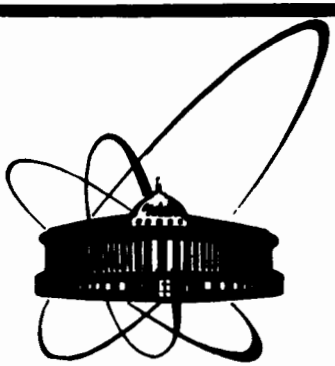

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E7-83-391

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# THE USE OF CR-39 PLASTIC DETECTOR FOR THE DETECTION AND IDENTIFICATION OF IONS WITH $2 \leq Z \leq 5$

Sumbitted to "Nuclear Instruments and Methods

1983

## INTRODUCTION

The study of the spectra of light charged particles emitted in heavy ion reactions at bombarding energies of about 10 MeV/nucleon can be successfully carried out using a magnetic spectrometer in conjunction with a $\Delta E-E$ semiconductor telescope [1]. In such reactions, the cross sections for the formation of different charged particles change by more than five orders of magnitude down to $10^{-5}$ mb/MeV.sr or less, while their energy varies from 4 to 30 MeV/nucleon. As a result, the measurement of the whole spectrum in such a way is very time consuming. In addition, for small cross sections the optimal conditions of measurement are met only for one or two types of particles at a time. For such reactions it is interesting to determine the end-point energies of the reaction products as this may give information about the reaction mechanism. The use of thin target in such experiments, especially at small observation angles, would lead to the fact that elastically scattered beam with different charge states will enter the spectrometer, thus making the measurements very difficult because of a high background.

These difficulties can be avoided if the $\Delta E-E$ semiconductor telescope is replaced by a dielectric detector. The aim of the present work was to study the possibilities of CR-39 plastic for the detection and identification of He, Li, Be, and B isotopes emitted in heavy ion reactions.

## CHOICE OF THE DETECTOR AND THE IDENTIFICATION METHOD

The CR-39 plastic [2] - allyl diglycol polycarbonate compound - has recently been widely used as a detector of charged particles due to its high sensitivity and efficiency. Its transparency and homogeneity make it suitable for nuclear reaction studies.

Most of the studies dealing with charged particle identification by aid of polymers were performed by determining the relation between the etchable track length and the residual range, or the dependence of the track etching rate on the residual range or differential energy loss. Another method is based on the track diameter determination [3]. Measuring the track diameter after etching makes it possible to

determine the particle energy if its charge is known. On the other hand, measuring the changes in the track diameter for different etching times gives the possibility of determining both the energy and charge of the recorded particle. This identification method is preferable for light particles whose track etching rate is close to the bulk etching rate. In this case the track diameter is a more sensitive function of the degree of ionization than the track etching rate. In principle this method works for particles entering the detector at any angle, though in practice the identification is substantially easier if they enter the detector perpendicularly.

The identification according to track diameters can be done at the entrance and at the exit of the detector by etching on both sides [4]. If the particle range is shorter than the plastic thickness, then the appearance of the track on the opposite side of the layer (with respect to irradiation direction) makes it possible to estimate the range of the particle. In this way one can, using a plastic detector, identify particles either according to their track diameter D which is a function of the energy loss, $D = f(dE/dx)$, or by measuring their range R which is a function of the particle total energy, $R = f(E)$.

The magnetic spectrometer makes this task easier as at each point of its focal plane and for a given magnetic field value, the energy of a particle with mass A and charge Z is given by the relation $E = kZ^2/A$, where k is a function of the magnetic field value alone.

For the particle identification according to track diameters, calculations were made for the range and restricted energy losses (REL) [5] for different particles in the CR-39 plastic. The calculations were performed using a program similar to that given in ref. [6]. In order to optimally determine the value of the parameter $\omega_0$ in $(REL)_{\omega_0} = Z^2_{eff} / \beta^2 \cdot f(\beta)_{\omega_0}$, a series of experiments to determine the track etching rate was carried out in which the plastic was irradiated by the following ions: $^4He$, $^{11}B$, $^{12}C$, $^{14}N$, $^{16}O$, $^{22}Ne$, $^{40}Ar$, and $^{129}Xe$, with energies ranging from 1 to 9 MeV/nucleon. These energies were determined with a 3% accuracy. The track etching rates were then determined as a function of the residual range and compared with REL calculations done for different $\omega_0$ values. As in ref. [7], the best agreement with experimental data was obtained for $\omega_0 = 200$ eV.

