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CHARGE-STATE DISTRIBUTIONS OF ACCELERATED ^{48}Ca IONS

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1. Introduction

When heavy ions pass through some material the ion-atom collisions cause them to experience fluctuations in charge due to the processes of loss or capture of electrons. The interest in such changes in the charge states of heavy ions is based on the fact that the obtained data may provide important information on the character of atomic collisions. Indeed, in these collisions the atoms of the material interact with the multi-charged ions, which have on their inner and outer shells a lot of electrons. The information on the charge exchange probability of heavy ions in matter, their mean equilibrium charge and charge-state distribution is necessary for a wide range of applications, such as designing and operating of heavy-ion accelerators, designing and using separators of products of heavy-ion-induced reactions and solving problems of registering and identification of nuclear reaction products. The knowledge of the charge-state distribution is necessary also when accelerating separated isotopes for determining the optimal conditions for extracting the beam from accelerators using the stripping method, in which after emerging from a thin foil a relatively wide charge-state distribution is obtained for the accelerated ions. The experimental information on charge state distributions is necessary also to test and improve existing empirical formulae and theoretical calculations, which is important in the evaluation and planning of investigations aimed at the search for new exotic radioactive isotopes. There are a lot of papers, experimental and theoretical, dedicated to the measurement of charge-state distributions and determination of the average (or mean) equilibrium charge state of heavy ions. A detailed review of the subject can be found in refs. [1-6].

There are several approaches used to estimate the average equilibrium charge of heavy ions ($\bar{q}$) and the distribution of the charge-state fractions $F(q)$ of the ion beam when heavy ions with atomic number Z, charge q and velocity v pass through a certain material thick enough for them to attain charge equilibration. The mean charge $\bar{q}$ is defined as $\bar{q} = \sum_q q \cdot F(q)$. For practical cases the charge-state distribution of heavy ions emerging from an "equilibrium" solid stripper foil (target) is approximated with a Gaussian curve [4,6]. However, the available experimental data have shown that the equilibrium charge values and the charge-state distribution of the ions (charge fraction of the ion in the beam) passing through some material are not always consistent with the generally accepted theoretical calculations and the empirical formulae [4,7-9]. In particular, oscillations of the equilibrium ion charge $\bar{q}$ and the charge distribution width d as a function of the ion atomic number Z and velocity v were observed [2,5,6,10]. These variations were found to be correlated with the closed-shell structure of the incident ion. The charge-state distribution is asymmetric in the case of charge states of ions with electron structure with completely filled inner shells, while the $\bar{q}$ value is usually somewhat lower than the expected value, especially at relatively small values of the energy (up to 2 MeV/nucleon). A problem also arises when one has to describe the charge-state distribution where fully or almost fully stripped ions constitute a significant part of the ion beam, i.e. when $q \approx Z$ [10,11].

As was mentioned, extensive investigation has been carried out of the charge-state distributions of various heavy ions in a wide range of energies penetrating different gaseous or solid strippers (targets). Nevertheless to our knowledge, experimental data on ^{48}Ca are not yet published, though there are data on ^{40}Ca and beams of ^{48}Ca are available since a long time.

In this work, we have measured the charge-state distributions and have determined the mean equilibrium charge of accelerated ^{48}Ca ions with energies 242.8 MeV and 264.5 MeV after passing through thin carbon and gold target foils.

2. Experimental setup

For measuring the charge states of heavy ions after passing through thin target foils one usually uses special setups including magnetic analysis of ions according to their charge states [3,12] or broad-range magnetic analyzers [3,13].

The setup used in the present work for the measurement of the charge-state distributions of ^{48}Ca ions accelerated at the U400 cyclotron of FLNR, JINR (Dubna), is schematically presented in Fig. 1.

