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HEAVY IONS STRAGGLING IN BIOLOGICAL MATTER

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In acest articol este prezentat un studiu sistematic al împrăştierilor laterale şi longitudinale ce apar în procesul de încetinire a ionilor de ^{12}C, ^{16}O şi ^{19}F în materiale de interes pentru radioterapie. Energia inițială a fasciculelor de ioni considerate în această lucrare este selectata pentru a asigura în apa lichidă un parcurs de 19,1 milimetri. Apa lichidă este utilizată ca mediu de referință pentru evaluarea împraştierilor laterale şi longitudinale. Pentru o abordare mai realistă a țesuturilor vii, studiul a fost extins la muşchi şi la os. Imprăştierile specifice au fost evaluate pentru fiecare tip de ion şi țintă. Întreaga abordare are la baza simulările numerice Monte Carlo efectuate cu ajutorul pachetului de programe SRIM.

In the present work it is performed a systematic study of the lateral and longitudinal stragglings occuring in the slowing down of ^{12}C, ^{16}O and ^{19}F ions in materials of interest for radiotherapy. The incident energy of the ion beams considered in the present work were selected in order to ensure in liquid water 19,1 mm range. Liquid water is used as a benchmark for evaluation of the lateral and longitudinal stragglings. To approach more realistic cases the study was extended to muscle and bone. The specific stragglings have been evaluated for each type of ion beam and target. The entire approach employed Monte Carlo numerical simulations based on the SRIM software package.

Key words: Heavy ion straggling, Bragg peak, Monte Carlo simulation

1. Introduction

Cancer is a disease of genes which favours the replication of cells with abnormal speed. Cells affected by this disease are called malignant. Cures have to stop this proliferation by killing malignant cells, but still sparing surrounding healthy tissues. In many cases therapies by using ionising radiations are efficient cures. For many years high energy photons or electrons beams (conventional radiotherapy) have been used with favourable results [1-2].

In irradiation of deep seating tumours the physical limitations of the conventional radiotherapy originate mainly in the depth dose profile with an

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exponential decrease. It produces high energy deposition at the entrance of the body, conducting to undesirable irradiation of the healthy tissues. In order to overcome this problem, charged hadronic beams have been proposed for irradiation [3]. This innovative technique, sometimes called “hadrono-therapy”, is successfully employed in the last decades [4]. It opens the possibility of a precise dose deposition in a well defined region inside the body by an accurate irradiation planning. This planning relays heavily on Monte Carlo simulations of the heavy ion stopping in biological tissues. Although in the first approximation the heavy ion trajectory in matter is a straight line, lateral and longitudinal beam stragglings are relevant effects and must be included in accurate simulations. Both electronic and nuclear processes are contributing to the processes [5-6].

It is the goal of the present study to investigate the magnitude of these straggling effects for ^{12}C, ^{16}O and ^{19}F ions. For the stopping medium, besides the liquid water (benchmark), were selected also real body tissues as muscle and bone. The simulations instrument relies on a Monte Carlo model based on the SRIM computational package [7]. Whenever available, the calculations are compared with adopted data from literature.

After a short description of the basic phenomena occurring at the interaction of the heavy ions with matter (Chapter 2), there are presented the stopping Bragg curves for ^{16}O bombarding water target (Chapter 3) and detailed straggling values for ^{16}O, ^{12}C and ^{19}F ions incident in water and real body tissues (Chapter 4). In the final section (Conclusions) are summarised the main contributions of the paper.

2. Basic phenomena at the interaction of heavy charged particles with matter

The charged particles in their passage through matter lose energy dominantly as a consequence of the excitation and ionization of the atoms and molecules of the medium. Energy-loss mechanisms as ionization and excitation could break chemical bonds and generate reactive species that cause further chemical reactions. In the second order of intensity occur elastic and inelastic interactions with the atomic nuclei of the stopping medium.

The atomic and molecular interactions occur through the Coulomb force between the positive charge of the beam particles and the negative charge of the electrons from the stopping medium. When a charged hadron passes near an electron in the medium, it transfers a small fraction of its momentum to the electron. As a result, the massive particle looses its kinetic energy almost continuously [8].