## EXPERIMENTAL

$^{nat}Ti$ targets were irradiated with $^{22}Ne$ (178 MeV) ions from the U-300 cyclotron of the JINR, Dubna. Reaction products were



Table 1

Isotopes of He, Li, Be, and B produced in the reaction $^{nat}Ti + ^{22}Ne$ and detected by the plastic CR-39

| Energy MeV | $^4He$ | $^6He$ | $^6Li$ | $^7Li$ | $^8Li$ | $^9Li$ | $^7Be$ |
|---|---|---|---|---|---|---|---|
| $E_1$ | 14.1 | | 21.3 | 18.2 | 16.0 | | 32.4 |
| $E_2$ | 22.0 | | 33.0 | 28.3 | 24.6 | 22.0 | 50.3 |
| $E_3$ | 31.5 | | 47.2 | 40.5 | 35.4 | 31.5 | |
| $E_4$ | 42.0 | | 63.0 | 54.0 | 47.2 | 42.0 | |
| $E_5$ | 54.0 | 36.0 | 81.0 | 69.8 | 60.8 | 54.0 | |

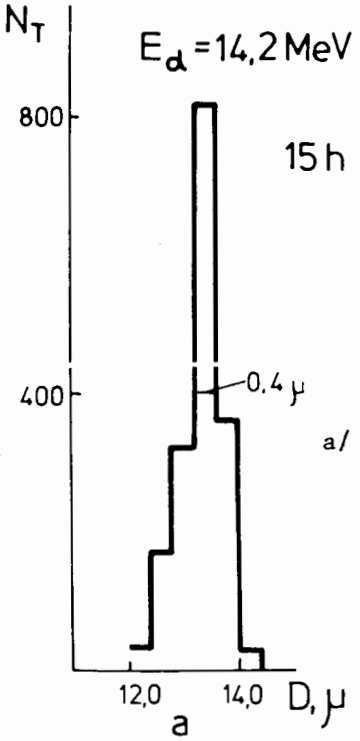
| Energy MeV | $^9Be$ | $^{10}Be$ | $^8B$ | $^{10}B$ | $^{11}B$ | $^{12}B$ | $^{13}B$ |
|---|---|---|---|---|---|---|---|
| $E_1$ | 25.2 | 22.7 | 44.4 | 35.5 | 32.3 | 29.6 | 27.3 |
| $E_2$ | 39.3 | 35.2 | | 55.0 | 50.0 | 45.8 | 42.3 |
| $E_3$ | 56.0 | 50.4 | | | 71.6 | | |
| $E_4$ | 74.7 | 67.2 | | | | | |
| $E_5$ | 96.0 | 86.4 | | | | | |

separated by a broad-range stepped-pole MSP-144 magnetic spectrometer [8]. In the focal plane of the spectrometer, plastic detectors were placed so that the products entered them perpendicularly. For comparison, a semiconductor $\Delta E$-E telescope was also placed in the same geometry. The plastic detectors were made of 500 $\mu$m CR-39 layers. The full thickness was chosen depending on the range of the products of interest.

Table 1 shows the energy ranges for different types of the particles studied in the reaction $^{nat}Ti + ^{22}Ne$. Their energies were determined with an accuracy better than 0.5%, mostly due to the finite dimensions of the detectors (~ 1 cm) as, along the focal plane coordinate x, the energy changes according to the law $E \sim x^2$.

In addition, the plastic detectors were irradiated with $^{4}He$, $^{11}B$, $^{12}C$, $^{14}N$, $^{16}O$, $^{22}Ne$, $^{40}Ar$, and $^{129}Xe$ ion beams with energies from 1 to 9 MeV/nucleon at 45° and 90° angles of incidence. In these cases the beam energy was determined with a 3% accuracy.

The plastic detectors were etched in a 20% NaOH solution at a temperature of 70±0.5°C. They were fixed in special stainless steel holders rotating continuously (~8 rot/min) during the entire etching period, as well as during the washing. After each five hours of etching the detectors were washed with tap water at room temperature and then dried in the open. Each subsequent etching was done with a new solution. The maximum time etching was 35 hours. The bulk etching rate $v_B$ and the thickness of the etched layer h were determined by measuring the diameter of the Xe track, $D_{Xe}$, in a sample that was etched together with the detector. The diameters were measured using a semiautomatic device including a microscope, a pulse generator and analyser, and a plotter. The precision of the track diameter measurement for 1000x magnification was ±0.2 μm.