Its basic element is the broad-range stepped-pole magnetic spectrometer MSP-144, which is described elsewhere [13,14]. In the present measurements the magnetic spectrometer stood at 0^0 with respect to the beam direction. A semiconductor detector, installed in the reaction chamber, was used for monitoring the beam and normalization purposes. The accelerated ^{48}Ca ions passed through a thin self-supporting carbon or gold foil 70 μg.cm^{-2} and 210 μg.cm^{-2} thick, respectively, mounted on a target holder in the reaction chamber. The target thickness was chosen so as to ensure optimal conditions for obtaining an average ion charge close to the equilibrium one [15,16]. The use of thicker "stripping" foils (targets)

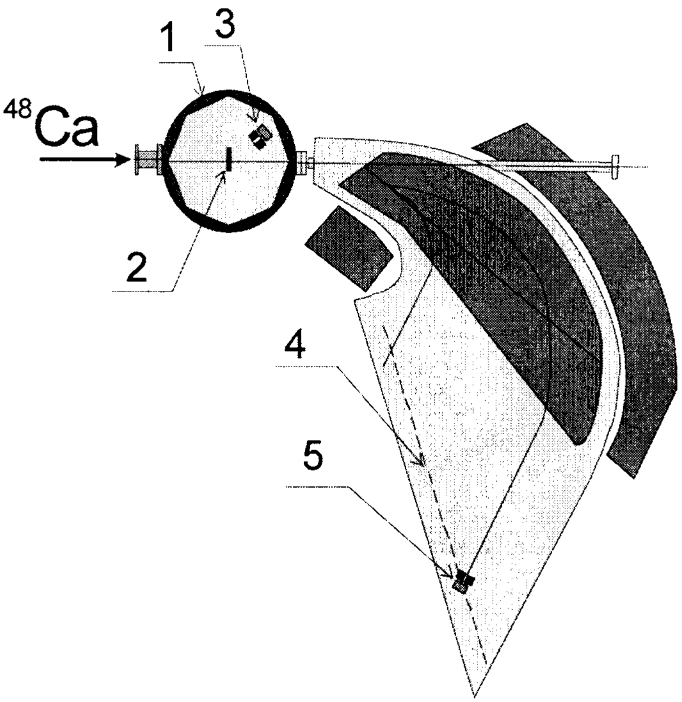

Fig. 1. Layout of the experimental setup used for measuring the charge-state distribution of accelerated ^{48}Ca ions with the magnetic spectrometer MSP-144:
1 – reaction chamber, 2 – target foil, 3 – monitor (silicon semiconductor detector), 4 – focal plane of MSP-144, 5 – device detecting the ions coming from the target and analyzed by the magnetic spectrometer.

increases the dispersion in angle and energy of the primary beam, which in turn would cause observation of deteriorated characteristics of the extracted beam. The magnetic spectrometer separated the monoenergetic ^{48}Ca beam emerging from the target into the different charge states and focused each one of them to a spot on the focal plane, defined by the chosen magnetic rigidity. Some measurements were performed without a target. In this case, a single beam charge state as extracted from the U400 cyclotron and transported according to the ion-optical tuning of the beam line entered the magnetic spectrometer.

We applied two methods to detect the beam particles and consequently determine the relative contribution of the various charge states in the beam.

In the first one a Faraday cup (FC), connected to a beam current integrator, or a Si semiconductor telescope, collimated in the horizontal direction to 3 mm, were mounted at a fixed position in the focal plane. By varying the magnetic field *B* (measured by a NMR probe) of the spectrometer by small steps, each charge state was moved across the Faraday cup (or the Si telescope). The monitor detector in the reaction chamber provided the normalization factor between the individual measurements. As a result, for each charge state (one – in the case without the target and a few – with the target), a distribution of the yield as a function of *B* was obtained, which could be approximated with a Gaussian. Thus, having determined the most probable magnetic field, knowing the position of the Faraday cup at the focal plane of MSP-144 and using the calibration of the magnetic spectrometer [14], it was possible to calculate the energy of the ^{48}Ca beam coming directly from the cyclotron or passing through the target foil. The equilibrium charge-state distribution was drawn after integrating the normalized yields for each charge state, measured with the target foil.

