The recruitment kinetics of DNA repair protein XRCC1 in the foci caused by phototoxicity and heavy ion hits were investigated. Fig. 1(c) shows that the intensity of foci induced by heavy ion hits rises rapidly and reaches the maximum (about 200% to the original intensity) within 80 s after irradiation, then declined slowly. This was because the free XRCC1 molecules in the nucleoplasm were recruited to the DNA strand breaks caused by nickel ion hits immediately after irradiation. Then the XRCC1 molecules were released when the repair was fished, and the free molecules can be recruited to other damages<sup>[3]</sup>. By contrast, the intensity of foci caused by phototoxicity increased very slowly (increase about 15% within 400 s, almost no change within 80 s). This demonstrates that the XRCC1 intensity at the SSBs formed by phototoxicity was much lower and had slower recruitment than the heavy ion induced DNA damage foci, and the spontaneous XRCC1 foci had little effect on the live cell imaging study of XRCC1 protein kinetics after ion irradiation. The phototoxicity induced XRCC1 foci provide a useful method to study the XRCC1 kinetics at single SSBs and can be used to verify the reliability of a live cell imaging system.

In conclusion, a few foci may form spontaneously due to the phototoxicity but this had little impact on the analysis of the XRCC1 recruitment induced by the ion irradiation.

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## 4 - 72 Interpretation of the Rectification of Single Conical Nanopores

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Due to the symmetry breaking, single conical nanopores show characteristics of ion-current rectification, which has a great potential in applications to ion separation, power supplier and chemical valve<sup>[1-5]</sup>. It is of great importance to study the electrical properties of nanopores and the modification methods of conical nanopores in order to understand the ion transport properties in nanoscale structures and to improve the application performance of conical nanopores.

Single conical nanopores were etched in tracked PET membranes (irradiated by single 6.9 MeV/u <sup>58</sup>Ni<sup>19+</sup> ion in LIHIM). One side of the membrane was bathed in etchant, 5 mol/L sodium hydroxide solution at 50 °C, and the other side was in a stop solution, 1 mol/L HCOOH and 1 mol/L KCl. Single conical nanopore with tip diameter of 9 nm and base diameter of 1 200 nm was used in the experiments.

Fig. 1 (a~c) show the I-V curves of the same conical nanopore measured in the LiCl, NaCl, KCl solutions at different concentrations. The result shows that all the I-V curves were significant asymmetry and nonlinearity, which demonstrates the ion-current rectification in single conical nanopores. Fig. 1(d) shows the rectification coefficient  $\gamma$  in the solutions of LiCl, NaCl and KCl at different electrolyte concentration at 2 V. The ionic concentration- $\gamma$  relationships of KCl, NaCl and LiCl solutions were similar. The rectification coefficient  $\gamma$  increased from about 2 to about 12 with the electrolyte concentration from 0.0001 mol/L to 0.0316 mol/L, and decreased from about 12 to about 3 with the electrolyte concentration from 0.0316 mol/L to 1 mol/L at 2 V.

To explain the experimental phenomena, a new theory was proposed. The influence of pore wall adsorption charge on potential depth is considered in this new theory, which is neglected by other theories. The potential in the single conical nanopores is shown in Fig.  $2^{[1]}$ , and there is a deep potential well in tip. When the single conical nanopores is in the electrolyte solution, the distribution of charge in nanopores is shown in Fig. 3(a). The adsorption of positive charges on the pore wall will change the potential well depth (shown in Fig. 3(d)). "0" curve indicates the potential well depth of no voltage, "+" curve indicates the potential well depth of positive voltage and "-" curve indicates the potential well depth of negative voltage. "+" well potential depth is shallower than "-" potential well depth, this is because the positive charge is accumulated in the pore wall at the positive voltage (shown in Fig. 3(b)), while it is depleted at the negative voltage (shown in Fig. 3(c)). The existence of the potential well in tip can accelerate the cation through the nanopores, and the difference of the potential well depth under the positive and negative voltage leads to difference of the current.

