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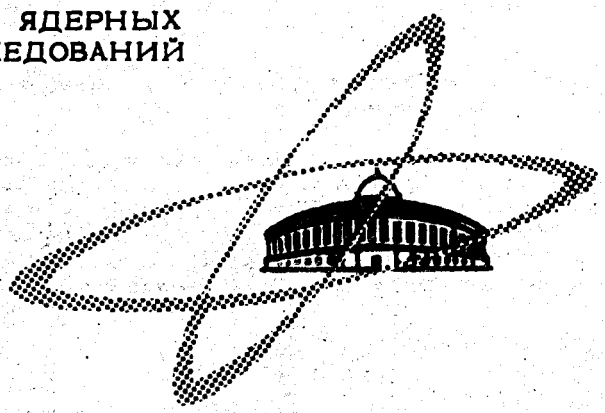

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IDENTIFICATION OF CHARGED PARTICLES BY COMBINATION OF THE MAGNETIC ANALYSIS AND THE $\Delta E, E$ METHOD

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1. Introduction

A reliable establishment of the atomic number Z and the mass number A of the nuclear reaction products is necessary both for studying the mechanism of nuclear reactions and for producing new isotopes.

When identifying nuclear reaction products with $Z \lesssim 10$ the following methods have been widely used.

1.1. The method of simultaneous measuring of particle specific energy losses ΔE and its total energy $E_0 = \Delta E + E$ with a telescope consisting of thin and thick detectors. For identification /1/ the relation

$$\Delta E \times E_0 \approx \text{const} \times AZ^2 \quad , \tag{1}$$

is used which follows from the Bethe-Bloch formula. The relation

$$T/\underline{a} = (E + \Delta E)^n - E^n \tag{2}$$

is also widely used[2] which follows from the empirical energy range dependence

$$R = \underline{a} \times E_0^n \quad . \qquad (3)$$

In relation (2) T is ΔE detector thickness, $\underline{a}$ is a constant depending on the particle type, $n \approx 1.73$ for a wide range of particles and energies.

The most important advantage of this method is rich information since all particles are detected within the solid angle irrespective of their charge states and in a wide energy region. However, sometimes its application faces serious difficulties. Two particles of which one has larger Z but smaller A can generate in the ΔE and E detector pulses close in values. Thus, the detection of neutron-rich or neutron-deficient isotopes turns out to be unreliable. The limited ΔE detector resolution ($\gtrsim 3\%$) complicates the isotope separation of elements heavier than oxygen or the separation of neighbouring isotopes greatly differing in their yields. The detector loading with elastic scattering particles makes it necessary to reduce beam intensity. This complicates the detection of reaction products with a low yield.

The combination of the ΔE, E method and the time-of-flight method[3,4] allows the improvement of isotope separation but in this case a smaller solid angle is used.

1.2. The magnetic analysis with simultaneous measuring particle energy with a detector in the output focus[5].

The energy of particles passed through the analyzer is determined from the expression

$$E_0 = \text{const}\ (BR)^2 \frac{Z_i^2}{A}\ , \qquad (4)$$

where BR is magnetic rigidity, Z_i is the ion charge. Identification is made by employing the Z_i^2/A parameter. This method provides high mass resolution (0.5 -1%). It permits one to remove the elastically scattered ions loading the detector by using the difference of particle magnetic rigidities. But this method ensures no unique identification of particles. Since for particles with $Z \geq 2$ various charge states are possible, particles-isobars having equal energies and ion charge, as for instance, $^{22}O^{+8}$, $^{22}F^{+8}$, $^{22}Ne^{+8}$ cannot be separated. No particle pairs can be separated which possess equal or very close values of Z_i^2/A as e.g. $^{4}He^{+2}$ and $^{9}Li^{+3}$, $^{14}B^{+5}$ and $^{9}Be^{+4}$.

By combining the magnetic analysis with the time-of-flight measurement[6] one improves the information property of the method but keeps ambiguity due to various charge states.

