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Упругое рассеяние ионов ^{40}Ca и ^{48}Ca на ядрах ^{208}Pb

В работе измерялись отношения сечений упругого рассеяния к сечению резерфордовского рассеяния ионов ^{40,48}Ca на ядрах ^{208}Pb при энергиях 302 и 252 МэВ соответственно. Наряду с экспериментами по рассеянию ^{40,48}Ca было измерено также упругое рассеяние ионов ^{40}Ar и ^{48}Ti на той же мишени ^{208}Pb, что позволяет определить их относительные характеристики рассения с высокой степенью точности, так как условия ускорения ионов ^{40}Ca и ^{40}Ar, равно как и ионов ^{48}Ca и ^{48}Ti, строго идентичны. Полученные экспериментальные данные анализировались в рамках полуклассической модели упругого рассеяния. Разность радиусов взаимодействия ионов ^{40}Ca и ионов ^{48}Ca с ядрами ^{208}Pb оказалась равной (0.19±0.03) Ферми, что согласуется со стандартным приращением радиуса, определяемого зависимостью $R \sim r_0 A^{1/3}$.

Работа выполнена в Лаборатории ядерных реакций, ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1977

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Elastic Ion Scattering of ^{40}Ca and ^{48}Ca by ^{208}Pb Nuclei

The elastic ion scattering of ^{40}Ca and ^{40}Ar at 302 MeV and of ^{48}Ca and ^{48}Ti at 252 MeV by ^{208}Pb nuclei has been investigated. The data obtained have been analyzed in terms of the classical model for elastic scattering. The distances of closest approach for classical Rutherford trajectories have been measured for ^{40}Ca and ^{48}Ca to differ by 0.19 fm, which corresponds to the normal radius growth defined by the function $R \sim r_0 A^{1/3}$.

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

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The neutron and proton spatial distributions are known to be the main nuclear characteristics which have been the subject of numerous experimental and theoretical studies. It is also known that the scattering experiments may provide rather precise information on the nuclear charge distribution These data essentially underly the present-day concepts of nuclear size and shape.

It is important to obtain an independent information on nucleon radii, which are used in plotting one or another nuclear potential employed to describe different processes of nuclear interaction. From this point of view it is interesting to study the Ca isotopes, the lightest and heaviest ones of which are doubly magic (Z=20, N=20 and 28) and differ from each other by 8 neutrons.

According to ref.[1] the rms charge radii of the ^{40}Ca and ^{48}Ca nuclei are practically equal within 0.01 fm. However, the results of various experiments performed to determine nucleon radii for these nuclei differ substantially.

The principal data on neutron distribution radii have been obtained in the proton, deuteron and α-particle scattering experiments at energies up to 100 MeV [2-5]. In those experiments the nuclear radius was determined as one of the optical potential parameters. In this case the value of the nucleon radius is unlikely to have been determined with the desired accuracy.

The most complete data seem to have been obtained recently in the proton elastic scattering experiments from ^{40}Ca and ^{48}Ca at 1 GeV [6], where the nucleon radius was determined in the framework of the Glauber model of the proton-proton scattering. [7] According to the data obtained, the difference between the rms radii of neutron distributions, Δ_n, in the ^{48}Ca and ^{40}Ca isotopes was found to be equal to

$$\Delta_n = \langle r_n^2 \rangle^{1/2} |_{^{48}Ca} - \langle r_n^2 \rangle^{1/2} |_{^{40}Ca} = 0.14 \text{ fm}.$$

(Note that the value of the normal radius growth, defined by the relation $R = r_0 A^{1/3}$ is equal to 0.22 fm). Naturally, this difference has been found with the accuracy with which the Glauber theory reproduces the true spatial nucleon distribution in the nucleus.

