CHARGE COLLECTION METHOD OF TOTAL REACTION CROSS-SECTION MEASUREMENTS FOR ALPHA PARTICLES

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The electric charge collection method was developed for measurements of the total reaction cross-section for the interaction of alpha particles with nuclei. The effect of electron capture by alphas in the target material was reduced by carbon foil placed behind the target. The results for natural targets of Ni, Co, Cu, Pd, Ag, In, Sn, Ta, Pt, Au, Pb, and Bi at alpha particle energies 23.2 MeV and 27.8 MeV are presented.

1. *Introduction*

Determination of the optical model parameters from the analysis of the elastic scattering angular distributions suffers from many ambiguities [1]. These ambiguities are especially troublesome for composite particles, which are strongly absorbed in nuclear matter [2]. It was suggested [3] that the total reaction cross-section for alpha particles with energy close to the Coulomb barrier should be particularly sensitive to the selection of the optical model parameters. In order to investigate this problem measurements of the total reaction cross-section as a function of energy or as a function of atomic number of the target nuclei are necessary. Such an experiment was undertaken in the Institute of Nuclear Physics, Cracow, using the alpha particle beam from the U-120 cyclotron.

Measurements in the vicinity of the Coulomb barrier were achieved by appropriate selection of the target nuclei instead of varying the particle energy. Since a large number of targets have to be investigated, the charge collection method of total reaction cross-section measurements was adopted as it seemed to be less time-consuming that the conventional beam attenuation method.

The present paper gives a full description of the experimental technique and procedure as applied to alpha particles together with the obtained results.

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2. *Experimental arrangement*

The charge collection method was primarily used by Bearpark *et al.* [4] for protons and deuterons. The principle of the method can be briefly explained as follows:

The alpha particle beam passes through a thin target made of electrically conducting material and is stopped in the Faraday cup. The attenuation of the beam is given by the ratio:

$$A = \frac{q}{Q}$$

where q is the charge transferred to the target system and Q denotes the total charge collected in the Faraday cup in the same time interval. The target system gains some charge even when the target is removed from the beam. This background attenuation defined

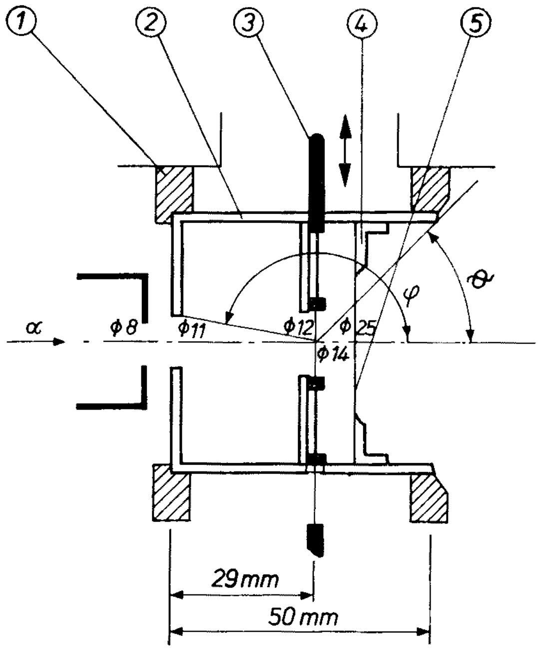

Fig. 1. Details of the target system. 1. insulators, 2. target chamber, 3. targets holder, 4. stripper holder, 5. carbon stripper

by $A_{out} = q_{out}/Q_{out}$ must be determined separately. Thus the true attenuation is given by the difference:

$$A = A_{in} - A_{out}$$

where A_{in} is attenuation with the target in the beam. For thin targets the attenuation is connected with the total reaction cross-section σ_R by the formula

$$\sigma_R = \frac{A}{n}$$

where n indicates the number of target nuclei per cm^2. This simple formula is subject to several corrections connected with the following effects:

1. change of the alpha particle charge due to the electron capture in the target material,
2. escape of the charged reaction products through the entrance and exit diaphragms of the target system (correction for inelastic processes),
3. capture of the elastically scattered alpha particles by the target system (correction for elastic scattering).

The target system is shown in Fig. 1. It consists of a metallic cylinder containing target and stripper holders. The system is electrically insulated from the rest of the apparatus. The charge left in the system was accumulated in a high stability capacitor ($\sim 3 \cdot 10^4$ pF) and the voltage across the capacitor was measured by means of a vibrating reed electrometer. The total charge Q transmitted through the target system collected in the Faraday