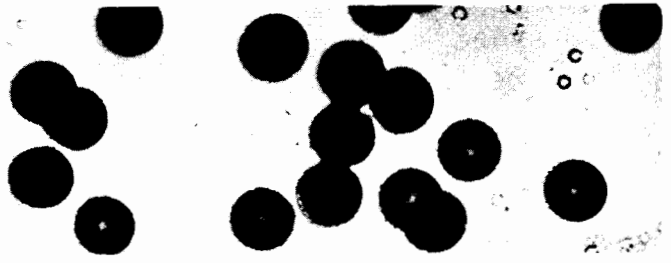




Fig.1. The histogram (a) and the photomicrograph (b) of the track diameters of 14.2 MeV α-particles, entering the detector perpendicularly. Etching time in 20% NaOH at 70°C is 15 hours. Magnification is 680x.



RESULTS

The energy resolution of the detector was deduced from the diameter distribution. For example, fig.1 shows the histogram and the photomicrograph of the track diameters for 14.2 MeV α-particles entering the plastic perpendicularly. The etching time was 15 hours. One can see that in the given case the detector resolution is not worse than the resolution of the measuring device. Similar histograms were obtained for all tracks of the particles under study and for different etching times.

In order to choose the processing mode corresponding to the best resolution of the reaction products, we studied the energy dependence of the track diameter for different thicknesses of the etched layer h, defined as

$$h = v_B \cdot t = D_{Xe}/2,$$

where t is the etching time.

Figure 2 shows the variation of track diameters for α-particles having energies $E_1$, $E_2$, and $E_5$ (from Table 1) as a function of h. In the measurement for $E_\alpha = 54$ MeV a two-layer de-

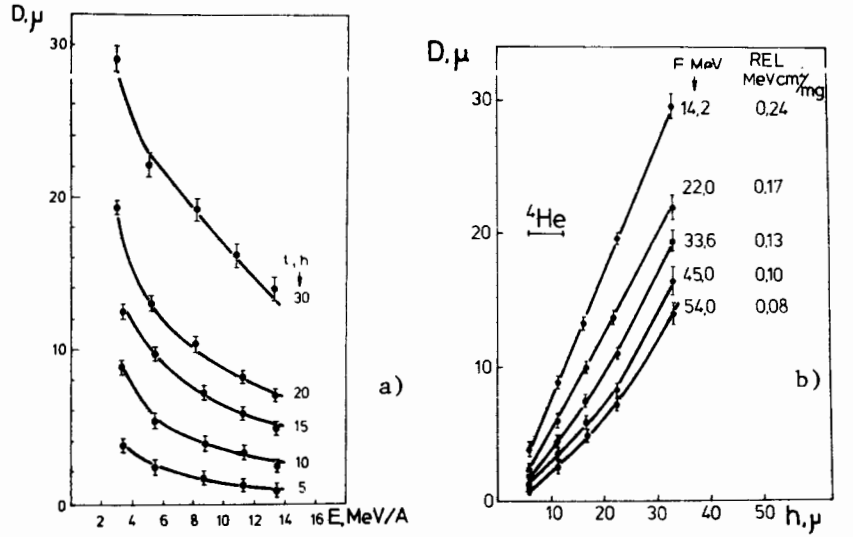



Fig.2. The dependence of the particle track diameters on: a) energy for 5, 10, 15, 20, and 30-hour etching times of the CR-39 plastic, b) h-thickness of the etched layer, for the same etching times. Initial α-particle energies and calculated restricted energy losses (REL) are also indicated.

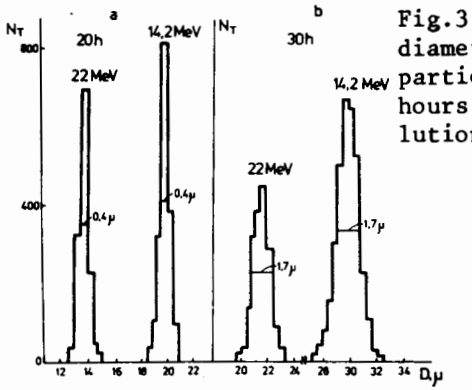



Fig.3. The histograms of the track diameters for 14.2 and 22 MeV $\alpha$-particles. Etching time was 20 and 30 hours, respectively. The detector resolution is shown.

tector was used, as the particle range exceeded the thickness of one layer. From the calculated dependence E = f(R) one can obtain the energies of $\alpha$-particles emerging from the first and second layer to be 45 MeV and 33.6 MeV, respectively. The track diameters of alphas were determined for these energies, too.

