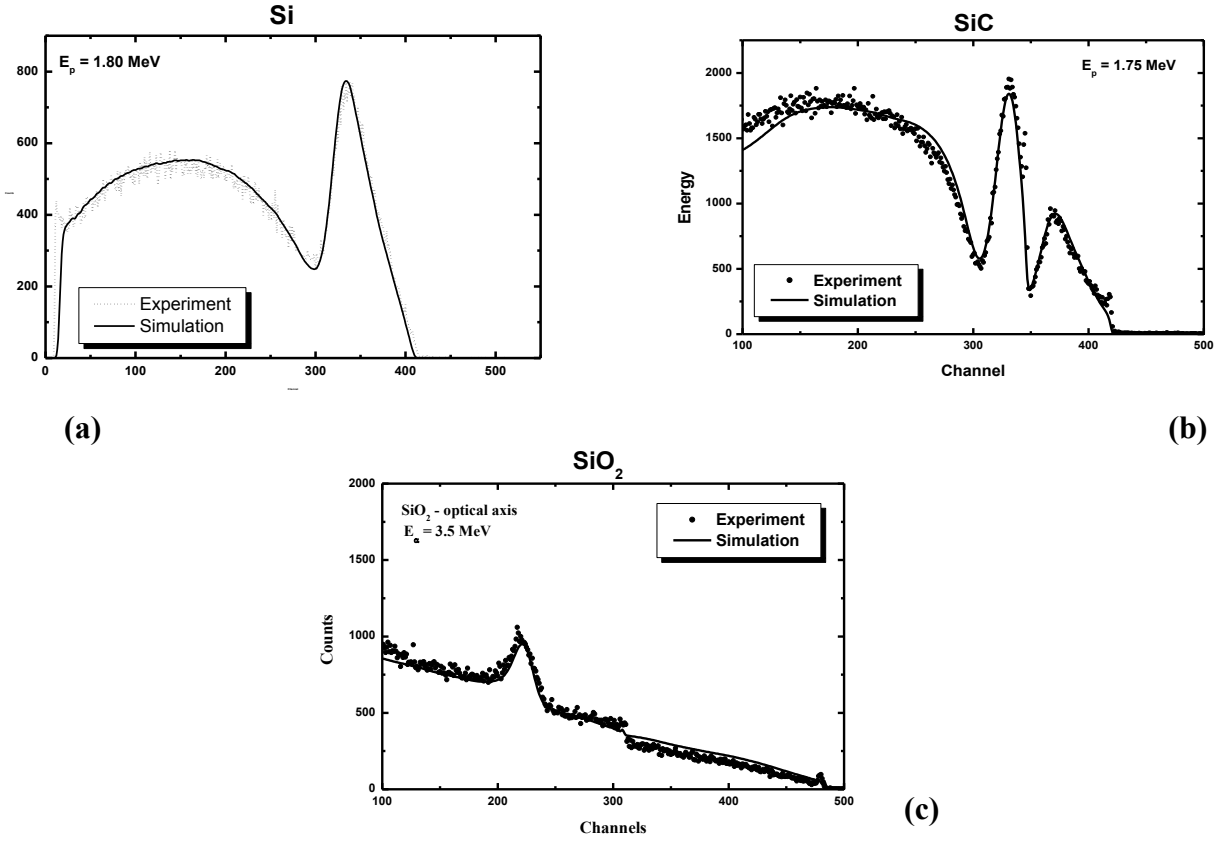
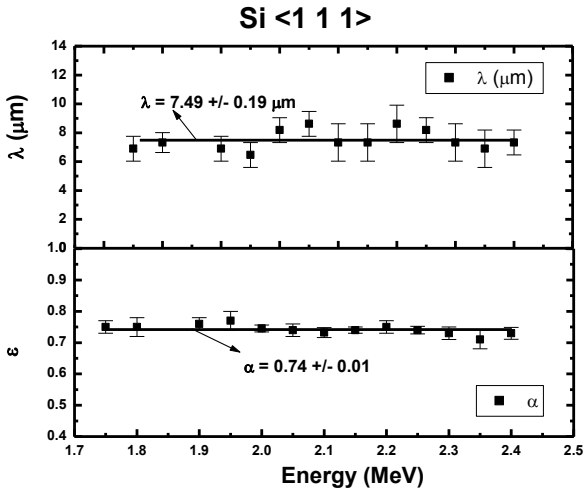


Fig.2*. Experimental and simulated channeling spectra at energies where resonances are excited between beam and target nuclei.*