In the second method the aim was to make it possible to visually observe all charge states produced after the passing of the projectiles through the target foils. For this purpose, in the same operating conditions of the accelerator and choosing the magnetic field of the magnetic spectrometer MSP-144 so as to ensure that a maximum number of charge states reached its focal plane simultaneously, the latter was covered with a thin Al foil (7 μm thick), behind which a solid state detector (a Mylar foil about 180 μm thick) was fastened. Their installation at the focal plane was done with an accuracy of about 1 mm. During the irradiation the beam charge states burnt out spots on the Mylar foil. The corresponding portions of the Al foil behind them were cut for γ-ray measurements of the total activity induced by each charge state. Each Al piece was in turn cut into 1-mm-wide strips, whose induced activity gave the spatial distribution of each charge state. The induced γ-activity was determined by the isotope ^{24}Na formed in a transfer reaction on ^{27}Al. As a result, in addition to the charge-state distribution, we could with high precision determine the position of the different charge states of the ^{48}Ca beam on the focal plane and the centers of gravity of their distributions. The position distribution is equivalent to the ^{48}Ca beam energy distribution. The average values of the beam energy, determined by using a Gaussian curve to describe the distributions thus obtained with the two methods, agreed within the experimental error.

It could be concluded that the two methods used in this work to measure the energy and the charge-state distribution of the ^{48}Ca beam extracted from the FLNR U400 cyclotron gave consistent results.

3. Experimental results

First of all we let the ^{48}Ca beam enter the magnetic spectrometer MSP-144 without passing through a target foil. For the two energies used in the present study, the most probable magnetic rigidity for the direct beam, corresponding to the FC position in the focal plane, was determined. It was found to be consistent with the acceleration of ^{48}Ca of charge state 18^+ or 19^+, extracted from the U400 cyclotron using a thin C stripper. The energy of the ^{48}Ca beam of charge state 18^+ in the first run and 19^+ in the second run was calculated. The width of the collimator of the Faraday cup made it possible to determine the energy with an accuracy of ±0.3 MeV. The values of the two incident beam energies were determined equal to 242.8±0.3 MeV and 264.5±0.3 MeV, respectively. The same values of the beam energy, within the experimental error and taking into account the thickness of the target, were obtained also in the measurements, where the relevant ^{48}Ca charge states (16^+, 17^+, 18^+, 19^+ and 20^+) emerging from the thin C and Au target foils were scanned one after the other along the focal plane of MSP-144. Close to these values were the ones obtained by measuring the elastically scattered beam using the semiconductor detector in the reaction chamber; however the uncertainty in this case was higher because of the approximation of the pulse height defect of the ^{48}Ca ions.

At each energy also the charge-state distributions of the ^{48}Ca ions were measured after passing through the thin carbon target. Both methods mentioned above (scanning by magnetic rigidity with registration with the FC and the measurement of the induced γ-activity) gave consistent results. Fig. 2 represents the charge-state distributions of the ^{48}Ca ions at the two energies 242.8 MeV and 264.5 MeV.

The parameters characterizing the charge-state distribution of a multi-charged ion beam passing through a target foil are the mean charge, the width and the shape of the distribution. The value of the mean equilibrium charge $\bar{q}$ and the distribution width d at the two energies were obtained by fitting the results with a Gaussian distribution:

$$F(q) = \frac{1}{d\sqrt{2\pi}} \cdot \exp\left[-(q-\bar{q})^2/2d^2\right],$$

where the standard deviation d is the charge-distribution width, defined as $d = \left[\sum_q (q-\bar{q})^2 F(q)\right]^{1/2}$.

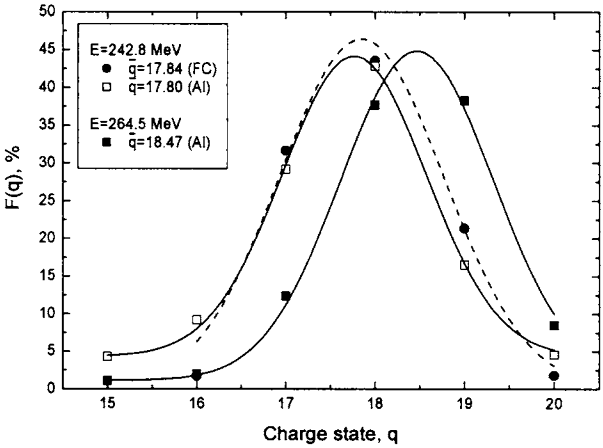

***Fig. 2.** Charge-state distributions of ^{48}Ca ions after passing through a thin C foil, measured with different devices. The distributions at 242.8 MeV, measured with the Faraday cup (FC), are denoted by black dots ● ($\bar{q}$ = 17.84), by the activation of Al – by open squares □ ($\bar{q}$ = 17.80), whereas the distributions at 264.5 MeV, measured by the activation of Al – by black squares ■ ($\bar{q}$ = 18.47). The experimental distributions are described by Gaussians: dashed curve – FC, solid curve – activation measurements.*

