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Measurement of fresnel diffraction of 29 mev alpha particles on ^{24}Mg, ^{25}Mg, ^{59}Co, ^{197}Au, ^{209}Bi nuclei

Abstract: The angular distributions of the differential cross sections of elastic scattering of alpha particles on ^{24}Mg, ^{25}Mg, ^{59}Co, ^{197}Au, ^{209}Bi at 29 MeV, obtained on the beam of alpha particles ejected from isochronous cyclotron U-150m with regulated ion energy, were measured. The geometry of the scattering chamber is described and the optimal parameters of the spectrometric system giving best angular resolution of the experimental setup were obtained. The parameters of nuclear targets on which the experiments were made are presented. The areas of Rutherford scattering, Fresnel and Fraunhofer diffraction were determined in a wide mass range of incident particles and target nuclei for the ion beam energy 29 MeV, the results which are presented in the form of the "diffraction diagram". The experimental data are described in the framework of the parameterized phase analysis and its analytic version taking into account higher approximations of the parameter of nucleus non-sphericity.
Key words: elastic scattering of alpha particles, Fresnel nuclear diffraction, method of parameterized phase analysis, even-even nuclei, odd-odd nuclei, nuclear non-sphericity.

Introduction

Common wave properties of electromagnetic and de Broglie waves in the experiment are expressed in the manifestation of both the Fraunhofer-type (diffraction on the disk) and the Fresnel-type diffractions (diffraction on an infinite half-plane). Nuclear Fraunhofer diffraction in the elastic and inelastic scattering enables us to determine the values and signs of nuclear non-sphericity for even-even nuclei having collective rotational and vibrational states.

Nuclear Fresnel-type diffraction enables us to obtain the same parameters for odd nuclei. In this work we experimentally obtained angular distributions of differential cross sections in angular ranges typical for both Fraunhofer and Fresnel nuclear diffractions for even-even and odd nuclei. We managed to obtain unique nuclear parameters characterizing these nuclei as rotational spheroids as well as values and signs of non-sphericity.

Methods of measurement

The cross sections of scattering processes were measured on the beam of alpha particles ejected from the fourth ion guide of 1.5m isochronous cyclotron U-150M of Institute of nuclear physics (INP, Almaty, Kazakhstan). Figure 1 shows the transportation scheme for the accelerated ion beam from the cyclotron to the scattering chamber located at a distance of 24 meters from the exit of the beam from the accelerator chamber. It includes a system of quadrupole lenses, rotary, distributing, two targeting magnets, and a system of passive collimators. A description of all elements of the cyclotron ion guide is presented in [1]. All targeting and correction elements provide a beam of charged particles with an aperture not more than 0.4° and a diameter of 3 mm on the target.

Targets and detectors are placed in the scattering chamber, one flange of which is connected to the exit ion guide of the cyclotron, and the second flange – to the Faraday cup with a current integrator. In one calibration mode in the scattering chamber it is possible to make precise measurements at small scattering angles (from 3 to 30°), whereas in the other calibration mode it is possible to make measurements in a wide range of angles (10°≤θ≤170°). The scattering chambers, in which scattered alpha particles were registered, and their detecting elements are described in detail [1]. The scheme of the scattering chamber geometry and the calculation of the angular resolution of the experimental setup are presented in [2].

