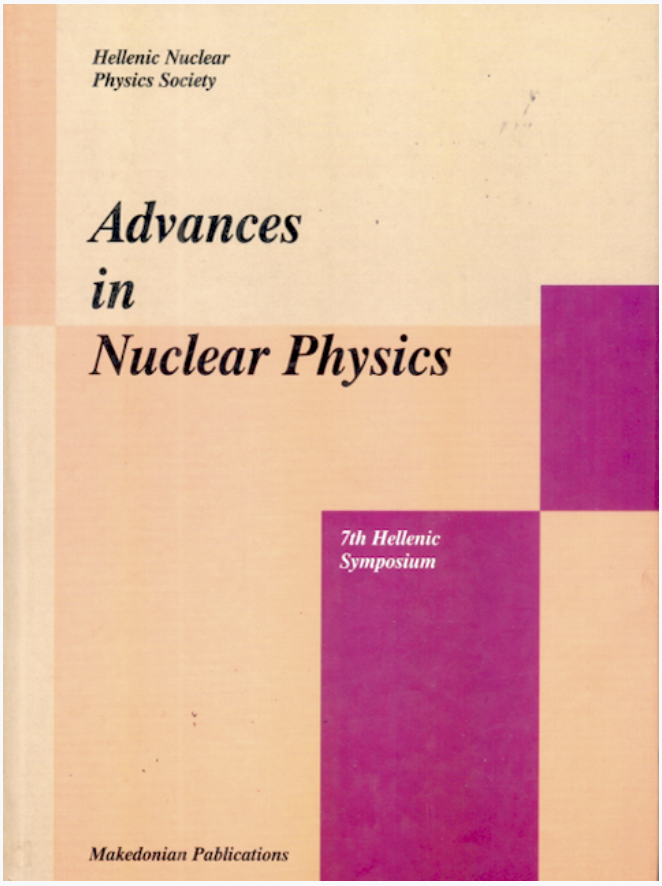
HNPS Advances in Nuclear Physics

Vol 7 (1996)

HNPS1996



A Method of Determining Channeling Parameters in Backscattering Geometry

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doi: 10.12681/hnps.2408

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Abstract

The energy loss of channeled protons in silicon has been measured in the past in the transmission geometry and was found to be approximately half of the normal loss, thus confirming the equipartition rule. Other measurements however, concerning different crystals (e.g. Ge), deviated from this theory. In the backscattering geometry, the most successful corresponding attempts combined RBS with the nuclear resonance phenomenon. Nevertheless, they involved either considerable additions to the standard goniometer setup commonly used, or tedious Monte-Carlo calculations, thus limiting their applicability. In the present work, a method for the determination of the energy loss and dechanneling probabilities of axially channeled protons in silicon [100], in the energy range Ep = 1.7-2.6 MeV, is presented. It is carried out in situ, using the same experimental setup and beam properties (size, divergence) with the ones present in the actual analysis of a sample. The results obtained are in good agreement with already existing values in literature.

1 Introduction

Several experiments have been carried out so far to establish the energy loss of channeled particles. The first measurements of this sort were carried out on thin silicon targets in the transmission geometry [1] and the experimental energy loss was found to be approximately half of the normal loss (incurred in a randomly oriented crystal), and so to confirm the equipartition rule [2]. Nevertheless, other experiments carried out with different crystals (such as Ge), using the same geometry, deviated from this theory [3]. In all the above

mentioned measurements, the determined quantity was the average energy loss of the so called best channeled particles. Such particles move far from the lattice nuclei in the region of low electron density and thus their energy losses are substantially less than the poorly channeled ones.

Recently, another experimental design has been used, in which the energy spectra of particles backscattered by a thick single crystal are registered. These measurements provided reliable numbers for practical purposes but they involved either considerable additions to the standard goniometer set-up commonly used, or tedious Monte-Carlo calculations, thus limiting their applicability. In these experiments the energy spectra measured with a crystallographic direction aligned to the incident beam are formed by particles dechanneling at different depths. The most successful of the above mentioned attempts were the ones using the nuclear resonance phenomenon, combining the RBS data with those of the $^{27}Al(p, \gamma)$ reaction [5], the $^{19}F(p, \gamma)$ reaction [6], or the $^{28}Si(p, \gamma)$ one [7].