Here a method of charged particle identification is proposed which is based on the combination of the magnetic analysis and the ΔE, E method. A telescope of thin and thick semiconductor detectors is put into focal plane of the magnetic spectrometer. Pulses from the detectors are sent to the multi-channel analyzer operating in the two-dimensional mode. Such a combination of methods permits, on the one hand, the conservation of valuable properties of the magnetic analysis, high mass resolution and detector unloading with elastically scattered particles and, on the other hand, the elimination of identification ambiguity. The comparison of the ΔE, E method, the magnetic analysis and their combination are shown schematically in Fig.1. Since our method permits the identification of particles whose properties satisfy simultaneously two equations (1) and (4)

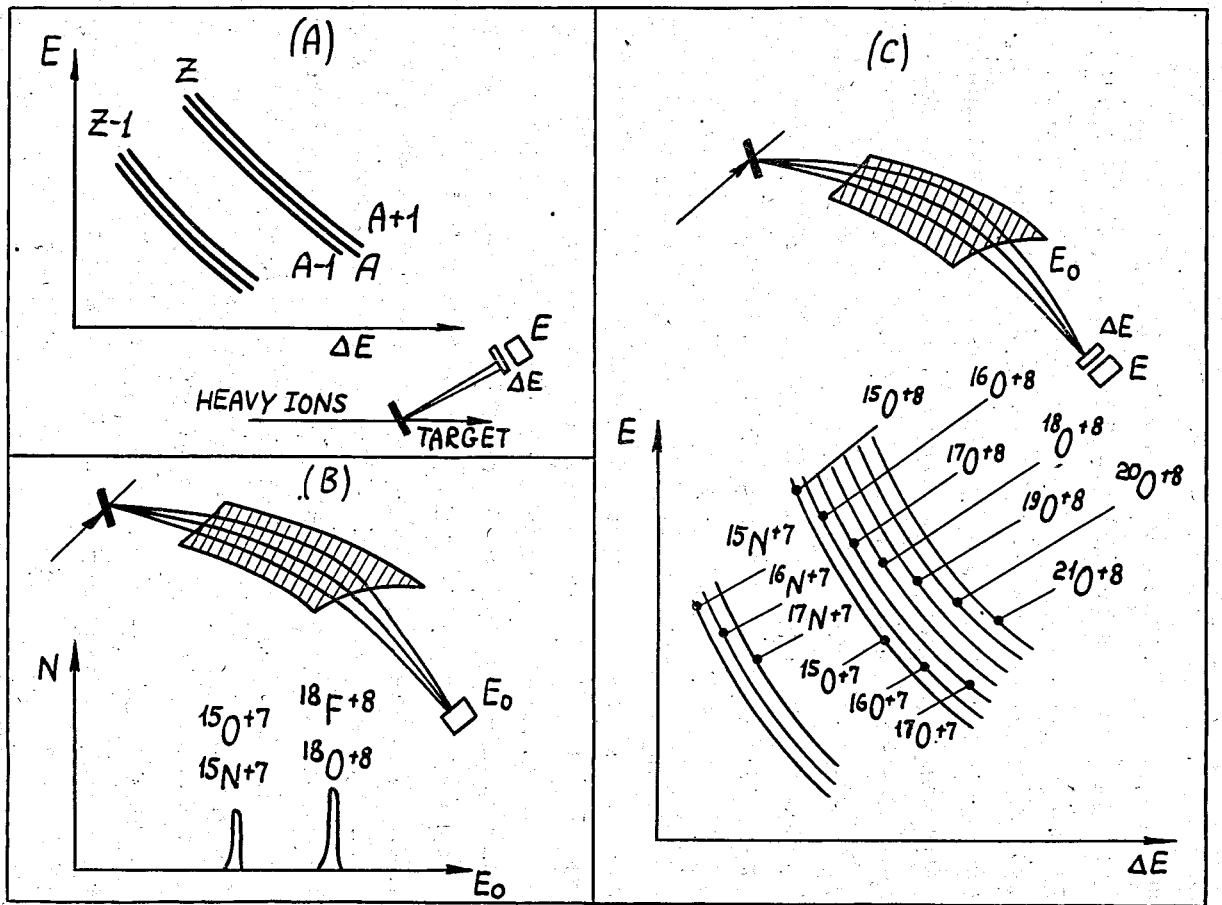

Fig.1. Comparison of the methods of particles identification: (A) - $\Delta E \times E$, (B) - the magnetic analysis with the measurement of the energy E_0. (C) - the combination of the magnetic analysis and the ΔE, E method.

the continuous hyperbolae of the ΔE, E method are broken into separate points, each of which corresponds to the definite isotope in a definite charge state.