However we believe that the difference in the nucleon radii of the Ca isotopes can be found and determined also in experiments on the elastic scattering of these nuclei by the same target nucleus. At about 5-7 MeV/nucleon the Ca ion wavelength is one hundredth of the sizes of the interacting nuclei. Therefore an analysis of the experimental data can be carried out in terms of the classical concepts of the trajectories of heavy particles in the target nucleus field. In this case the distance of closest approach is related to the scattering angle in the following way

$$D = \frac{a}{2}\left(1 + \csc\frac{\theta}{2}\right), \qquad (1)$$

where $a = Z_1 Z_2 e^2/E$ is the distance of closest approach in head-on collisions, Z_1 is the target nucleus charge, Z_2 is the projectile charge, and E is the c.m. energy.

When D is equal to the sum of nuclear radii in lead and calcium, in the elastic scattering channel one will observe a sharp change in the cross section due to nuclear absorption. At a certain angle Θ_{crit} there will also be observed a sharp decrease in the experimentally measured ratios $(\frac{d\sigma}{d\Omega})/(\frac{d\sigma}{d\Omega})_R$. According to ref. [7] this ratio may be presented in the form

$$\left(\frac{d\sigma}{d\Omega}\right)/\left(\frac{d\sigma}{d\Omega}\right)_R \sim 1 - \exp\left(\frac{[d(\theta) - d_0](A_1^{1/3} + A_2^{1/3})}{\Delta}\right), \qquad (2)$$

where $d = D/(A_1^{1/3} + A_2^{1/3})$, A_1 and A_2 are the mass numbers of the target and projectile nuclei, respectively, and Δ is a parameter characterizing the diffuseness of the nuclei.

Thus, by experimentally determining the angle θ_{crit} one can, within the framework of this approach, determine rather accurately the distance corresponding to the grazing collision of two nuclei. The character of the change in the ratio $\frac{d\sigma_{el}}{d\sigma_R}$ at $\theta > \theta_{crit}$ reflects to a certain extent the nucleon density distribution at the nuclear edge since, as the nuclei approach each other and their surfaces begin to overlap, the elastic scattering cross section will decrease sharply.

Essentially the method described permits the measurement of the interaction radius rather than the nuclear size, and the nuclear radius may be related to nuclear size if one takes into account the contribution of all the inelastic channels which may lead to the distortion of the classical elastic scattering pattern. Taking into account inelastic processes in this manner involves singificant difficuties, and this in turn contributes to an uncertainty in the absolute values of the radii of the colliding nuclei.

However it is reasonable to assume that the difference in the radii of the interactions of ^{40}Ca and ^{48}Ca with ^{208}Pb nuclei is due to the difference between the nucleon radii of the ^{40}Ca and ^{48}Ca nuclei to the extent to which the nucleon density distribution at the nuclear edge influences the nature of the nuclear interaction. Under the given experimental conditions the latter depends on the change of $\frac{d\sigma_{e\ell}}{d\sigma_R}(\theta)$ at $\theta>\theta_{crit}$ the more sensitively the wider the range of the change. In the experimental data given below this range is equal to 1 to 10^{-3}, which has been achieved by using the doubly-magic ^{208}Pb nucleus as a target and by reaching the required accuracy in the measurements of the energy and angular distributions of the ions scattered. For the nuclei ^{40}Ca, ^{48}Ca and ^{208}Pb the first excited levels lie sufficienly high at energies of 3.3, 3.8, and 2.6 MeV, respectively, and this fact lowers substantially the inelastic scattering probability. On the other hand, at the projectile energy

resolution of $\Delta E \sim 2$ MeV it was possible to distinguish clearly the elastic scattering maximum up to $\frac{d\sigma_{e\ell}}{d\sigma_R} \simeq 10^{-3}$.