Several characteristics of the particle-deceleration process are important in understanding their behavior. The first one is the **stopping power** of the medium, a quantity that measures the rate of energy loss per unit distance along the path:

$$S(E) = - dE/dx \qquad (1)$$

At lower energies there are two components of stopping power of ions traveling through matter, electronic (S_e) and nuclear (S_n) stopping power:

$$S(E) = S_e(E) + S_n(E) \qquad (2)$$

Electronic stopping power considers slowing down of the ion due to the inelastic collisions with electrons in the medium. The nuclear stopping power takes into account nuclear elastic and inelastic scattering processes. The electronic stopping power is by far larger than the nuclear stopping power, till the last part of the trajectory where the nuclear becomes dominant [5-6].

The electronic stopping power can be estimated by a semi-classical formula (Bethe-Bloch) as given for example in Ref. [9]:

$$-\frac{dE}{dx} = \frac{4\pi k^2 z^2 e^4 n}{mc^2\beta^2}\left[\ln\frac{2mc^2\beta^2}{I(1-\beta^2)} - \beta^2\right] \qquad (3)$$

where:
$k = 8.99 \times 10^9$ [Nm^2/C^2] – electric constant as defined in Ref. [9]
z - atomic number of the heavy ion
e - electron charge
n - number of electron per unit volume in the stopping medium
m - electron rest mass
c - velocity of light in vacuum
β = v/c – velocity of the heavy ion relative to c
I - mean excitation potential of the atoms in the stopping medium

The average distance traveled by a particle with initial energy E_0 before reaching the thermal energy of the medium (**range)**, is related to *S(E)* by the relation:

$$R(E) = \int_{E_0}^{0} \frac{1}{|S(E)|} dE \tag{4}$$

At very high energies (larger than several hundred MeV/A) the slowing down of all charged particles is strongly affected by bremsstrahlung, Cherenkov radiation and nuclear reactions [8].

Heavy charged particles produce the depth-dose profile closest to the ideal case, a so-called "inverse dose profile" - a slowly increasing energy deposition with the depth, practically constant until near the end of the range, followed by a sharp increase of the dose, and then by a steep decrease (Bragg curve – Fig. 1). The position of the Bragg peak depends on particle energy - the greater the energy, the deeper the Bragg peak is located. By adjusting the energy of the incident beams can be changed continuously the location of their maximum dose deposition.

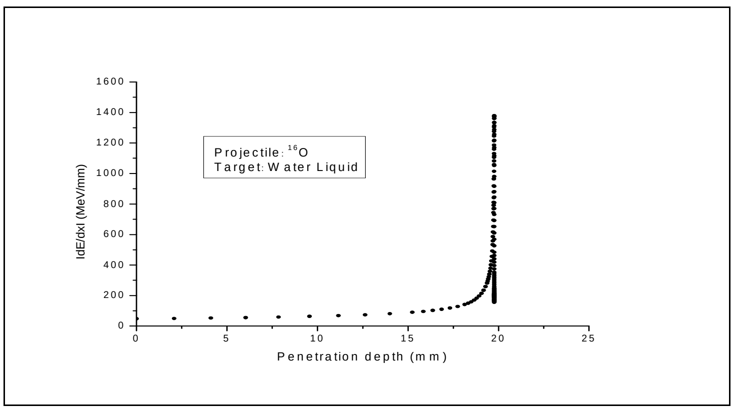

Fig. 1. Example of the Bragg curve for ^{16}O ions with a incident energy of 1.6 GeV on a liquid water target. The calculations were performed in a Monte Carlo model included in SRIM computer code.

During the slowing process the mono-energetic parallel beam of heavy ions suffer both an angular and an energetic spreading (straggling) very important for the applications. In the present work we are interested on accurate prediction of the angular straggling, based on Monte Carlo simulations of the stopping process.

3. Range of heavy ions in materials of biological interest

Due to the fact that biological tissues exhibit a large diversity, a liquid water target is usually chosen as a common benchmark. Although significant deviations appear from water to real tissues (see Fig. 3-5), the primary target selected for the present Monte Carlo simulations is liquid H_2O.

A primary objective in designing an irradiation procedure is to establish incident beam energy. This is related to the depth of the region were the tumour is irradiated and the structure of the stopping tissues. As can be observed from Figure 2, the calculations shows that in order to irradiate a volume from a target of liquid water, located at 19.1 mm under the surface, with a beam of ^{16}O ions, is necessary to use a beam with 1600 MeV incident energy. Calculations performed with the Monte Carlo computer code SRIM are comparable with the data adopted in the ICRU -73 Report [10]. The Bragg peak position is shown in the Fig. 3 for a beam of ^{16}O ions having an initial energy of 1.6 GeV in a target of liquid water, $1 g/cm^3$ density.