2. Apparatus and the Method of Measurements

The ion beams accelerated with the Dubna 310-cm heavy ion cyclotron were used for our measurements.

The magnetic analyzer with the homogeneous field and the double focusing of the second order was an identical version of the analyzer developed earlier for analysing 400 MeV/c electrons.[7] It has the following basic parameters:

Radius of central trajectory	1.26 m
Deflection angle	70°
B_{max}	18 kG
Solid angle	$3 \cdot 10^{-3}$ sr
Momentum dispersion	12.7 mm/1%
Momentum resolving power with a source 10 mm in diameter	0.3%

The spectrometer magnet is of armour type, it weighs 40 tons. The magnetic field is stabilized within 10^{-2}%.

The silicon surface-barrier detectors ΔE were 26-200 μ m thick, plane-parallelism was ≈ 0.1 μm and the sensitive region was 10-25 mm in diameter. The peculiarities of detector operation in heavy ion beams have been considered in ref.[8]. The typical energy resolution of these detectors when detecting heavy ions was about 4%. Pulses from the ΔE and E detectors after amplifying are sent to the input of the multi-channel amplitude analyzer operating in the 64x64 channel mode.

The two-dimensional amplitude spectrum obtained in bombarding the ^{232}Th target 4.4. mg/cm^2 thick with the 174 MeV ^{22}Ne ions is shown in Fig.2. The detection angle of nuclear reaction products is 40°. The ΔE detector is 46 μ m thick and 16 mm in diameter. The magnetic rigidity is 9.68 kGm. The number of counts in each channel is proportional to the circle area squared.

The identification of maxima was carried out as follows. The energy of all particles, which passed through the magnet and hitted the telescope, has fixed values determined by equation (4). Knowing these energies one can determine energies released by a definite isotope in the ΔE and E detectors by using the range-energy curves and, consequently, to establish its position on the ΔE , E plane. Energy calibration of the ΔE and E detectors was carried out according to elastically scattered ions. The initial energies of all particles were also determined according to relation (4) with respect to the energy of elastically scattered ions. This made it possible to reduce considerably the influence of errors in the determination of ions initial energy and the ΔE detector thickness on the accuracy of identification. The discrepancy between the calculated position of maxima and the experimental one in Fig.2 is within one channel both in E and ΔE .

Maxima in the two-dimensional spectrum corresponding to the isotopes of the given element lie on the curves of hyperbolical type which are approximately described by the equation

$$(\Delta E)^{1/4} \times E_0 = \text{const} \times BRZZ_1 \qquad (5)$$

It has been obtained from relation (1) when taking into account eq. (4). As has been mentioned in ref.[1] expressions (1) and respectively (5) contain, in fact, the effective charge $Z_{eff} \leq Z$ instead of Z.