The experiments were carried out at the 300-cm heavy ion cyclotron of the JINR Laboratory of Nuclear Reactions. A 3x8 mm^2 ion beam was incident on a monoisotopic ^{208}Pb (enriched to 98.3) target 200 mg/cm^2 thick prepared by depositing the target substance onto a 30 mg/cm^2 carbon backing. Scattered ions were detected by a silicon surface-barrier detector with an energy resolution of 30 keV for 5.1 MeV α-particles. The slit support placed at the entrance into the detector separated a 0.5° interval in the reaction plane and a 1.5° interval in the plane perpendicular to the reaction plane. The angular resolution of the detector was not worse than ±0.2°. The beam monitoring was furnished by a second detector positioned at 20° with respect to the beam direction.

Figure 1 shows the energy spectra of the inelastic ion scattering of the ^{48}Ca nucleus by ^{208}Pb at three values of the scattering angle.

Alongside the experiments to investigate the elastic ion scattering of $^{40,48}Ca$ we have also carried out measurements of the ion elastic scattering of the ^{40}Ar and ^{48}Ti nuclei by the same target nucleus, ^{208}Pb. It should be noted that the conditions of accelerating the ^{40}Ca and ^{40}Ar ions as well as of ^{48}Ca and ^{48}Ti ions were strictly identical. This has made it possible to determine the relative scattering characteristics of these ions with a high degree of accuracy.

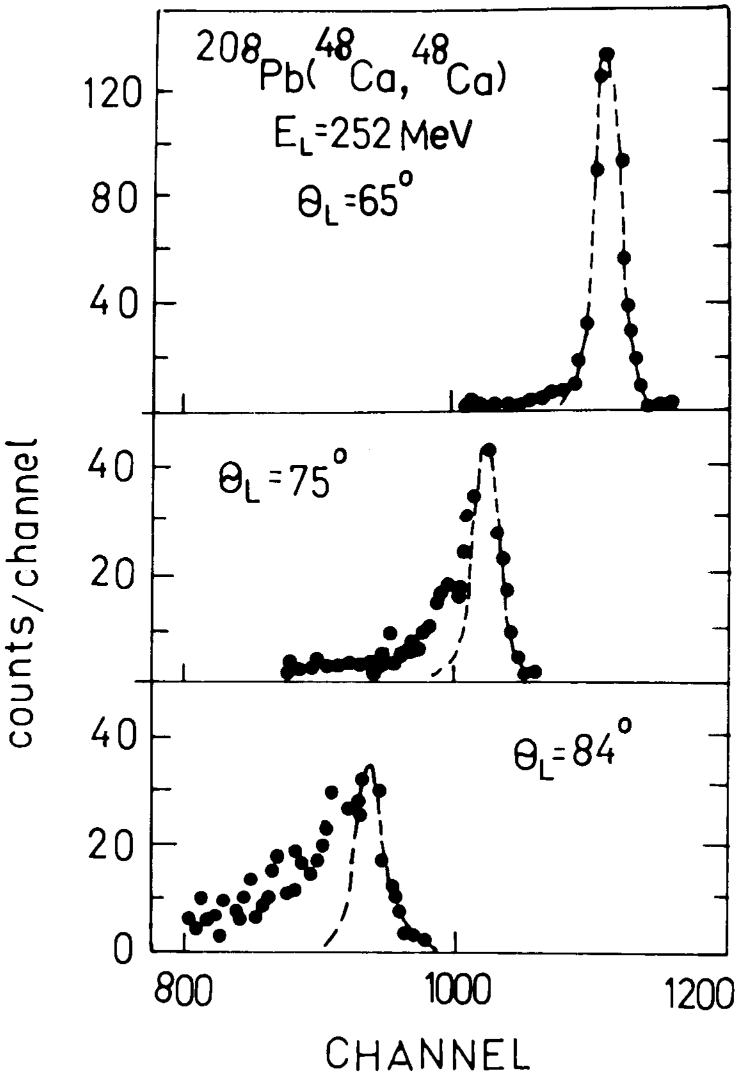

Fig.1. Energy spectra of the ^{48}Ca ions elastically scattered by the ^{208}Pb nuclei at angles of 65°, 75° and 84°.