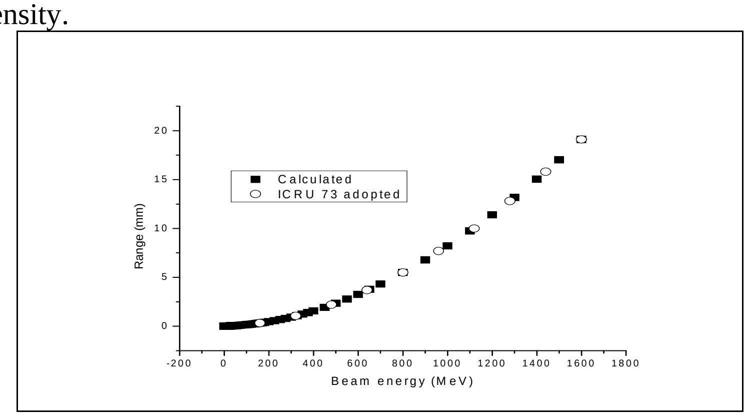

Fig. 2. Range as a function of energy for a beam of ^{16}O ions stopped in a liquid water target. Adopted (experimental) data from ICRU – 73 Report are presented for comparison.

The nuclear and electronic stopping powers are presented independently.

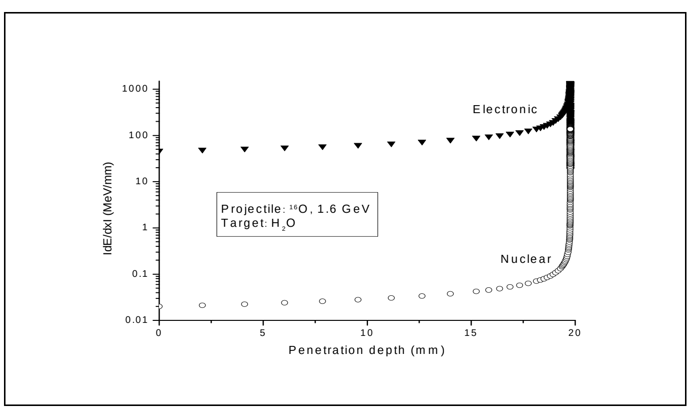

Fig. 3. Electronic and Nuclear Bragg curves for 1.6 GeV ions of ^{16}O stopped in liquid water.

As can be observed from the figure, electronic stopping power is higher than the nuclear one and there is a steep increase of the nuclear stopping power around the penetration depth of 19.8 mm.

4. Straggling of heavy ions in bio-materials

Beams of charged particles stopped in materials are geometrically (angular) laterally and longitudinally straggled. The study of the lateral stragglings and projected range are important to determine detailed trajectories of charged particles in matter. Since there are very few experimental measurements of stragglings, a strong need appears for accurate numerical simulations. In Figure 4 are presented simulations performed with the Monte Carlo code SRIM for lateral stragglings of beams of ^{16}O, ^{12}C and ^{19}F ions in water liquid, muscle and bone. The incident energy of the ion beams were selected in order to ensure a range of 19.1 mm. As can be observed from Figure 4 a, the lateral straggling for a beam of ^{16}O ions with an initial energy of 1.6 GeV in water liquid is 0.114 mm. The incident energy necessary to ensure the range of 19.1 mm for the beam of ^{12}C ions in the same target is 1.01 GeV. In this case the lateral straggling is 0.135 mm, with 0.021 mm larger than the lateral straggling of the beam of ^{16}O ions. When the incident beam is of ^{19}F ions, a heavier ion, the initial energy is 1.97 GeV. The lateral straggling decreases at 0.105 mm, with 0.009 mm smaller than the lateral straggling of the beam of ^{16}O ions.