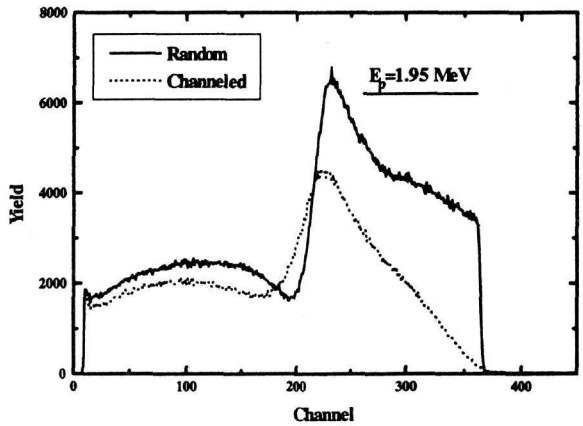

FIGURE 1. Random and channeling spectra of Si [100] at Ep = 1.95 MeV. The change of the resonance shape and the shift of the minimum are clearly visible.

In the present work a method of analyzing RBS spectra is presented in the energy range of proton resonances in ^{28}Si, allowing an estimation of the energy losses of channeled protons in situ, using the same experimental setup and beam properties (size, divergence) with the ones present in the actual analysis of the sample. The obvious advantage in this case is that since the channeling parameters are very sensitive, depending on the quality of the target, the energy and the collimation of the beam, the ambient temperature and the very nature of channeling (axial or planar), the method can be customized to provide reliable results in any experimental setup and it can be extended to other projectile-target combinations.

2 Experimental setup

The experimental setup at N.C.S.R. Demokritos includes a goniometer system (RBS-400 by Charles Evans and Associates) which permits experiments for backscattering spectroscopy in the case of oriented or non-oriented crystalline targets [12].

The proton beam was well collimated and the beam spot dimensions remained almost unchanged during the measurements (1.5 × 1.5 mm^2 with a variation of 10% at the most). The crystal was of average quality, showing a surface χ_{min} of approximately 5% for the analyzed energy range.

3 Principle of the method

The cross section for elastic scattering of protons shows two strong resonances in the energy range into consideration (Ep = 1.7-2.6 MeV) at Ep = 2.09 MeV and at Ep = 1.67 MeV with corresponding natural widths of 52.0±0.8 and 15.6±0.6 keV (8). In fig. 1, a typical backscattering spectrum is shown where in the random case the interference pattern between nuclear and Rutherford scattering can be observed [7, 8]. The interference minima, which will be the focus of the present work, occur at Ep = 2.07 MeV and Ep = 1.62 MeV respectively and appear shifted towards lower energies in the channeling geometry. The motion of a proton originally channeled, as shown in fig. 2, can be described as follows: The proton moves within the low electron density channel for a length ℓ losing energy at a rate $S(E)_{ch}$. The energy of the proton of initial energy Eo at the point of dechanneling (A) can be described in general by the following equation:

$$E_\ell = E_o - \int_0^\ell S(E')_{ch}\, dr \quad (1)$$

where $E_\ell \leq E \leq Eo$.

Using the quantity ε, defined [10] as the ratio of the average stopping power in the channel to the one in the amorphous medium:

$$\varepsilon = \frac{\overline{S}(E)_{ch}}{\overline{S}(E)_r} \quad (2)$$

and replacing the integral with the average value $\overline{S}(E')$the equation finally becomes:

$$E_\ell = E_o - \varepsilon \cdot \overline{S}(E')_r \cdot \ell \quad (3)$$

Assuming an exponential decay law with depth for the intensity of the channeled beam, the dechanneling distance ℓ can be related to the decay constant λ as follows [6]:

$$\ell = -\lambda \cdot ln(\tfrac{1-R}{Io}) (4)$$

where: Io = fraction of initially channeled protons and R = ratio of the integrated channeled to random spectra over the same energy region.

After dechanneling, the particle moves on along the same direction (the small angle of dechanneling can be ignored for all practical purposes) for a distance x, but now in a medium considered to be amorphous, until the backscattering occurs. The motion of dechanneled particles can be subsequently described by equations derived for the case of amorphous targets [9].