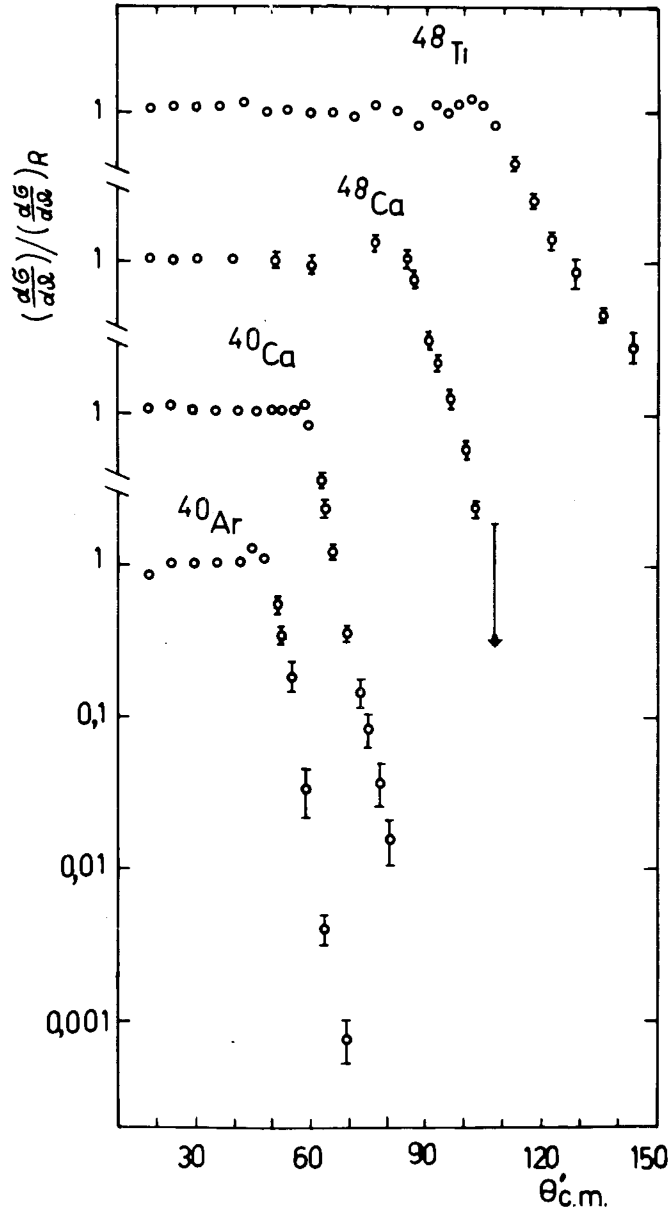

Fig.2. Elastic scattering angular distributions for ^{40}Ar, ^{40}Ca, ^{48}Ca and ^{48}Ti ions scattered by ^{208}Pb.

The experimantally determined ratios of the elastic scattering cross section to the Rutherford scattering one, $\frac{d\sigma}{d\Omega}/(\frac{d\sigma}{d\Omega})_R$, for four reactions as a function of the angle $\theta_{c.m.}$ are presented in figure 2. As is seen from this figure, the experimental points are in good agreement with the calculated Rutherford scattering cross section up to θ_{crit}, but a sharp decrease in the cross section is observed at $\theta > \theta_{crit}$. The errors given in the figure were determined from the statistics obtained in the elastic scattering peak measurements. For the ^{40}Ar and ^{40}Ca ions the elastic peak has been determined reliably up to the angles at which $\frac{d\sigma}{d\sigma_R} \sim 10^{-3}$, while for ^{48}Ti and ^{48}Ca up to the angles corresponding to this ratio equal to 10^{-2}.