Monte Carlo computations were also performed for the beams of ^{16}O, ^{12}C and ^{19}F ions travelling through muscle tissue (see Fig. 4 b). The incident energy of the ion beams were also selected in order to ensure a range of 19.1 mm. The standard values (e.g. SRIM library) used for the molecular composition of the muscle tissue are: H (62.7 %) + C (8.9 %) + N (1.6 %) + O (26.6 %) + K (6.4 %) + S (5.9 %) + P (4%) + Cl (1.8 %). The density of muscle tissue was considered to be equal to 1.05 g/cm^3. The incident energy necessary to ensure the penetration depth of 19.1 mm for the beam of ^{16}O ions is 1.64 GeV. The lateral straggling in this case is 0.113 mm. For the beam of ^{12}C ions the incident necessary energy is of 1.04 GeV and the lateral straggling is 0.134 mm, with 0.021 mm larger than the lateral straggling of the beam of ^{16}O ions. When the incident beam is of ^{19}F ions, the initial necessary energy is 2.01 GeV. The lateral straggling decreases at 0.104 mm, with 0.009 mm smaller than the lateral straggling of the beam of ^{16}O ions.

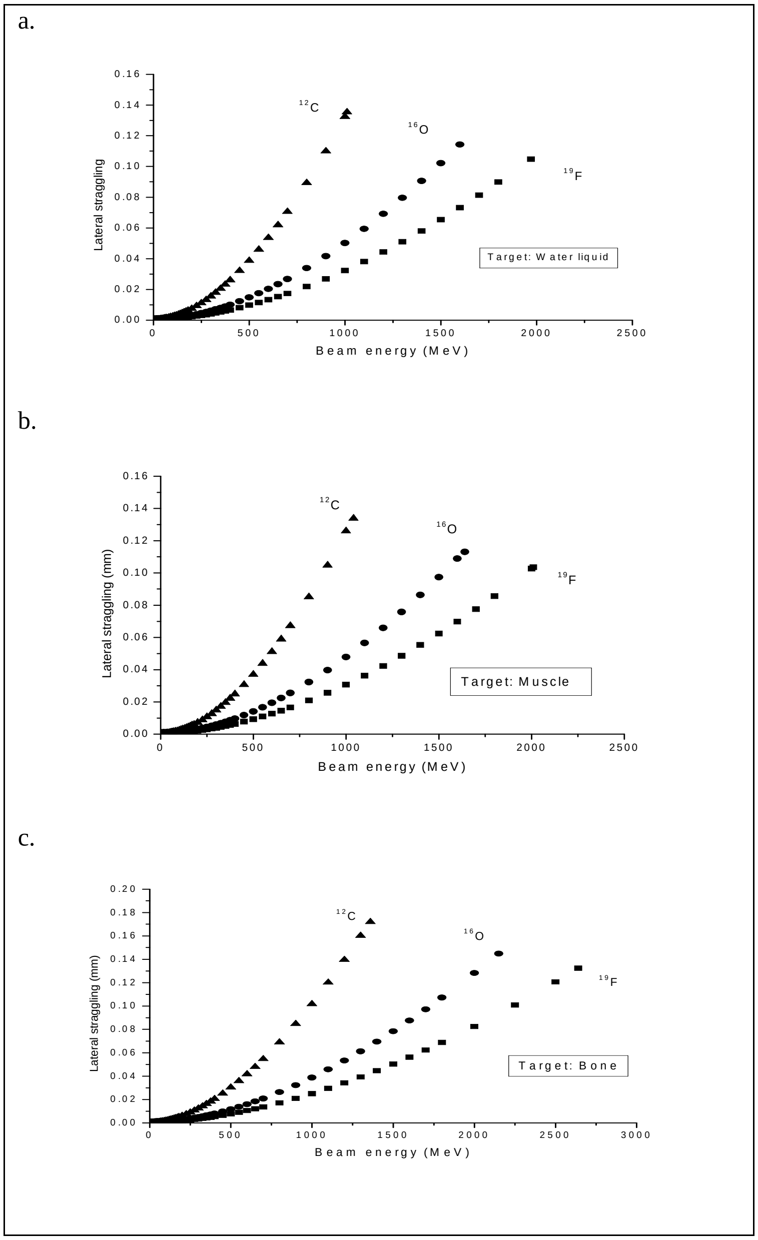

Fig. 4. Lateral stragglings versus beam energy for beams of ^{16}O, ^{12}C and ^{19}F ions in liquid water, muscle and bone. The incident beam energies are chosen in order to reach the 19.1 mm range for all beams and targets (see text for details)

The lateral stragglings were also evaluated for the beams of ^{16}O, ^{12}C and ^{19}F ions travelling through bone, a denser tissue (see Fig. 4 c). The molecular composition of bone was considered as Ca (6.5%) + P (3.9%) + H (39.3%) + C (15%) + N (3.5%) + O (31.6%) + S (0.11%) + Mg (9.57%) and its density was considered to be equal to 1.92 g/cm^3. In this case, the incident energy ensuring the 19.1 mm range for the beam of ^{16}O ions is 2.15 GeV, and the lateral straggling become 0.145 mm. For the beam of ^{12}C ions the incident necessary energy is 1.36 GeV. The lateral straggling is 0.172 mm, with 0.027 mm larger than the lateral straggling of the beam of ^{16}O ions. The same Monte Carlo computations were made for a beam of Fluorine ions. The incident necessary energy is 2.64 GeV and the lateral straggling is 0.132 mm, with 0.013 mm smaller than the lateral straggling of the beam of ^{16}O ions.

