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Range of Medium and High Energy Protons and Alpha Particles in NaI Scintillator

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Abstract: We have calculated the range of proton and alpha particle in NaI scintillator which is a commonly used substance in scintillation detector manufacturing. The stopping power of proton and alpha particle in NaI is calculated first by using the theoretical treatment of Montenegro *et al*.[1]. The range calculation has been performed by using a technique that we developed in the earlier works[2,3]. We compared the results with Monte Carlo simulation program SRIM2003 and PRAL[4]. The obtained results are in satisfactory agreement with the literature.

Key words: NaI Scintillator, Range of Protons, Alpha Particles

INTRODUCTION

A scintillator material is that it converts energy lost by ionizing radiation into pulses of light. For most scintillation counting applications, the ionizing radiation is in the form of X-rays, γ-rays and α- or β-particles ranging in energy from a few thousand electron volts to several million electron volts. Sodium Iodide Thallium doped, NaI (Tl) offers a good compromise for all these specifications but has a low stopping power. It is the most widely used scintillator. For protons with energies of the order of 50 MeV, the response of NaI (T1) crystals is linear[5]. Therefore, NaI scintillators can also be used for energy measurements of proton beams. The response of protons in a NaI (T1) crystal was studied by Romero *et al*.[6]. They parameterized the differential light output as a function of the stopping power using the results of various measurements.

In the present work, we aimed to find penetration depth of protons and alpha particles by combining a suitable stopping power mechanism with the ion range calculation method. We used the electronic stopping power of Montenegro *et al*.[1] as an input quantity. We applied the technique from a previous work[2,3] to calculate proton and alpha particle ranges in NaI scintillator.

Theory: In calculating the ion ranges in solid targets, there are numerous techniques and calculation methods[8,9]. Among these techniques, one method was improved by Biersack for slowing down of ions in matter based on the analysis of the directional angular spread of ion motion as a function of energy[16]. Although this method has been widely used since 1982, it was Bowyer *et al*.[10] who revised the Projected Range Algorithm (PRAL) and called this new set of equations to be Kent Range Algorithm (KRAL). Kabadayi *et al*.[2,3] studied one of the KRAL equations by an approximation. In this approach, the second order ODE is reduced to the first order by dropping off the second order derivative. Then the first order differential equation, Eq. 1, is combined with a simple the electronic stopping power formulation of Montenegro *et al*.[1]. The first order differential equation to be used in the range calculation is the following:

$$\left(S_t-\frac{\mu Q_n}{2E}\right)\frac{d\overline{R_p}}{dE}-\left(-\frac{\mu S_n}{2E}+\frac{(1-2\mu)\,Q_n}{8E^2}\right)\overline{R_p}=1 \qquad (1)$$

In this equation, $\overline{R}_p$ stands for the projected range, E is the initial ion energy and $\mu = M_2/M_1$ where M_1 is the ion mass and M_2 is the target mass. S_n and S_t stand for the nuclear stopping power and the total stopping power, respectively. Q_n is the second moment of the nuclear energy loss and $\mu = M_2/M_1$.

We solved Eq. 1 by using higher order Runge-Kutta numerical solution method by the use of the built-in functions in Maple 8 symbolic computation program. In order to solve an Eq. 1 numerically, the coefficients of differential equation must be determined. These are mainly given by the electronic energy loss, nuclear energy loss, the second moment of nuclear energy loss. For calculating the electronic stopping power S_e, the formulas derived by Montenegro *et al*.[1] for ions moving in solid targets at non-relativistic velocities were used. These formulas differ from those used by Ziegler *et al*.[9] applied to PRAL and also from those previously used by Bowyer *et al*.[10] applied to KRAL. This formula can be applied in a wide energy range with a single expression and are easy to handle. However, Ziegler's electronic stopping power expression consists of different formulas for various energy regions and a number of fitting parameters which is a time consuming process in the calculation.