In this experiment the homogeneity of the properties of the two opposite sides of the layers was checked. For this purpose the diameters of the 45 MeV $\alpha$-particle tracks on the two surfaces in contact were measured and proved to be the same within experimental errors. One can see (fig.2a) that the energy resolution of the plastic detector is better for lower $\alpha$-particle energies and for larger diameters obtained in a prolonged etching. In fig.2a the curve obtained in 30 hours etching (corresponding to h = 33 $\mu$m in fig.2b) has the steepest slope. The dependence of D on E is mostly linear down to 5.5 MeV/nucleon, while at lower energies D increases faster. However, it should be noted that for long etching times the plastic structure starts to manifest itself. The surface becomes granular and the track well is deformed, so the resolution worsens. In fig.3 histograms for two $\alpha$-particle energies and two etching times - 20 hours (h=22 $\mu$m) and 30 hours (h=33 $\mu$m) - are shown. Obviously the spectra for the 30 hour etching time are broader than those for 20 hours.

From the point of view of the kinetics of the track diameter increase with h for different energies, one can see from fig.2b that a proportional rise is observed for the higher energies only for the greater values of h. A linear dependence is also seen for energies from 22 MeV down to 14.2 MeV for which REL $\geq$ 0.17 MeV/mg.cm$^{-2}$. For 30 hours etching time in the $\alpha$-particle energy range 54-22 MeV the change in the track diameter, $\Delta$D, for $\Delta$E = 1 MeV equals 0.25 $\mu$m/MeV, while for E values in the range 14.2-22 MeV $\Delta$E rises to 0.96 $\mu$m/MeV. On the other hand, $\Delta$D corresponding to $\Delta$REL = 0.01 MeV/mg.cm$^{-2}$ equals 1 $\mu$m for the whole range of energies and is constant within experimental errors. Hence it follows that reliable ion identification is possible at $\Delta$REL $\geq$ 0.01 MeV/mg.cm$^{-2}$. For 15 hour etching time this threshold rises to 0.02 MeV/mg.cm$^{-2}$.



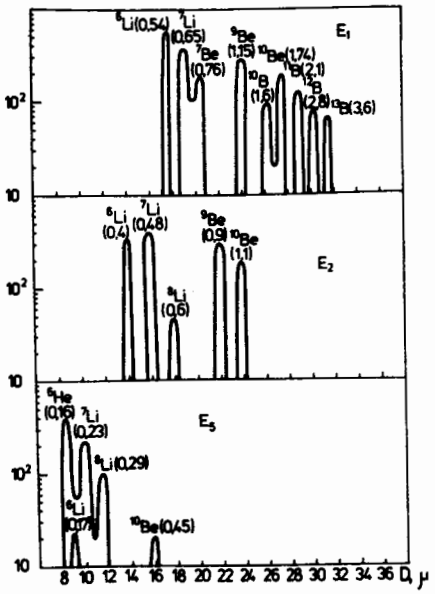
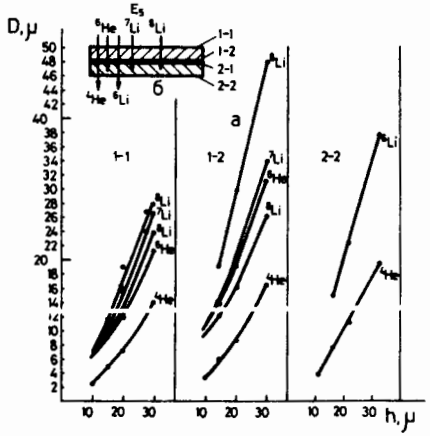



Fig.5. The track diameters for He and Li isotopes (a) with energy $E_5$ (Table 1) are shown on different surfaces (1-1, 1-2, 2-2) of a two-layer detector, for different h corresponding to etching times of 10, 15, 20, and 30 hours.

Fig.4. The track diameter distribution of isotopes with energies $E_1$, $E_2$, and $E_5$ (Table 1) entering the detector perpendicularly. In the brackets, REL values in MeV/mg/cm$^2$ are indicated. Etching time is 15 hours.