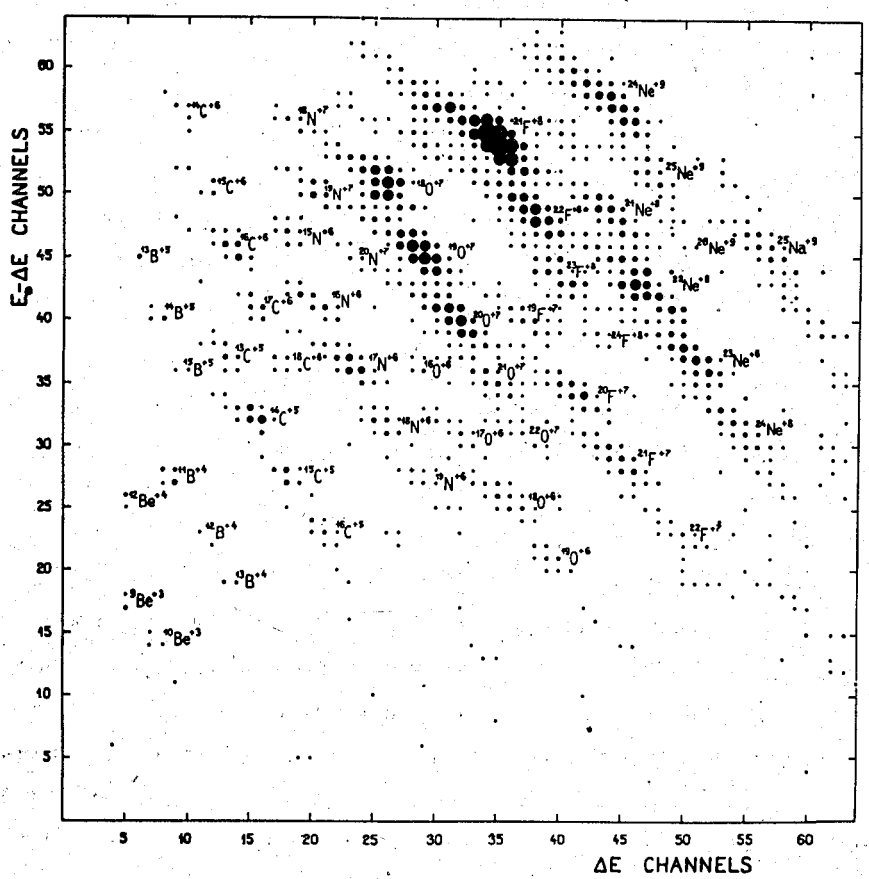

Fig.2. Two-dimensional amplitude spectrum obtained in bombarding the ^{232}Th target with 174 MeV ^{22}Ne ions. The area of each circle is proportional to the square root of the number of counts in each channel.

Owing to the fact that the energies of the detected isotopes are reduced with increasing A according to relation (4), their Z_{eff} are also reduced. This results in streightening the curves in two-dimensional spectra.

Fig. 3 shows data describing the E separation of Ne and F isotopes. Each point has been obtained by summing up the counts in the ΔE channels, referring to a definite element in the fixed charge state in the two-dimensional spectrum in Fig.2.

Fig.4 shows spectra from the ΔE detector, which correspond to the cutting-off the two-dimensional spectrum in the maxima of $^{25}Ne^{+9}$ and $^{23}F^{+8}$ isotope yields.

As it is seen from the figures, the isotope resolution is sufficiently reliable both in E and in ΔE .

The absence of Ne and F isotopes in spectra in the charged states $Z_1 = Z$ is due to the choice of the magnetic rigidity.

3. Mass Separation

With $\Delta E \ll E_0$ from formulas (1) and (4) for the isotopes in the given charge state and with the fixed magnetic rigidity we obtain

$$\Delta E \approx \text{const} \times A^2 \quad . \qquad (6)$$

The comparison of (6) and (1) shows that the difference in the specific ionization produced by the neighbouring isotopes of one element is increased by two times when using our method compared to the conventional ΔE, E method.

The relative variation of E for the isotopes of the given element depends on the ΔE detector thickness. Considering $E = E_0 - \Delta E = \text{const} \; 1/A - \text{const} \times A^2$ according to relations (1) and (6) it can be easily shown that