Thus, the depth D_{Rmin}, at which the resonance minimum is observed, can be expressed, according to the above arguments, as:

$$D_{Rmin} = x + \ell = \int_{E_\ell}^{E_{Rmin}} \frac{dE}{S(E'')} - \lambda \cdot ln(\tfrac{1-R}{Io}) (5)$$

where E_{Rmin} the energy of the interference minimum and $E_{Rmin} < E < E_\ell$. If we replace the integral with the average value of the stopping power $\overline{S(E)}$, the above relations can be simplified and combined as follows:

$$D_{Rmin} = \frac{E_{Rmin} - E_\ell}{\overline{S}(E'')} - \lambda \cdot ln(\tfrac{1-R}{Io}) \Rightarrow$$

$$\Rightarrow D_{Rmin} - \frac{Eo - E_{Rmin}}{\overline{S}(E'')} = -\left(1 - \varepsilon \frac{\overline{S}(E')}{\overline{S}(E'')}\right) \cdot \lambda \cdot ln(\tfrac{1-R}{Io}) (6)$$

Close to the target's surface, where $\overline{S}(E') \;/\; \overline{S}(E'') \simeq 1$, the relationship is linear with slope equal to $-(1-\varepsilon)\cdot\lambda$. We can therefore use the experimental points close to the surface for an approximate determination of this product.

4 Results and discussion

Dividing the aligned spectra channel by channel with the random ones, the function χ(x) is obtained. The part containing the resonance region is excluded (fig. 3) and the remaining points are fitted with an exponential function of the form: $\chi(x) = Io.(1-e^{-x/\lambda})$. For the energy range into consideration, the decay constant was found to vary between 7.5±0.2 and 8.4±0.2 μm (fig. 4), showing that the initial beam divergence was roughly constant. For the analysis we used the value: $\overline{\lambda} = 8.1 \pm 0.2$ μm.

It should be noted that the most striking difference between the random and

channeled spectra is the shape of the peaks. In the random case the shape of the peak still resembles the shape of the thin target yield as presented in the literature [8]. In the axial case [100], which is analyzed in the present work, the broadening is much larger. Another effect is the progressive shallowing of the minimum that preceded the peak in the random spectrum, which is caused by particles with a lower energy loss on their incoming trajectories. The resonant shapes are further broadened with increasing initial energy, mainly due to the energy straggling, since the shapes appear at greater depths. It is also important to note the ever increasing contributions from particles continuously dechanneling along the way till they reach the resonance energy, with the two extreme cases being particles dechanneled initially at the surface and particles dechanneling immediately before reaching the resonance energy. With the use of the mean channeling distance we average over the different trajectories.

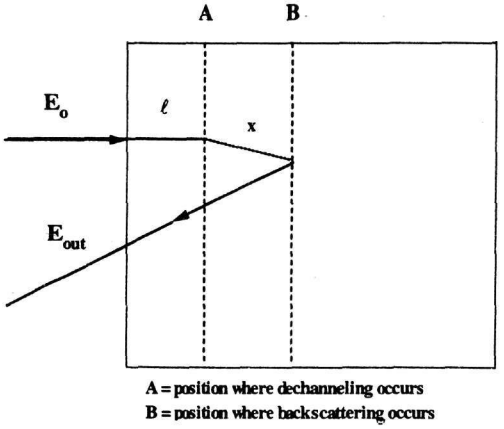

FIGURE 2. Diagram showing the scenario of the proton movement inside the silicon target.

If we constrain the analysis to initial energies relatively close to the energy of each resonance, meaning that the corresponding resonance shape appears at a depth of a few microns at the most, we can ignore the straggling factor. For these depths it can be assumed that since the maximum appears at the same channel -due to the strong contribution of the initially dechanneled particles of the beam, the whole information of the channeling procedure is contained in the change of the position of the minimum. The position of the resonance minimum in the random spectra can be used with a RUMP-like program to recalibrate the energy scale of the MCA into a depth scale. Thus, the position of the correponding minimum, D_{Rmin}, from the channeled spectra can be calculated , under the assumption that the backscattered particles exit the crystal in a random direction.

The corresponding fractions R are determined by integrating over the entire range of the resonance up to 3σ, thus for 98% of the energy region where the resonant term in the total cross section is dominant. The total error in R

(including statistical error of experimental data and systematic error due to the method of integration adopted) is estimated to be of the order of 10%. After the extraction of the experimental quantities involved in eq. 6, the values of the modified distance $D_{Rmin} - [(Eo - E_{Rmin}) / \overline{S(E)'}]$ versus the modified logarithm $-\ln[(1-R) / Io]$ can be plotted as shown in fig. 5, including experimental points from both resonances. The offset of the line is very close to zero (0.09 ± 0.16), demonstrating the validity of our hypothesis near the target surface. The inclination of the line, determined with the least squares fit method assuming weighted errors in both individual parameters, was found to be 2.8 ± 0.4 μm, leading to a value of $\varepsilon = 0.64 \pm 0.07$, in good agreement with the transmission experiments. For the corresponding mean stopping powers, standard values from literature have been used [10].