In fig.4 the track diameter distributions for the reaction products mentioned in Table 1 with energies $E_1$, $E_2$, and $E_5$ are shown. The numbers given in brackets are the mean values of REL taking into account the etched layer thickness h after 15 hour etching. One can see that a good differentiation of reaction products is achieved for h = 16.5 $\mu$m. However, as REL increases, the identification threshold for $\Delta$REL also rises (for example, the $^{12}$B and $^{13}$B tracks at $E_1$). As is seen, it is difficult to differentiate isotopes having $\Delta$REL~0.01 MeV/mg.cm$^{-2}$ (see $^6$He and $^6$Li for $E_5$).

In order to identify particles with a REL difference below the treshold value changes in REL along the track have been calculated. In this way one can determine the depth at which $\Delta$REL for the particles studied is the largest one and exceeds the threshold. For example, in the case of $E_5$ (Table 1), the detector was made of two 500 $\mu$m layers. After the simultaneous etching, the layers were reassembled. The track diameters were

Table 2

REL and D values for the three surfaces 1-1, 1-2 and 2-1 specified in fig.5. REL is in units of MeV cm$^2$/mg, D is in $\mu$m.

| Isotopes | 1 - 1 | | 1 - 2 | | 2 - 1 | |
|---|---|---|---|---|---|---|
| | REL | D | REL | D | REL | D |
| $^4$He | 0.085 | 5.0 | 0.10 | 6.0 | 0.10 | 6.0 |
| $^6$He | 0.16 | 8.8 | 0.37 | 14.0 | 0.37 | 14.0 |
| $^7$Li | 0.22 | 10.0 | 0.37 | 14.0 | 0.37 | 14.0 |
| $^8$Li | 0.29 | 11.0 | 0.73 | 19.0 | 1.05 | 23.0 |

measured at each surface. Moreover, the track diameter was followed along the entire thickness of the detector. The results of this measurement for three surfaces and different etching times are shown in fig.5. One can notice that a difference in track diameters for the $^6$He and $^6$Li ions is seen well at the back surface of the first layer, this difference increasing for a longer etching time. For $^6$He and $^7$Li ions, a contrary situation occurs. While at the first surface (1-1) one can differentiate them, at the second one (1-2) their diameters are very close to each other as, along the track, REL rises faster for $^6$He than for $^7$Li .

A photomicrograph of the first three surfaces (1-1, 1-2, 2-1) is also shown in fig.6. The etching time was 15 hours. In this figure one can easily see a change in the track diameter for $^4$He, $^6$He, $^7$Li, and $^8$Li isotopes as a function of REL. Table 2 summarizes the REL and D values for these isotopes on the three surfaces chosen. One can see that the difference observed in the track diameter for the $^7$Li and $^6$He ions on surface 1-1 practically disappears on surfaces 1-2 and 2-1, while the track diameters for $^8$Li and $^7$Li have an opposite tendency.

Moreover, the particle range can be used as a complementary check of the identification. Indeed, fig.5 shows that on surface 2-2 one can observe the tracks of $^6$Li alone since its range is greater than that of $^6$He. By scanning tracks along their length all through the plastic one can easily isolate a given particle.

It is noteworthy that tracks like those shown in fig.6c (magnified in fig.6d) serve as a control of the present identification. The "ears" correspond to the two $\alpha$-particles emerging