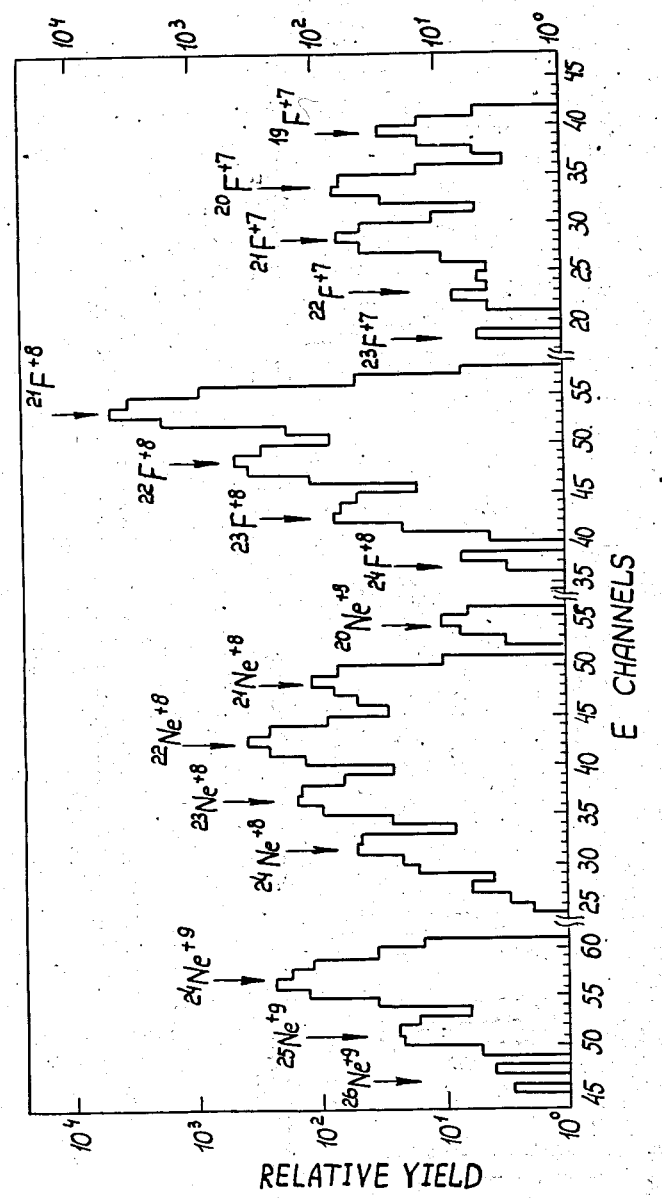

Fig.3. Ne and F isotope yields obtained from the two-dimensional spectrum, shown in Fig.2.

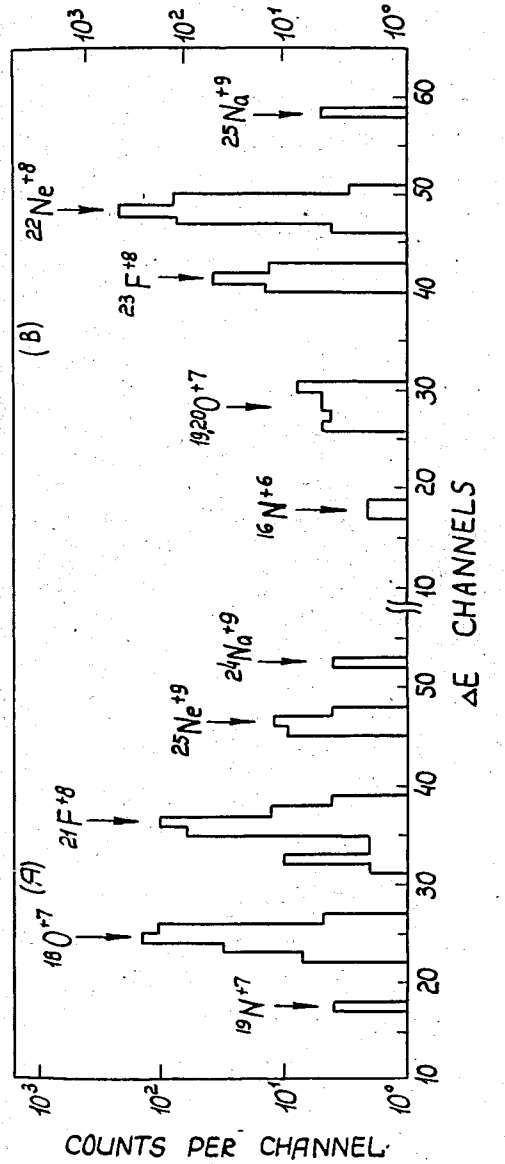

Fig.4. Spectra from the ΔE detector corresponding to the cut-offs of the two-dimensional spectrum from Fig.2 in the maxima of $^{25}Ne^{+9}$ - (A) and $^{23}F^{+8}$ - (B) yields.

$$dE/E = - \frac{(E_0/\Delta E)+2}{(E_0/\Delta E)-1} \times \frac{dA}{A} \quad (7)$$

The expressions for ΔE and dE/E can also be obtained by using relations (3) and (4). The obtained expressions are valid for ΔE comparable with E_0, they are clumsier than relations (6) and (7), but provide results close to them. This makes it possible to obtain approximate estimations of relations (6) and (7) also for rather thick ΔE detectors.