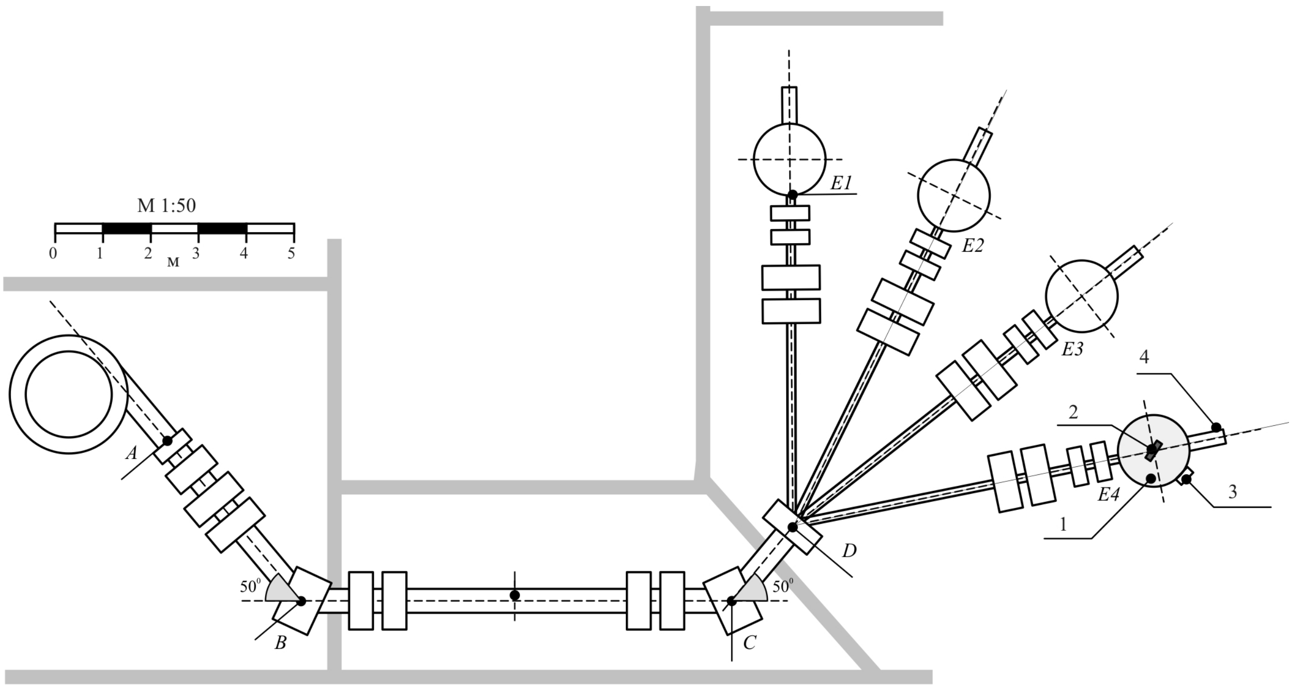


Figure 1 –Isochronous cyclotron U-150m with a regulated ion energy and a transportation scheme of the ion beam to the scattering chamber. A, B, C, D, E are the characteristic points and the turning points of the accelerated ion beam; 1 - scattering chamber; 2 - studied target; 3 - the turning detector of scattered particles; 4 - Faraday cup.

Table 1 presents the results of calculations of angular resolution at the apertures of collimators for the nearer telescope of the Δ*E*-*E* detector (NT) and the farther telescope of the Δ*E*-*E* detector (FT), in which the experiments were performed. All notations are defined in [1, 2]. In the experiments, we used targets of isotopically enriched chemical elements (Table 2).

Table 1 – Geometry of the experiment and its angular resolution

Chamber	d_1, mm	d_2, mm	L, mm	l, mm	L_{td}, mm	d_{sd}, mm	d_t, mm	$\Theta\Delta_k$, degree	$\Theta\Delta_{td}$, degree	$\Theta\Delta_{sd}$, degree
NT	3.0	3.0	700.0	630.0	189.0	3.0	8.40	0.49	3.45	3.49
FT	3.0	3.0	700.0	630.0	849.0	3.0	8.40	0.49	0.77	0.91

Table 2 – Nuclear targets

Isotope	Target characteristic	Thickness,mg/cm^2	Isotopic enrichment, %
^{24}Mg	metal. foil	0.816	99.9
^{25}Mg	metal. foil	0.78	97.87
^{59}Co	metal. foil	~2	100
^{197}Au	metal. foil	~1	100
^{209}Bi	metal. foil	~2	100

The system of registration and identification of elastically and inelastically scattered alpha particles is based on the standard ΔE-E technique based on the simultaneous measurement of specific energy loss of a charged particle in the ΔE -detector and its total kinetic energy in the E-detector. The total energy resolution of the alpha-spectrometer for registration of secondary particles is about 2%. All measurements were made on the measuring and computing complex of the laboratory, based on the system of multidimensional analysis of processes including ORTEC and PC / AT.