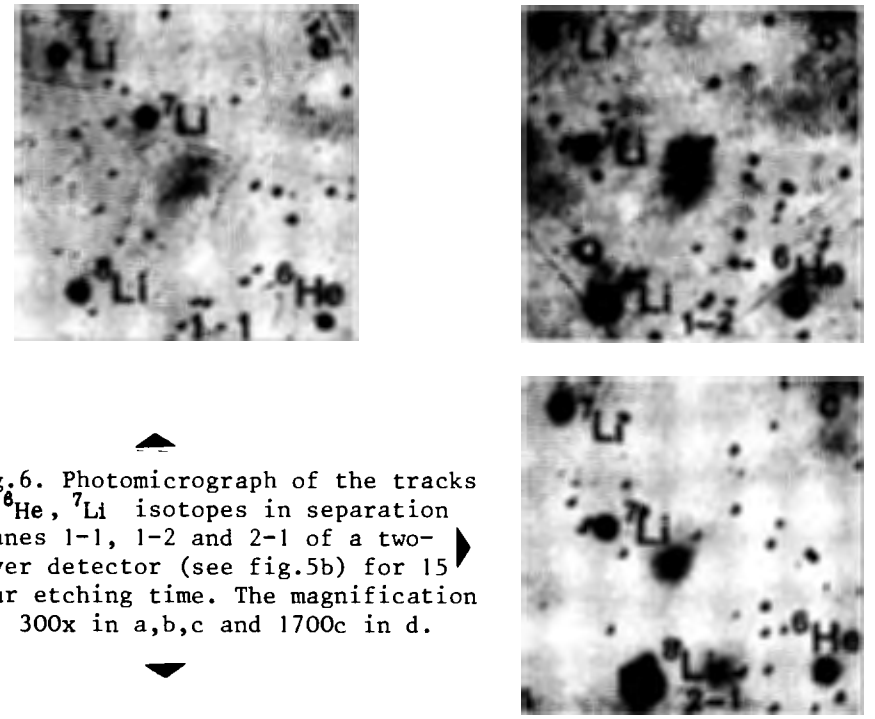



Fig.6. Photomicrograph of the tracks of $^6$He, $^7$Li isotopes in separation planes 1-1, 1-2 and 2-1 of a two-layer detector (see fig.5b) for 15 hour etching time. The magnification is 300x in a,b,c and 1700c in d.

from $^8$Be decay in the chain $^8$Li $\xrightarrow{\beta}$ $^8$Be$^* \rightarrow 2\alpha$. This particular reaction was studied in more detail by irradiating the plastic at an angle of 45°. The length of the $\alpha$-particle tracks was measured and found to agree well with the calculated $\alpha$-particle range in CR-39 plastic, as well as with the results obtained for photoemulsions [9].

The data obtained for track diameter distributions was used to construct the dependence of D on REL (calculated with $\omega_0$ = = 200 eV) for three different values of h (see fig.7). This calibration curve includes data for He, Li, Be, and B ions of different masses and energies (Table 1). All the points lie on a smooth curve indicating the correctness of the calculations and also the homogeneity of the detector properties. It should be noted that for REL values $\leq 0.7$ MeV/mg·am$^{-2}$ the identification is better than for higher values. Levelling off of the curve for REL $\geq$ 1,2 and especially for REL $\geq$ 2.0 makes the identification according to track diameters difficult and ambiguous. In this case we made use of the dependence R(E) by etching the detector from the surface opposite to the beam entrance and looking for the places where particles come to rest. The position of these places could be calculated and that dictated the etching time. The yields of different isotopes for the energies shown in Table 1 coincided within a 10% error with the corresponding yields determined by means of a semiconductor $\Delta E$-E telescope.

It is necessary to comment on the optical properties of the plastic, which are responsible for particle identification possibilities. After etching, the track of a particle entering the plastic perpendicularly, as looked through a microscope, has the form of a spot with a sharp edge. Depending on ionization, energy, mass and impact angle this image changes. For REL $\leq$ 0.1 MeV/mg·cm$^{-2}$ the track is light grey and less contrasting. This is due to its shallowness (2-3 $\mu$m); indeed, for such REL values the etching rate for nonirradiated polymer and the rate of etching along the track are quite close [10]. As REL increases, the track becomes black and contrasting. At the centre of the track there appears a bright spot the position of which depends on the impact angle (see the photomicrograph shown in fig.1). The displacement of this spot relative to the centre allows one to estimate the impact angle which should be taken into account in diameter measurements. Decreasing the impact angle of the particles (the spot is displaced relative to the centre) brings forth an ellipsoidal track and, for such particles, REL increases faster along the detector depth than for a particle entering the detector perpendicularly.

The interference rings within the spot also help the identification as their number and the contrast of the spot change with the type and residual range of the particle. It was observed that for residual ranges less than 200 $\mu$m and etching times of 20-30 hours, the inner part of the track may have a greater diameter than the entrance one, especially for isotopes with Z > 4. This fact may lead to some ambiguities.