The charge state of the projectile during the energy loss procedure have been studied and has an extensive literature[1,11-13]. As the ion moves through the medium certain events such as excitation, charge exchange,

ionization to occur. At high energies, ionization is the main source of energy loss, however other processes such as electron capture and loss and excitations becomes important at low energies. As the Montenegro formula combines of all the probabilities from low, medium and high energy regions, it takes into account all of contributions depending on the velocity of the particles. Thus, this technique can be used even for the slow ions since Montenegro formula that we used in our calculations is designed for all energy regions and consider contributions from all energy loss mechanisms[1].

Bragg's Rule: Bragg's rule which states that the stopping power of a compound may be calculated by the linear combination of the stopping power of the individual elements is used to find the stopping powers in multi element targets[15]. We applied Bragg's rule to find the stopping powers and the second moment of the stopping powers in NaI. There is another method to find the stopping powers in a diatomic target. In this technique, an artificial single element is formed by taking averaged atomic numbers and averaged atomic mass of the elements in a compound. Bowyer *et al*.[10] showed that Bragg's rule is superior to the average atomic number technique. However, Bragg's rule was applied only to the electronic stopping in PRAL. Therefore, in the present work, Bragg's rule was applied to all stopping powers. By using Bragg's rule input quantities which are the coefficients of (1) can be found as follows: The nuclear and electronic stopping power from diatomic NaI target is found first by adding stocihiometrically weighted stopping powers of each element. Then the total stopping power in the compound is obtained by adding the electronic and nuclear stopping powers obtained for the compound. The same method applies to the nuclear energy loss moment Q_n in order to find the value of Q_n in NaI scintillator[3].

Numerical Calculation: The program is coded in Maple8 symbolic computation platform and built-in functions of Maple 8 is employed to solve the equation numerically. There are various numerical solution techniques to solve Eq. 1 numerically. Bowyer *et al*.[10] an employed iterative refinement technique based on the method developed by Winterbon[16] and a variable step ODE solver based on Adam's method to calculate the ranges of ions in solids by using their modified set of equations.

In our technique we applied higher order Runge-Kutta Method to solve Eq. 1 numerically[2,3]. The numerical solution of (1) is, in principle, the solution of an initial value problem where the initial conditions must be well defined. In order to find initial conditions, we employed the same method as that proposed by Biersack[8] in the low energy region. In the first step of the calculation, our algorithm calculates the electronic stopping power, the nuclear stopping power and the nuclear energy loss straggling. These results are then used to determine the coefficients of the differential equation at numerical solution. Afterwards, high order Runge-Kutta solver is applied to find the numerical solution of Eq. 1.

RESULTS AND DISCUSSION

The comparisons with literature in the range of high energy protons and alpha particles in NaI scintillator are presented. The results of this work with respect to the range of protons are compared with the results calculated from PRAL[4] and SRIM2003 (TRIM part)[4]. In order to find PRAL results, we employed SRIM2003 package. In the main menu of the SRIM2003 package program, we choose "Stopping and Range Tables" section to generate PRAL results and computer generated a list of stopping and range values. The results referred as SRIM2003 is calculated by choosing "TRIM calculation" section in the main menu of SRIM2003 package. For the data evaluation and SRIM2003 calculations we have assumed that the atomic density of NaI target is 3.67 g cm^{-3}. We performed SRIM2003 calculations for 2000 ions per simulation.

Figure 1 is a plot of the range versus the incident proton energies for NaI target. The solid curve represents calculated results using our technique and squares show the SRIM 2003 and comparison with PRAL is also given in Fig. 1.

As it is shown in Fig. 2, there is a satisfactory agreement between the calculated ranges and other methods. This comparison shows that SRIM and PRAL give similar results; however, our results somewhat differ from these results. The deviations are energy independent and random. We found this level of agreement with literature even with the simplifications that we employed in the current work. However, the reason for the deviation from SRIM is thought to be an effect of inadequate treatment of electronic stopping power in Montenegro formula and neglect of the electron energy loss straggling. Our results for the range are satisfactory for the range of protons and alpha particles implanted into NaI.