In Figure 5 are presented simulations for longitudinal stragglings of beams of ^{16}O, ^{12}C and ^{19}F ions in water liquid, muscle and bone. The incident energy of the incident beams were also selected in order to ensure a range of 19.1 mm. In the liquid water target (see Fig. 5 a) the longitudinal straggling for a beam of ^{16}O ions, with the initial energy of 1.6 GeV, is 0.731 mm. For the beam of ^{12}C ions the incident necessary energy is of 1.01 GeV and the longitudinal straggling is 0.828 mm, with 0.097 mm larger than the longitudinal straggling of the beam of ^{16}O ions. When the incident beam of ^{16}O is replaced with a beam of a heavier ion, ^{19}F with the initial energy of 1.97 GeV, the longitudinal stragglings decreases at 0.713 mm, with 0.018mm smaller than the longitudinal straggling of the beam of ^{16}O ions .

Longitudinal stragglings were also evaluated for the beams of ^{16}O, ^{12}C and ^{19}F ions travelling through muscle tissue (see Fig. 5 b). As mentioned before, the incident energies of the ion beams are selected in order to ensure the range of 19.1 mm. The incident energy of the beam of ^{16}O ions is 1.64 GeV and the longitudinal straggling is 0.710 mm. For the beam of ^{12}C ions the incident necessary energy is of 1.04 GeV and the longitudinal straggling is 0.810 mm, with 0.1 mm larger than the longitudinal straggling of the beam of ^{16}O ions. When the incident beam is of ^{19}F with the initial energy of 2.01 GeV the longitudinal straggling is 0.732 mm, with 0.022 mm larger than the longitudinal straggling of the beam of ^{16}O ions.

In bone the incident energies necessary to ensure the range of 19.1 mm are, 2.15 GeV for the beam of ^{16}O ions, 1.36 GeV for the beam of ^{12}C ions and 2.64 GeV when the beam is of ^{19}F ions. The longitudinal straggling for the beam of ^{16}O ions is 0.724 mm. For the beam of ^{12}C ions the longitudinal straggling is 0.758 mm, with 0.034 mm larger than the longitudinal straggling of the beam of ^{16}O ions and for the beam of ^{19}F ions longitudinal straggling is 0.766 mm, with 0.042 mm larger than for the beam of ^{16}O ions.