Discussion of the results

Experimental random and aligned spectra of the beam particles backscattered into the Si detector were taken at ~10 different energies in the region of interest for each combination of beam and target isotopes. By fitting these spectra, the values of α and λ, giving the best χ^2 minimization, were determined for the energy interval under consideration in each reaction. In all cases the two parameters did not show any particular trend with regard to energy dependence. Typical results are shown in Fig. 3 for the case of protons on Si cut at the <111> axis. The values of the two parameters in the energy interval 1.8-2.4 MeV, produced an average of α= 0.74±0.01 and λ=7.49±0.19μm. Similarly, values

of α and λ were extracted by fitting the experimental data of other combinations of beam particles traveling along crystal axis in various crystalline materials. The results are shown



in Table I.

Fig. 3. *The dechanneling parameters α and λ as functions of energy in the case of protons on Si cut at the <111> axis.*

Table 1

crystal	**ORIENTATION**	**BEAM**	**ENERGY (MeV)**	**α ± δα**	**λ ± δλ (μm)**
Si	*[110]*	*p*	*1.7-2.5*	*0.65 ± 0.02*	*N/A*
Si	*[100]*	*p*	*1.7 - 2.5*	*0.69 ± 0.01*	*9.54 ± 0.24*
Si	*[111]*	*p*	*1.7 - 2.5*	*0.74 ± 0.01*	*7.49 ± 0.19*
Quartz	*c-axis*	*p*	*1.7 - 2.5*	*0.71 ± 0.03*	*4.3 ± 0.3*
SiC (4H)	*[0001]*	*p*	*1.7 - 2.5*	*0.74 ± 0.04*	*10.7 ± 0.2*
SiC (6H)	*[0001]*	*p*	*1.7 - 2.5*	*0.79 ± 0.04*	*9.0 ± 0.03*
SiC (15R)	*[0001]*	*p*	*1.7 - 2.5*	*0.82 ± 0.04*	*9.2 ± 0.2*
SiC (21R)	*[0001]*	*p*	*1.7 - 2.5*	*0.81 ± 0.04*	*8.9 ± 0.3*
Quartz	*c-axis*	*α*	*2.9 - 3.5*	*0.81 ± 0.05*	*3.7 ± 0.4*
MgO	*[100]*	*α*	*2.9 - 3.5*	*0.58 ± 0.08*	*4.5 ± 0.9*

Although the two parameters α and λ are not independent, it should be noted here that α is related to the nature of the crystal channeling axis, while λ is much more sensitive and depends strongly on the quality of the investigated crystal axis as will as on the initial beam alignment.

From the results of protons in Si crystals, cut at different crystallographic directions, it can be noted that as the channels get narrower the energy loss gets closer to the random value as α varies from 0.65 for <110> axis to 0.74 for the <111> axis, while the mean dechanneling distance λ.gets shorter. In the case of SiO_2 crystal, studied with protons and alphas, it can be seen that, as expected, the aligned alphas loose energy at a higher rate with respect to the random ones, than the protons and that they have a shorter mean dechanneling distance. In the case of SiC, as more layers are added in the crystalline structure, the aligned protons loose more energy as α varies from 0.74 for (4H) to 0.81 for (21R), while λ gets shorter.

Conclusions

In this paper we present a method for determining, in the backscattering geometry, the energy loss and mean dechanneling distance of light charged particles traveling along a low index axis of a crystalline material. This method is based on the use of resonance reaction cross sections together with an exponential dechanneling process, to simulate backscattering spectra and compare them to the experimental ones. It has been applied to the systems $p+^{28}Si$ at three different crystallographic axis, p+SiC with different number of structures, $p+SiO_2$ as well as $\alpha+SiO_2$ and α+MgO, and has given satisfactory results. In this approach, the dechanneling process is defined by only two parameters, the average ratio, α, of stopping powers in the channeling and random directions (over the energy range in which the particle travels inside the channel) and the mean dechanneling distance, λ. This technique allows *in situ* measurements and can be applied to several bulk single crystals (simple or compound) without any particular sample preparation, provided that the beam particles exhibit a resonance with the target nucleus, in order to extract reliable parameters from the data fitting procedure.

It should be mentioned, however, that when we are dealing with alpha or heavier beam particles and with more complex crystals, such as Al_2O_3, the reproduction of the experimental data is not satisfactory. There are strong indications that a more complicated

dechanneling function is needed to describe the behavior of heavier charged particles in crystals. This project is currently under investigation.

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