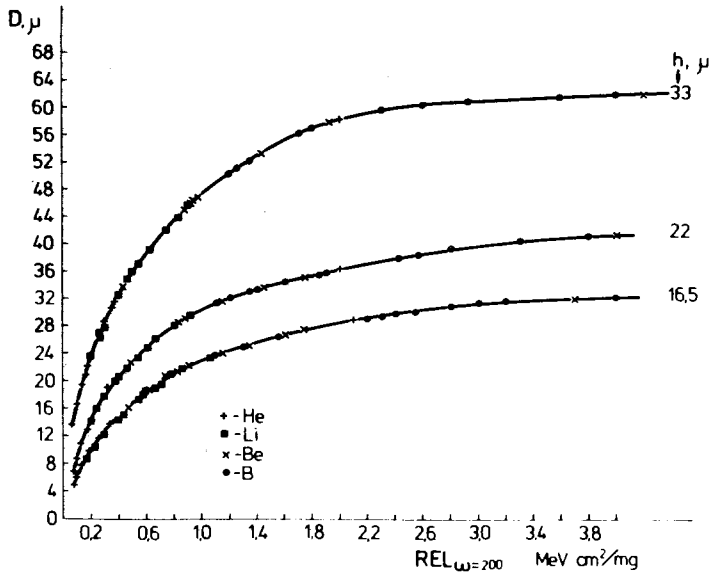



Fig.7. The dependence of the track diameters of the $2 \leq Z \leq 5$ particles on REL $_{\omega_0 = 200}$ for 15, 20 and 30-hour etching time.

## CONCLUSIONS

The CR-39 plastic detector has proved to have good spectroscopic properties which make it useful for heavy ion reaction studies. The identification of reaction products by using the dependence of their track diameter on REL is substantially easier if a magnetic spectrometer is used, because in this case, for each given place in the focal plane, the energy of all reaction products is exactly known. A multilayer detector provides a more reliable identification, especially for products having close values of energy losses.

The experimental calibration curve showing the dependence of the track diameter D on REL, together with the calculated range values R for different energies E, may be used to provide a reliable identification.

This plastic detector has several advantages in comparison with semiconductor detectors. These are:

(1) It can cover the entire focal plane of a spectrometer and record the spectra of all reaction products simultaneously.

(2). It is capable of recording rare events against the high background of other products.

(3) It gives a precise position in the focal plane, this in turn allowing a precise energy determination.

(4) It is capable of storing large amounts of information for a practically indefinite time.

However this detector has a resolution worse than a semiconductor telescope. In addition, there are some limitations concerning the track density, especially for large track diameters. This can possibly be avoided by some other processing, for example, by etching in alcohol solutions[11]. This procedure allows a higher recording threshold and also a better energy resolution.

The authors are grateful to Prof. Yu.Ts.Oganessian for his permanent support of this work, Dr. Yu.E.Penionzhkevich for useful advices and discussions, L.V.Jolos, K.I.Merkina and V.A.Ponomarenko for their help in processing and scanning of the plastic detectors, and to the U-300 cyclotron team.

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Received by Publishing Department
June 10,1983.



Третьякова С.П., Борча К., Калпакчиева Р. E7-83-391
Использование пластика CR-39 для регистрации и идентификации ионов с $2 \leq Z \leq 5$

С помощью пластика CR-39, расположенного в фокальной плоскости магнитного спектрометра, помещенного под углом 0° к пучку, определялась возможность регистрации и идентификации изотопов гелия, лития, бериллия и бора, полученных в ядерной реакции $^{ест}$Ti + Ne /178 МэВ/. Идентификация продуктов реакции проводилась по диаметрам треков частиц в зависимости от энергии и удельной ионизации. Представленные данные по регистрации продуктов реакции с помощью диэлектрического детектора совпадают с точностью до 10% с результатами, полученными с использованием полупроводникового ΔE-E телескопа.

Работа выполнена в Лаборатории ядерных реакций, ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1983

Tretyakova S.P., Borcea C., Kalpakchieva R. E7-83-391
The Use of CR-39 Plastic Detector for the Detection and Identification of Ions with $2 \leq Z \leq 5$

The possibilities of the CR-39 plastic for the detection and identification of the He, Li, Be, and B isotopes produced in heavy ion reactions were studied using a magnetic spectrometer placed at 0° with respect to the beam. The products of the reaction $^{nat}$Ti + $^{22}$Ne (178 MeV) were incident on the CR-39 detector at an angle of 90°. Their identification was performed by track diameter determination as a function of energy and restricted energy loss. The presented results coincide within 10% with those obtained using a semiconductor ΔE-E telescope of the same geometry.

The investigation has been performed at the Laboratory of Nuclear Reactions, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna 1983