The trends of current rectification coefficient first increased and then decreased with the electrolyte concentration from 0.0001 mol/L to 1 mol/L. A small amount of cations in the low concentration solution results in little difference in the potential well depth ( $\Delta V$ ) under the positive and negative voltage, so the rectification coefficient  $\gamma$  is small. When the solution concentration increases and approaches the optimum concentration,  $\Delta V$  will raises with the increase of cations in the solution, so the  $\gamma$  becomes larger. When the concentration exceeds the optimum concen-



Fig. 1 (color online) The current-voltage curves of single conically shaped nanopore with tip diameter of 9 nm and base diameter of 1 200 nm in the solutions of (a) LiCl (b) NaCl (c) KCl. (d) Rectification coefficient in the solutions of LiCl, NaCl and KCl as a function of electrolyte concentration at 2 V.



Fig. 2 (a) Scheme of an axial cut of a conical pore (b) profile of the electrical potential, V(z), inside a tapered-cone pore<sup>[1]</sup>.



Fig. 3 (color online) The charge distribution of a single conical nanopores in the electrolyte solution with (a) no voltage (b) positive voltage (c) negative voltage. (d) Schematic diagram of the potential well depth in single conical nanopores.

tration, the number of cations in the solution is too much, and the negative charge of the inner surface of the nanopores wall can be effectively shielded whether or not there is voltage.  $\Delta V$  decreases, and the  $\gamma$  becomes smaller (shown in Fig. 4).



Fig. 4 (color online) Schematic diagram of the potential variation of a single conical nanopores in different concentration solutions (a) low concentration (b) optimum concentration (c) high concentration.

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## 4 - 73 Current Hysteresis and Potential Energy Barrier Breakdown in Nanopores

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Asymmetric conically shaped nanochannels fabricated by ion-track-etching have been proved to be a versatile platform for biosensor and single molecule analysis<sup>[1-4]</sup>. Just as biological nanochannels, single conical nanopores possess some special physicochemical functions, such as ion selectivity, current rectification and current switch<sup>[5,6]</sup>. This work presents the recent characteristic study of the polymer nanopores prepared by single ion hits.

PET (polyethylene terephthalate) membranes (diameter=25 mm, thickness=13  $\mu$ m) were irradiated with a heavy <sup>86</sup>Kr<sup>26+</sup>ions of 25 MeV/u energy at the Lanzhou Interdisciplinary Heavy Ion Microbeam (LIHIM) to create a single damage track through the membrane. Then, the single conical nanopore has been successfully prepared in every PET membrane by chemical etching. The transport properties of the nanochannels, were studied by measuring the current-voltage (I-V) curve of these single conical nanopores in different electrolyte solutions.

In order to study the properties of conical nanopore in detail, we used a measurement method which can give two sets of I-V curves in a form of hysteresis. Here, we firstly measured the current under the positive voltage and then measured it applying the negtive voltage. After a ferric chloride solution or chromium chloride solution immersion, nanochannel adsorbs the corresponding trivalent ions, and hence it is hardly cleaned by ultra pure water. The inner wall of the channel has a positive charge due to the excessive adsorption of trivalent cations. Therefore, in the low concentration of potassium chloride solution, there is reverse rectification and cation selectivity.

As shown in Fig. 1, the conical nanopore has was soaked by the ferric chloride solution when concentration of the potassium chloride solution increases gradually, providing an interesting phenomenon. When the positive voltage was applied increasuring to about 1.5 V, the current decreased suddenly. This phenomenon occursred only once at the measurement with appropriate concentration of the potassium chloride solution in a group of different concentrations of the potassium chloride solutions. We believe that the reason for this phenomenon is that the ferric ions attracted by the nanochannels were expelled from this nanopore by electric field force. When the solution concentration increases, the electric double layer became thinner, and interaction between the anions in the double layer and the ferric ions on the nanopore wall increased. In the case of increasing the applied voltage, the sum of the other forces of some ferric ions exceeded the threshold of the pore wall adsorption force, and then leaved the nanopore under the action of electric field force. Due to the decrease of the positive charge, the potential well in the nanochannel decreased abruptly in a short time, leadsing to the sudden decrease of the current.