To observe the diffraction patterns in the angular distributions of the elastic scattering of charged particles the following conditions must be satisfied [3, 4]:

$$\begin{cases} kR \sim 1, & \text{Rutherford scattering} \\ kR >> 1, \quad n \sim 1 & \text{Fraunhofer-type diffraction} \\ kR >> 1, \quad n >> 1 & \text{Fresnel-type diffraction,} \end{cases} \tag{1}$$

where $k = \sqrt{2 \cdot M \cdot E}/\hbar$ – wave number; $n = Z_1 \cdot Z_2 \cdot e^2/\hbar \cdot \nu$ – Sommerfeld parameter; R – radius of interaction of alpha particles from the nucleus. Conditions (1) correspond to different diffraction regions depending on the charge of the target nucleus, the charge and energy of the incident particle. Such areas were first determined in [5] as a "diffraction diagrams". Figure 2 shows the diffraction areas of various nuclear diffraction phenomena for incident particles with an energy of 29 MeV. To observe oscillations of Fresnel-type nuclear diffraction the boundary angle between Fresnel and Fraunhofer nuclear diffractions corresponded to $\theta_c > 0.1$, where $\theta_c = 2 \cdot \mathrm{arctg}(n/(l_0 + 0.5))$.

In [1, 6] the boundary angles in a wide range of energies, mass numbers of incident particles and target nuclei were obtained. Based on the chosen conditions, the elastic scattering of alpha particles on ^{24}Mg, ^{25}Mg, ^{59}Co, ^{197}Au and ^{209}Bi was measured. Figure 3 shows the experimental data for ^{24}Mg and ^{25}Mg.

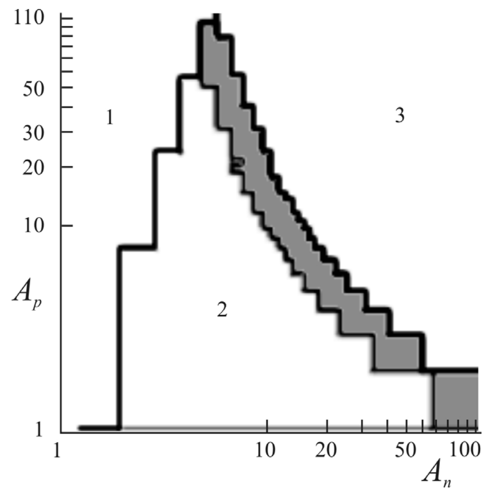


Figure 2 – The diffraction surface for the energy of incident particles 29 MeV. A_p is the mass number of the incident particle; A_n is the mass number of target nuclei; 1 - area of Rutherford scattering; 2 - area of Fraunhofer-type diffraction; 3 - area of Fresnel-type diffraction; the dark area - area of interference of the two types of diffraction.