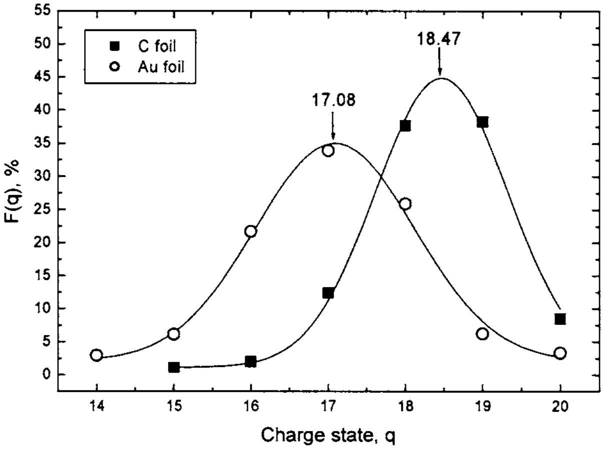

Fig. 3. Charge-state distributions of ^{48}Ca ions at 264.5 MeV after passing through a thin Au foil (●) and a thin C foil (■).

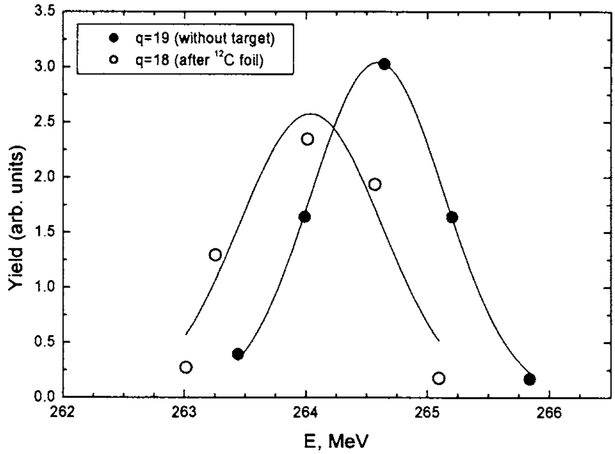

Fig. 4. Energy distributions of ^{48}Ca ions at 264.5 MeV extracted from the cyclotron with q = 19 (●) and of ions emerging from a thin C target foil with q = 18 (○). The experimental points are determined with an accuracy of ±300 keV.

This fit gave the following values for the equilibrium mean charge $\bar{q}$ and the distribution width d: $\bar{q} = 17.8$ and $d = 0.83$ at 242.8 MeV and $\bar{q} = 18.47$ and $d = 0.86$ at 264.5 MeV. The charge-state distribution of the ^{48}Ca ions at 264.5 MeV passing through the 210-μg.cm^{-2} gold target is shown in Fig. 3. In this case the distribution is characterized by different values of the parameters, viz. $\bar{q} = 17.08$ and $d = 1.08$. For comparison the distribution after passing the C foil at the same incident beam energy is also shown in Fig. 3. The experimental values of $\bar{q}$ and d, obtained in the present work, are listed in Table 1 (first row). Fig. 4 presents the energy distribution of the ^{48}Ca ions at 264.5 MeV with charge states q = 19 and 18 as a distribution of energy (calculated from the position distribution along the focal plane of MSP-144), as the ions come directly from the accelerator (i.e. without passing a target). In the same figure, also the distribution of the charge state q = 18, after passing through the thin carbon target, is shown. It can be seen that the thin stripping carbon target does not cause a significant decrease of the projectile energy and does not influence strongly the energy dispersion.