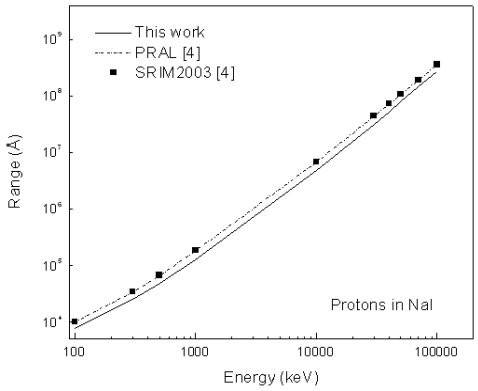

Fig. 1: Comparison of the Calculated Ranges of Protons in Sodium-iodide with SRIM2003 and PRAL for Energies from 100 keV to 100 MeV. The Solid Line Represents the Data Calculated by the Present Method

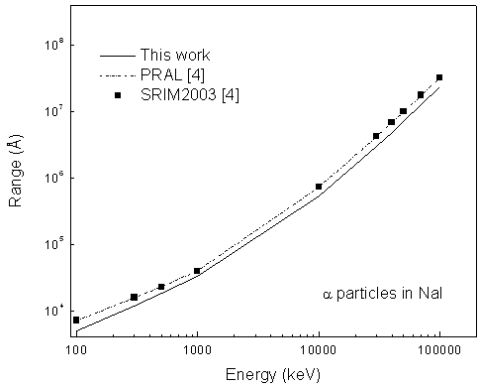

Fig. 2: Comparison of the Calculated Values of the Range with SRIM2003 and PRAL for Alpha Particles Implanted into NaI at Energies between 100 keV and 100 MeV. The Solid Line Represents the Results of this Study; the Squares Represent the SRIM2003

The electronic energy loss straggling Q_e that we neglected in this work is expected to contribute to the range of higher energies. The deviations of our data from SRIM was random and energy independent (e.g., the deviations did not increase with increasing energies). Therefore, we think that the main reason for the deviations from SRIM is inadequate treatment of the electron energy loss S_e. Although the electron energy loss formula that we employed is easy to handle and consist of a single expression for a wide energy interval, it sacrifices numerical accuracy if one assumes that SRIM program produces better results.

We made above comparisons with respect to the SRIM calculations since we have not found any experimental data in the literature for the range of protons and alpha particles in NaI scintillator. The differences are energy independent and of the order of 35% for protons and alpha particles when compared with SRIM.

CONCLUSION

This work presents the results of the range calculation for protons and alpha particles in NaI scintillator. We have used the author's method from a previous work[2,3] to calculate the mean range of protons and alpha particles. This method based on the solution of a first order ODE's for the easy and efficient calculation of the range of diatomic target materials. Montenegro *et al*. The formula for the electronic stopping power which is valid for all non-relativistic energies allowed us to calculate the ranges of particles for energies from 100 keV to 100 MeV. Although, the Monte Carlo programs calculate ion ranges and angular distributions quite well, the major disadvantage of this method is that it is inherently a computer time-consuming procedure for a large number of ions is required to simulate only for one energy input. The proposed method is simpler and satisfactory when compared with similar procedures in the literature. We have found a satisfactory agreement for the range of ions for wide energy interval with when compared with the results of SRIM. The calculated values of the range of implanted medium and high energy protons and alpha particles in sodium iodide-scintillator have been compared with SRIM and PRAL due to scarcity of experimental data in the literature. The comparison shows that the calculated results are in an agreement for the behavior of range curve. There is a systematic but energy independent deviation from SRIM. The reason for this systematically lower range value is thought to be an effect of inadequate treatment of the electronic stopping power for such a big energy interval.

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