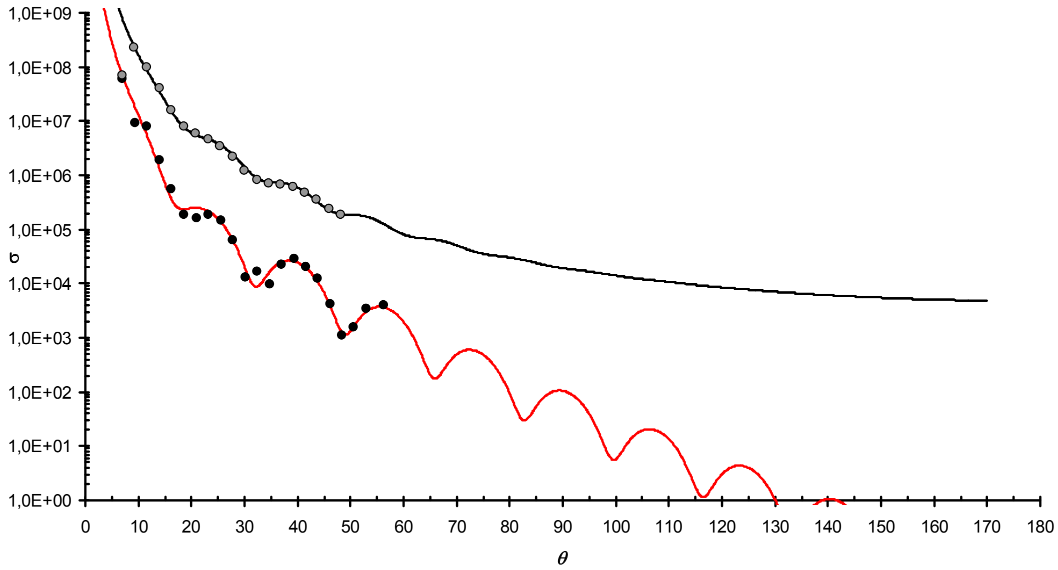


Figure 3 – The angular distribution of the differential cross sections for elastic scattering of alpha particles with energy of 29 MeV on isotopes of magnesium. Black points correspond to the experimental data on ^{24}Mg; gray points correspond to ^{25}Mg; the curve is their theoretical estimate

Theoretical analysis

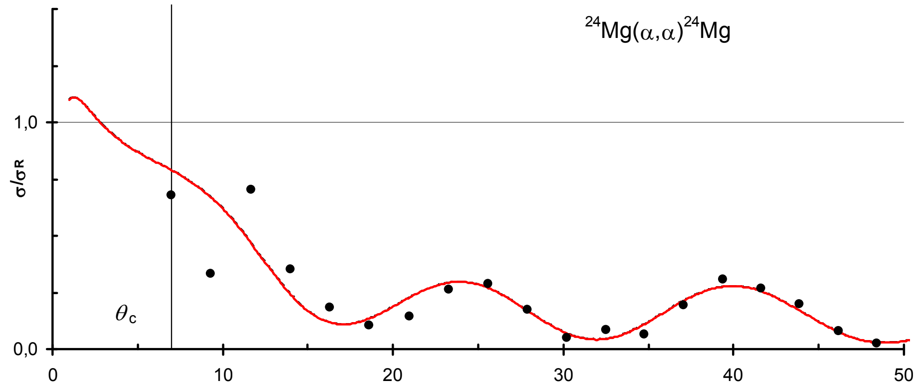
Figure 4 a-c shows the results of the experiment, which shows that, depending on the wave number k and the Sommerfeld parameter n the competing areas of the Fresnel and Fraunhofer diffraction widen to the angular area, differentiable in the experiment. This figure also presents the theoretical analysis of the experimental data based on the theory of Fresnel diffraction developed in [7, 8], in which the scattering amplitude is described by:

$$f(\theta)=\left[G(\theta)+\mathrm{sign}(\theta_c-\theta)\frac{\exp(-ix-i\pi/4)}{2\sqrt{\pi x}}\right]f_R(\theta)+\tilde{f}^{(+)}(\theta)+\tilde{f}^{(-)}(\theta), \qquad (2)$$