Table 1. Experimental and calculated values of the parameters $\bar{q}$ *and d of the charge-state distribution F(q) of* ^{48}*Ca ions at 242.8 MeV and 264.5 MeV after passing through thin carbon and gold target foils.*

	^{12}C - target		**^{12}C - target**		**^{197}Au - target**	
	242.8 MeV		**264.5 MeV**		**264.5 MeV**	
	$\bar{q}$	d	$\bar{q}$	d	$\bar{q}$	d
Experiment This work	17.80	0.83	18.47	0.86	17.08	1.08
Calculation						
Shima [17]	18.280	0.896	18.520	0.861	16.900	0.861
Baron [19]	17.943	0.862	18.138	0.826	16.274	1.088
Schiwietz [11]	17.663	0.909	17.789	0.873	16.983	1.007
Nikolaev [18]	17.430	0.945	17.580	0.922		

4. Discussion of the results

It is interesting to compare the measured charge-state distributions and the obtained values of the mean equilibrium charge of ^{48}Ca after passing through thin carbon or gold foils with calculations using the known formulae for predicting such quantities for different ions and energies. The values of $\bar{q}$ and d for accelerated ^{48}Ca ions, calculated with the different formulae at the energies used in the present work, after passing a thin carbon target are presented in Table 1. The formulae used are those of Nikolaev-Dmitriev [18] and Schiwietz [11], where $\bar{q}$ and d are power functions of Z and v, and those of Baron [19] and Shima [17], where these quantities depend on Z and v exponentially. Table 1 contains also the values of $\bar{q}$ and d, calculated with the formulae from [11,17,19], for ^{48}Ca ions at 264.5 MeV passing through a thin gold target. One can see from Table 1 that for different energy regions closest to the experimental ones are the values of $\bar{q}$ and d calculated with the formulae of Baron [19] and Shima [17]. The calculations according to Shima [17] and Schiwietz [11] are in good agreement with the experimental data for ^{48}Ca ions passing through an Au target foil. In any case, we have found out that the experimental values for the equilibrium charge states agree within one charge state with the calculations. Also, as expected [2,6,17], we see that the mean equilibrium charge state increases with increasing the beam energy and that a higher-charge state is observed after passing through the lighter C-foil. We shall note, however, that although Schiwietz [11] gives a formula for calculating $\bar{q}$, he does not give one for evaluating the charge-state distribution width d. The same author suggests in every concrete case to calculate d on the basis of the experimental data on charge-state distributions. It should also be noted that none of the approximations concerning the width d takes account of the Z and A of the stripping target foil.

In addition, for ions of low velocity and in the region of higher energies the charge-state distributions deviate from the symmetric Gaussian distribution. For the analysis of asymmetric charge distributions Sayer [8] for the first time introduced an asymmetric function.

In a series of papers [4,9,20] it has been shown that the charge-state distributions of heavy ions can be approximated with χ^2, Gaussian and reduced χ^2 distributions depending on the incident energy. The χ^2 and reduced χ^2 distributions can be represented with a common expression:

$$F(q) = c[2^{\nu/2}\Gamma(\nu/2)]^{-1} t^{\nu/2-1} \cdot \exp(-t/2),$$

where Γ is a gamma function, $c = 2(\bar{q}+2)/d^2$, $\nu = 2(\bar{q}+2)^2/d^2$, $t = c(\bar{q}+2)$ in the case of χ^2-distributions and $c = 2(Z-\bar{q}+2)/d^2$, $\nu = 2(Z-\bar{q}+2)^2/d^2$, $t = c(Z-\bar{q}+2)$ in the case of reduced χ^2-distributions. The χ^2-distribution is usually used for low energy heavy ions ($v \le 2\cdot10^8$ cm.s^{-1}). It has been seen that the Gaussian distribution gives good results at intermediate energies (23keV$\le E_p/A \le 1$-$2\cdot10^3$ keV), whereas the reduced χ^2-distribution – at higher beam energies ($v_p > 3.6\cdot10^8\cdot Z_p^{0.45}$). The boundary between them is rather conditional. Because of this, for the description of the experimental data either a Gaussian or a reduced χ^2-distribution is used [4,9].

We should note that at the ^{48}Ca beam energy 242.8 MeV, the anomaly in the ionization of the K-shell does not lead to asymmetry in the charge-state distribution *F(q)* and, consequently, to changes of the values of $\bar{q}$ and d. On the other hand, for the ^{48}Ca ions at 264.5 MeV the charge-state distribution after passing through the carbon foil can be described by an asymmetric shape, due to the absence in the distribution of ^{48}Ca ions with $q > 20$. Thus the distribution width d in this case turned out to be somewhat narrower compared to the width in the case of ^{48}Ca ions of the same energy, but passing through a gold target (see Table 1).