The distributions obtained may be transformed into the curves $\frac{d\sigma}{d\sigma_R} = f(D)$ according to eq.(1). These curves are presented in figure 3. One can see from this figure that the experimental points for all the four reactions lie within the experimental accuracy on the curves that may be described by an empirical relation of the following form

$$d\sigma/d\sigma_R = 1 - P_{absorp.}(D)$$

$$P_{absorp.}(D) = \begin{cases} 0 & \text{at } D > D_0 \\ 1 - \exp(\frac{D - D_0}{\Delta}) & \text{at } D < D_0 \end{cases} \qquad (3)$$

If the nuclear radii exactly follow the relation $R = r_0 A^{1/3}$, then all the points of the curves in figure 2 should be described by a dashed curve representing the dependence of $d\sigma/d\sigma_R$ on d, where $d = D/(A_1^{1/3} + A_2^{1/3})$ (fig.4). One can see that the experimental

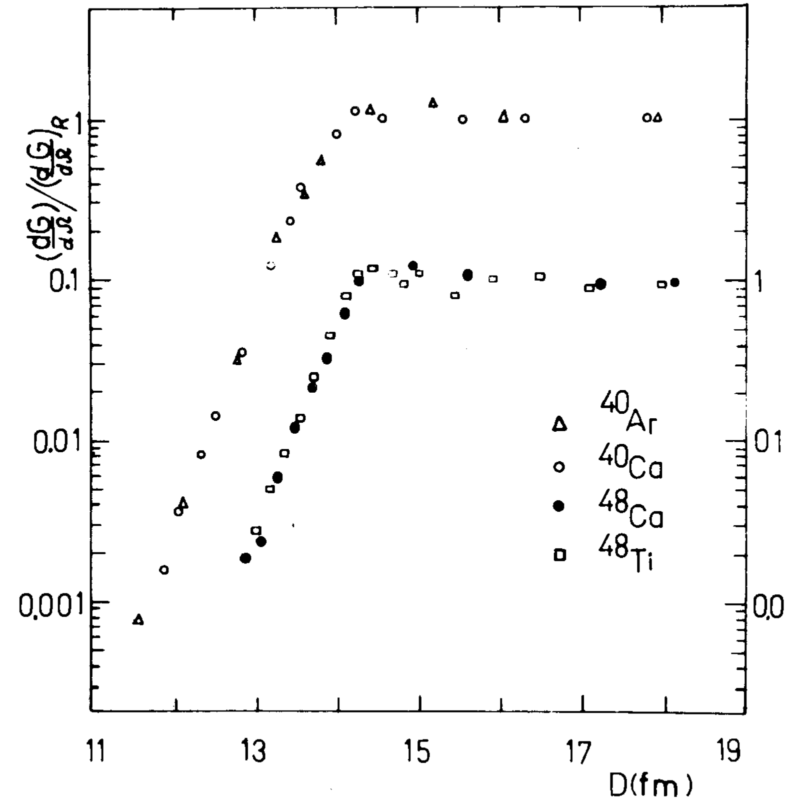

Fig.3. Ratio of elastic scattering to Rutherford scattering as a function of the distance of closest approach for Coulomb trajectories.

points obtained for reactions induced by ^{40}Ar, ^{40}Ca, ^{48}Ca, and ^{48}Ti well agree with each other and with the assumptions that $R \sim A^{1/3}$ and the nucleon density distributions at the edges of these nuclei have the same shapes.

The results of data handling using the least-square method and eq.(3) are shown in the table.