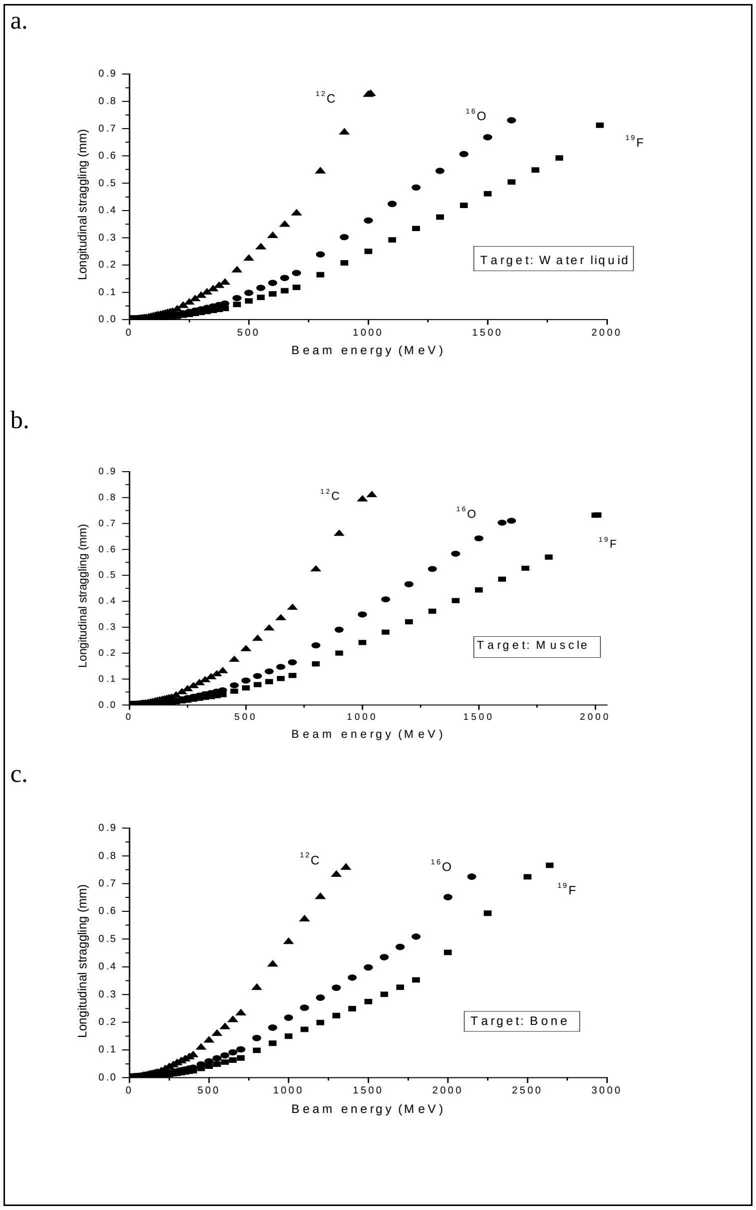

Fig. 5. Longitudinal stragglings versus beam energy for beams of ^{16}O, ^{12}C and ^{19}F ions in liquid water, muscle and bone. The incident beam energies are chosen in order to reach the 19.1 mm range for all beams and targets (see text for details)

5. Conclusions

In the present paper there are calculated the lateral and longitudinal stragglins of ^{16}O, ^{12}C and ^{19}F ions in water liquid, muscle and bone. The incident energy of the ion beams considered in the present work were selected in order to ensure in liquid water penetration depth if 19.1 mm. Liquid water is used as a benchmark for evaluation of the lateral and longitudinal stragglings. To approach more realistic cases the study was extended to muscle and bone. The calculations showed that the lateral and longitudinal stragglings are dependent on atomic number of heavy particle and the target density.

In radiotherapy the lateral straggling is more important than the longitudinal one as it determines the geometrical resolution of the irradiation [11].

The biologically effective dose in the tumor and the corresponding stragglings can be optimized by selecting the appropriate ions and energies. Further increase in the precision of dose estimation can be obtained by considering the real geometry (shape of the cross section, divergence) of the beams, a task for a forthcomming study.

R E F E R E N C E S

[1] *H. E. Johns and J. R. Cunningham*, The Physics of Radiology, Fourth Edition, C. C. Thomas Publisher, Springfield, IL, 1983.
[2] *J. J. Bevelacqua*, Contemporary Health Physics, Problems and Solutions, John Wiley & Sons, Inc., New York, 1995.
[3] *R.R. Wilson*, Radiological use of fast protons, Radiology **47**, 487-491, 1946
[4] *G. Kraft*, Tumor Therapy with Heavy Charged Particles, Progress in Particle and Nuclear Physics **45**, S473, 2000.
[5] *N. Bohr*, Mat. Fys. Medd. Dan. Vid. Selsk., **Vol 18**, No. 8, 1948.
[6] *A. Bohr*, Mat. Fys. Medd. Dan. Vid. Selsk, **Vol 24**, No. 19, 1948.
[7] *J. F. Ziegler, J. P. Biersack and U. Littmark* The Stopping and Range of Ions in Solids, Pergamon Press, New York, 1985.
[8] *P. Marmier, E. Sheldon*, Physics of Nuclei and Particles, Academic Press Inc. New York and London, 1971
[9] *J.J. Bevelacqua, Bevelacqua Resources,* Systematics of Heavy Ion Radiotherapy, Radiation Protection Management, **Vol 22**, No. 6, 2005
[10] Stopping of Ions Heavier than Helium, Journal of the ICRU Vol 5 No 1, 2005 Report 73, Oxford University Press.
[11] *A.I. Malakhov, J. Ružička,* Med-Nuclotron of the JINR, Proposal On the Extended Use of JINR Facilities for Ion Oncology Therapy, Dubna, 2004.