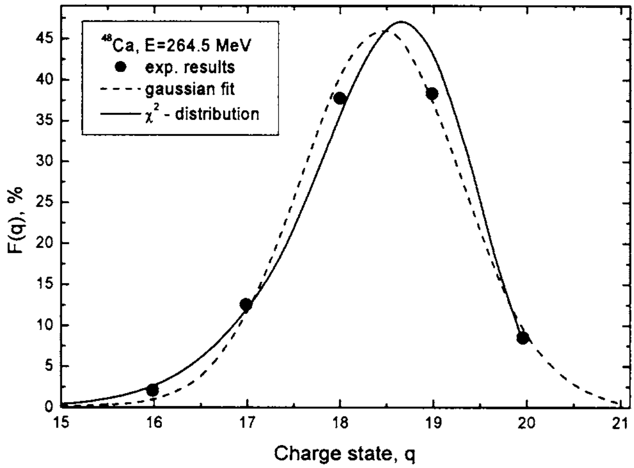

Fig. 5. *Approximation of the charge-state distribution of ^{48}Ca ions at 264.5 MeV with a Gaussian (dashed curve) and a reduced χ^2-distribution (full curve). The black dots (●) denote the experimental results from the present work.*

Fig. 5 shows the experimental data and the results for the charge-state distributions of ^{48}Ca ions at 264.5 MeV after passing through the carbon foil, calculated under the assumption that the charge-state distribution can be described either by a purely Gaussian distribution or by a a reduced χ^2-distribution. It can be seen that the two functions quite well fit the experimental data. This may be due to the relatively small contribution of the charge state $q = 20$ to the total charge-state distribution $F(q)$.

The distribution in energy of the ^{48}Ca ions of a definite charge state on the focal plane in our case depends on three quantities: the dispersion of the magnetic spectrometer D [13], the energy dispersion of the beam at the moment of extraction from the cyclotron and on the way to the magnetic spectrometer, as well as on the straggling in the stripping foil (target) and the interaction with the nuclei of the foil material. For this reason, the uncertainties, obtained by us in determining the energy, concern only its value, but not the width of the energy distribution, in the determination of which all three factors should be accounted for.

The comparison of the experimental charge-state distributions of ^{48}Ca ions with the ones calculated using the formulae of Shima [6] and Baron [15,19] shows that the calculated values should be used only as estimations when one wants to determine the contribution of each charge state to the total charge-state distribution. The problem of the loss and capture of electrons by accelerated heavy ions when passing through thin stripping foils (targets) and the determination of their thickness necessary for the establishment of the equilibrium charge need further experimental studies and comparison with theoretical calculations. Therefore, it is necessary to carry out experiments aimed at the study of charge-state distributions of ions passing through various thin foils of different thickness in a broad range of energies. It is also interesting to compare the charge-state distributions of accelerated isotopes of the same element, e.g. the isotopes of calcium ^{40}Ca and ^{48}Ca at the same velocity and energy after passing thin stripping targets so that to exactly estimate the influence of the velocity and mass number of the projectile on the charge-state distribution. Using magnetic spectrometers makes it possible to perform such measurements with high precision.

5. Acknowledgements

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Зарядовые распределения ускоренных ионов ^{48}Ca

С помощью широкодиапазонного магнитного анализатора со ступенчатыми полюсами измерены зарядовые распределения ускоренных ионов ^{48}Ca для двух значений энергии 242,8 и 264,5 МэВ после их прохождения через тонкие углеродные или золотые фольги-мишени. Проведено сравнение зарядовых распределений ионов ^{48}Ca и средних равновесных зарядов с расчетными значениями. Показано, что расчетные зарядовые распределения можно использовать лишь как оценочные.

Работа выполнена в Лаборатории ядерных реакций им. Г. Н. Флерова ОИЯИ.

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Skobelev N. K. et al. E7-2003-195

Charge-State Distributions of Accelerated ^{48}Ca Ions

A stepped pole broad-range magnetic analyzer has been used to measure the charge-state distributions of accelerated ^{48}Ca ions at the two incident energies 242.8 and 264.5 MeV after passing through thin carbon or gold target foils. The measured charge-state distributions and the mean equilibrium charge of the ^{48}Ca ions are compared with various calculations. It has been shown that the calculations can be used only for evaluation purposes.

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

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