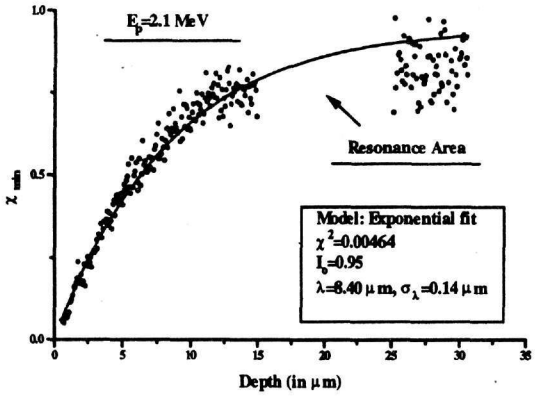

FIGURE 3. A typical spectrum at Ep = 1.7 MeV, showing χ as a function of depth (with the use of RUMP for the depth calibration of the MCA) with the appropriate exponential fit following the exclusion of the interference region where great anomalies in the ratio occur.

5 Conclusion

This method offers a simple tool for the determination of the average channeling energy losses of protons in a silicon bulk target. The results are obtained in situ for the crystal into consideration and no complicated mathematical analysis is required. The value of ε extracted can be subsequently used in a RUMP-like program for elemental analysis in channeling geometry. It is believed that it can be applied to other projectiles, namely α-particles in silicon [11], as well as in more complicated crystals, such as Al_2O_3 and MgO.

Nevertheless, due to all the analyzed arguments, it is evident that at greater depths the simplified hypothesis cannot reproduce the experimental data, the linearity is lost, and the method used for the integration fails. A detailed

simulation would have to take into account the different impact parameters, different trajectories, energy and spatial straggling, thermal effects, initial divergence of the beam as well as the total cross section for the whole spectrum. An interesting attempt presented recently [7], clearly demonstrates the difficulties and compromises in accuracy one should tolerate if such a task is undertaken. It is believed that a lot of fine and complex details need to be studied before a standard method for the analysis of any sample in channeling geometry is established.

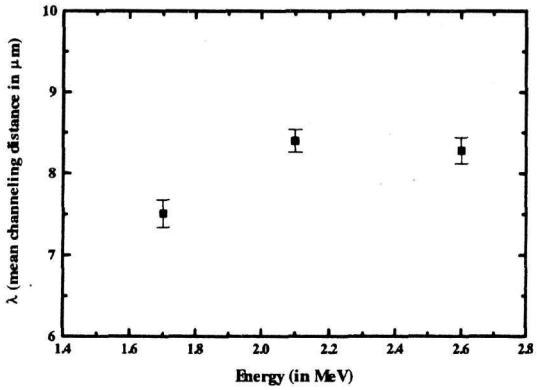

FIGURE 4. Mean channeling distance at Ep = 1.7, 2.1 and 2.6 MeV, showing that λ varies insignificantly for the energy range into consideration.

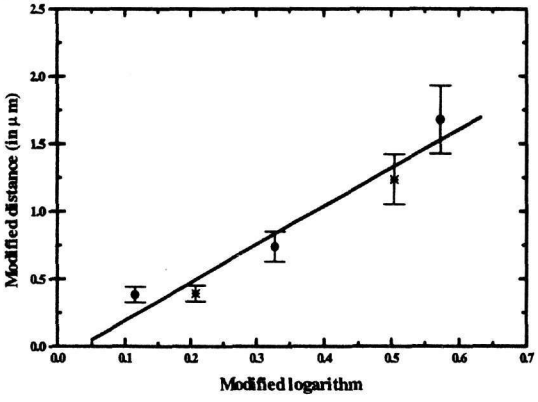

FIGURE 5. Plot of the modified distance (eq. 6) versus the modified logarithm using the experimental points at Ep = 1.7, 1.75, 1.8, 2.15, 2.2 MeV for the linear fit (• → points from the resonance at 1.67 MeV, * → points from the resonance at 2.09 MeV).

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