Keeping in mind that according to refs./9,10/ the ΔE detector has optimal energy resolution with $\Delta E \approx \frac{1}{2} E_0$ one obtains in this case

$$dE/E = -4 \frac{dA}{A} .$$

The peak width in our spectra is determined by the statistical spread of pulse amplitudes in ΔE and E detectors and by the target and detector dimensions. The selection of target and detector sizes is determined usually by the reasonable compromise between the resolution and sensitivity requirements. Since the coefficient of horizontal magnification of our spectrometer is 0.36, while momentum dispersion is 12.7 mm/1%, the target and detector 10 mm in diameter provide amplitude spread in the ΔE and E detectors smaller than 2%.

4. Identification Reliability

In our experiment we need to establish four particle characteristics: Z, A, Z_1, E_0. In order to determine them we have four equations: (1), (4), $E_0 = \Delta E + E$ and $\Delta E = f(E_0, Z, A, T)$.

The latter equation is determined by the range-energy curves. A question arises on the uniqueness of particle identification.

To provide the condition when two different particles might produce a similar effect in the detecting system, it is necessary that their E_0 and ΔE should coincide or be close in values. The conventional ΔE, E method can provide such coincidence for heavy isotopes of the Z_1 element, and the light isotopes of the $Z_2 = Z_1 + 1$ element (see Fig.1). In our method with $Z_1 = Z$ these isotopes turn out to be greatly energy-shifted according to relation (4). As a result, the identification of light isotopes for the case $Z_1 = Z$ turns out to be always unique. For heavy isotopes the situation turns out more complicated.

As it is shown by the analysis, in some cases the light isotopes of $Z_2 = Z_1 + 1$ element which is in the charge state $Z_{21} = Z_2 - 2$ can imitate the effect of the heavy isotopes of Z_1 element, in the charge state $Z_{11} = Z_1$. Such a situation arises for a pair of isotopes which has close values of Z_1^2 / A and the close range-energy curves in the energy interval under study. However, the difference in the charged states of the particle of interest and of the background particle considerably simplifies the problem of separating the effects of light and heavy isotopes with our technique compared to the conventional ΔE, E method. The matter is that at energies of tens MeV at which nuclear reactions on heavy ions occur, the particle yield from the target in the charged states $Z_{21} = Z - 2$ is tens times as small as in the charged states $Z_{11} = Z$ /11/.

This fact allows the precise check experiments with our technique. By changing the magnetic regidity to Z_{21} / Z_2 times we shall detect light isotopes with a considerably higher efficiency. The

effect from heavy isotopes when retreating from the magnetic rigidity optimum can only be decreased.

The check experiment of ref.[12] has performed just in this way, when new ^{22}O , ^{20}N , ^{18}C isotopes have been obtained in irradiating the ^{232}Th target with ^{18}O ions. It has been established that the admixture of the effect from $^{17}F^{+7}$, $^{14}O^{+6}$ and $^{12}N^{+5}$ isotopes to that from $^{22}O^{+8}$, $^{20}N^{+7}$ and $^{18}C^{+6}$ isotopes, respectively, does not exceed 1%.

It is worth noting that to hold conditions (1) and (4) simultaneously is a more rigid requirement than to hold the same requirements separately. We have performed the analysis of energy-range curves by using the computer for the isotopes of elements with $Z \leq 10$ in the energy interval below 200 MeV. It turned out that in all the cases by selecting the ΔE detector thickness in our method it is possible to provide conditions when the difference in the ΔE and E values for any two isotopes will be 5-10%. This allows quite reliable separation of effects both from light and heavy isotopes in each definite case.

5. Method Application

Our technique has been used to identify neutron-rich isotopes of light elements in experiments with heavy ions accelerated with the Dubna 310-cm cyclotron. In these experiments together with the already known isotopes such as ^{8}He , ^{11}Li , ^{12}Be , ^{15}B ^{17}C and others, new ^{18}C , ^{20}N , ^{22}O [12] isotopes have been obtained in bombarding ^{232}Th with ^{18}O and besides new ^{23}F , ^{24}F and ^{25}Ne and ^{26}Ne [13] isotopes have been obtained by bombarding ^{232}Th with ^{22}Ne .

The employment of the method for detecting neutron-deficient isotopes proves still more effective.

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