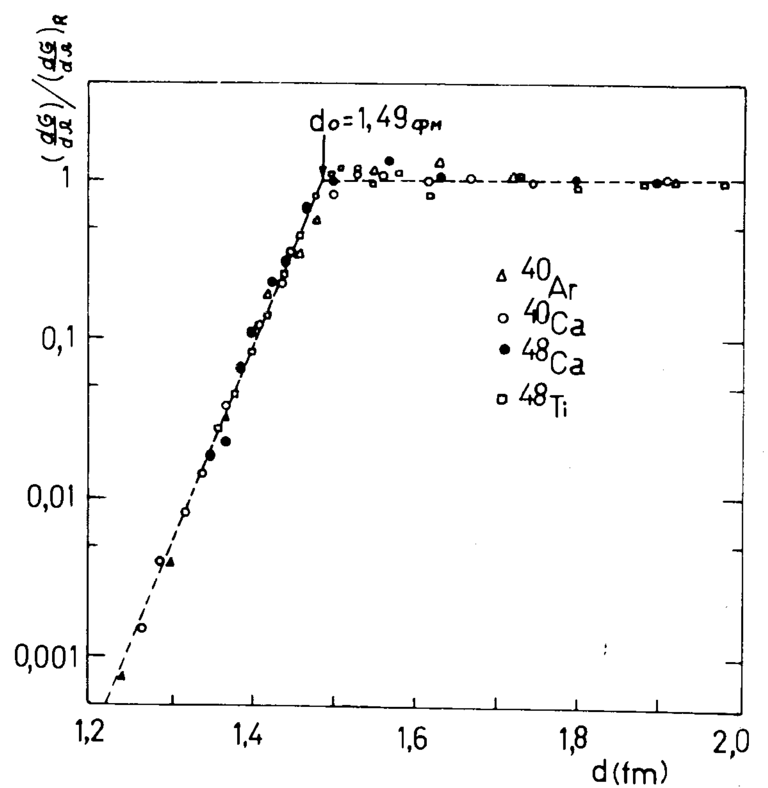

Fig.4. Elastic scattering cross sections for ^{40}Ar, ^{40}Ca, ^{48}Ca and ^{48}Ti ions scattered by ^{208}Pb plotted versus $d=D/(A_1^{1/3}+A_2^{1/3})$. The cross sections are divided by the Rutherford cross sections.

From this one can see that the difference between the D_0 values for the ^{40}Ca and ^{48}Ca nuclei is equal to 0.19±0.03 fm, and this corresponds, within the experimental accuracy, to the normal radius growth determined by the relation $R \sim A^{1/3}$.

The fact that the curve for ^{48}Ca in fig.4 has practically the same dip angle as that

Table

Ion	Lab. energy (MeV)	D_0 fm	Δ fm	d_0 fm	$r_{1/4}$ fm
^{40}Ar	302	14.03 ± 0.02	0.35 ±0.01	1.51	1.45
^{40}Ca	302	13.98 ± 0.02	0.33±0.01	1.49	1.44
^{48}Ca	252	14.17 ± 0.02	0.30 ±0.01	1.48	1.44
^{48}Ti	252	14.21 ± 0.02	0.34 ±0.01	1.49	1.44

for the ^{40}Ar, ^{40}Ca, and ^{48}Ti nuclei indicates that the nature of the nucleon density distribution at the edges of these nuclei slightly differs. The table shows that the difference Δ(^{48}Ca) - Δ(^{40}Ca) is equal to 0.03±0.015. This value is somewhat smaller than that obtained in ref./6/, where a(^{48}Ca) - a(^{40}Ca) = 0.06±0.02 fm.

Since the rms radii of the charge distributions in the ^{40}Ca and ^{48}Ca nuclei are practically the same, and the difference observed between the nucleon radii is about 0.2fm, one can draw some conclusions concerning the structure of the ^{48}Ca nucleus. Similarly to the ^{40}Ca nucleus, the ^{48}Ca nucleus has a doubly magic core (Z = 20 and N = 20) above which the eight extra neutrons are arranged in such a way that they increase the nuclear size by about 0.2 fm. For ^{48}Ti nearly the same situation occurs.

The neutron excess on the surface of the ^{48}Ca nucleus, from our point of view, deserves special attention for a study of neutron correlations and for searches for bound states, which may take place in this unique nucleus.

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