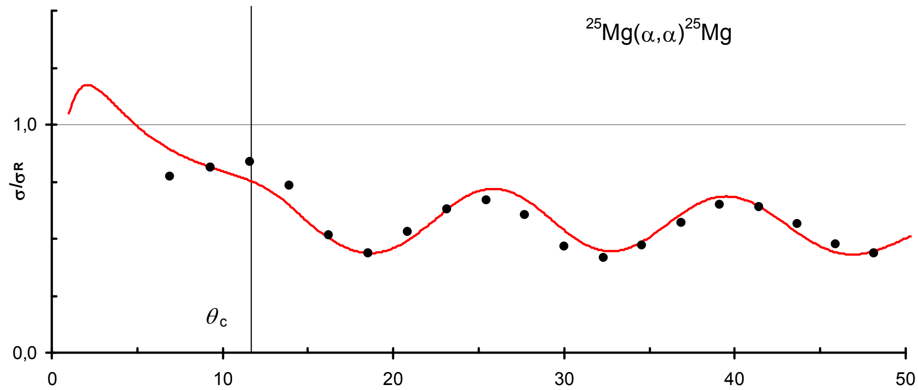
where all the symbols are defined in the works of Kotlyar-Shebeko [7, 8]. The Fresnel-type phase shift in the oscillations is determined by [8]:

$$\varphi^{(\pm)}=\mathrm{sign}\beta_2\left\{\mathrm{arctg}\left[S(|y_\pm|)/C(|y_\pm|)\right]-\frac{1}{3}|y_\pm|\right\}, \qquad (3)$$

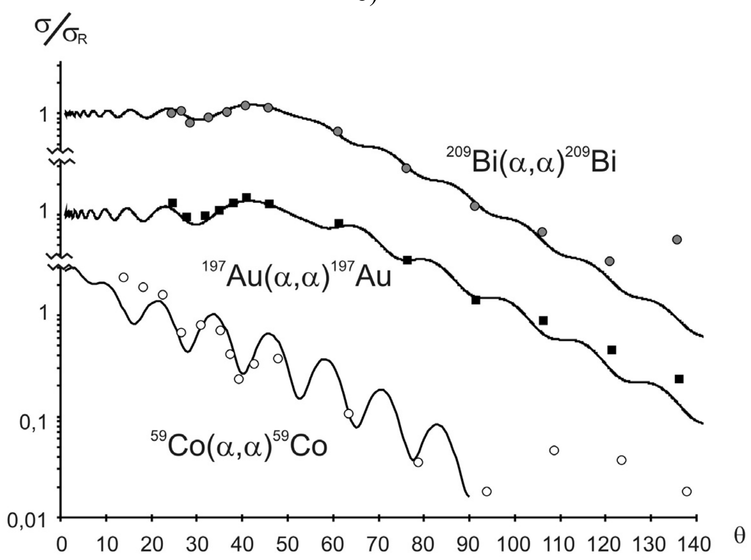
where $C(x)$ and $S(x)$ are Fresnel integrals; $y_\pm=-\frac{3}{4}\sqrt{\frac{5}{\pi}}\frac{R_0}{R_{int}}\beta_2 L(\theta_c\pm\theta)$, where R_{int} – radius of the area of strong interaction; $L=l_0+1/2$.



a)



b)



c)

Figure 4 –The angular distribution of elastic scattering of 29 MeV alpha particles on different nuclei.
Points correspond to the experiment; the curve corresponds to the diffraction theory (2).

When comparing the theoretical and experimental curves in the Fraunhofer diffraction region (Figure 3), it is seen that they are in satisfactory agreement, which enables us to determine the values and signs of deformation for even-even nuclei (taking into account the inelastic scattering).

Conclusion

The most interesting result of this work is the comparison of approximations by the method of the parameterized phase analysis (PPA) and the Kotlyar-Shebeko method (KSh), as though the classic parameterized analysis gives a detailed description of the experimental curve, it does not include such important characteristics as a sign of the quadrupole nuclear deformation. This comparison gives an opportunity to reveal the phase shift between the corresponding maxima and minima between the PPA and KSh for odd nuclei. Therefore, for the first time in measurements of angular distributions of differential cross sections for elastic and inelastic scattering of alpha particles the authors managed to measure the effect of "flattening-elongation" both in the even-even and odd nuclei. The above analysis of the Fresnel and Fraunhofer diffractions shows that the nucleus of ^{59}Co is flattened, and the nuclei of ^{197}Au and ^{209}Bi are elongated.

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