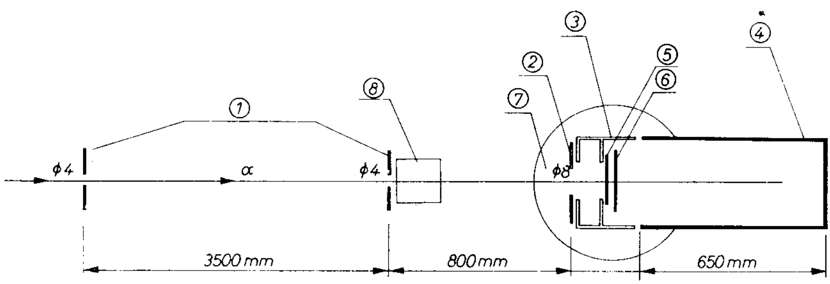

Fig. 2. The experimental set up. 1. collimator slits, 2. antiscattering baffle, 3. target chamber, 4. Faraday cup, 5. target, 6. carbon stripper, 7. pole of 1 kGs magnet, 8. pole of corrective magnet

cup was measured by a current integrator. In order to minimize the background attenuation special precautions has been taken to assure a good collimation of the beam (see Fig. 2) and enough low pressure. The whole system was placed in a magnetic field of about 1 kGs in a direction perpendicular to the beam line to suppress the effect of the emission of secondary electrons. The slight deflection of the beam spot on the target due to this magnetic field was compensated by an additional magnet situated in the neighbourhood of the last collimating slit (see Fig. 2).

3. *Corrections*

The three correction to the raw attenuation measurements mentioned in Sec. 2 were treated in a different manner.

a) Electron capture

Ions and atoms passing through a target capture or lose electrons due to interaction with atoms of the target material. In a thin layer of the order of 100 Å an equilibrium of these two competing processes is established. Thus the beam can be considered as a combination of a few fractions, each of them corresponding to one of the possible degrees of ionization of atoms. After equilibrium has been reached the average charge of the ion is independent of the target thickness and the charge state of the incident beam but depends on the energy of the moving particles and on the atomic number of the target material. For alpha particles at energies around 25 MeV only a small fraction of the single ionized helium atoms of the order of 10^{-4} will occur. Although small in itself this effect is comparable to the charge collection effect due to nuclear reactions and may completely obscure the measurement of the total reaction cross-section. The process of two electron capture is negligible.

Supposing that the attenuation measurements were done for target thicknesses greater than that necessary to establish the equilibrium of the charge state of the beam we may write for the ratio

$$\frac{q}{Q} = \frac{1}{2}\frac{N_1}{N_2} + C\sigma_R \Delta x,$$

where N_1 and N_2 indicate the numbers of single and double ionized helium atoms in the beam behind the target, Δx — the target thickness, σ_R — the total reaction cross-section,

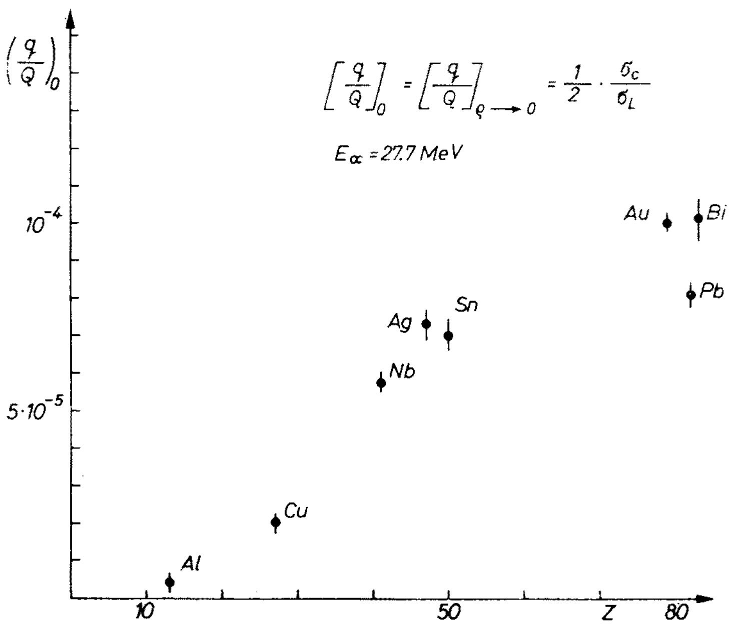

Fig. 3. The dependence of q/Q_0 extrapolated to the zero target thickness on atomic number Z

C — the proportionality constant. Extrapolating to the zero target thickness we can evaluate N_1/N_2. The ratio N_1/N_2 in the equilibrium state is equal to the ratio of the cross-section for the electron capture to that for the electron loss σ_c/σ_1. Fig. 3 shows the results of measurements of $\frac{1}{2}N_1/N_2$ by the method described above as a function of the Z number of the target nuclei. The dependence is very strong, the ratio σ_c/σ_1 being by an order of magnitude larger for the heavy elements than for the lighter ones. This general trend can be explained by the following considerations. As is known [5], the ratio σ_c/σ_1 decreases rapidly with the increasing velocity of the moving ions. According to Bohr [6], for light absorbers:

$$\frac{\sigma_c}{\sigma_1} \propto \left(\frac{v_0}{v}\right)^5$$

where v_0 is the orbital velocity of the helium electron and v is the velocity of the ion. For a heavy nucleus its orbital electrons move faster than for a light one. Smaller velocity of such electrons relatively to the passing ions will cause an enhancement of the capture cross-section for heavy elements as compared with lighter ones. Since a very thin layer of the target is sufficient to obtain equilibrium of the electron exchange process, the ratio

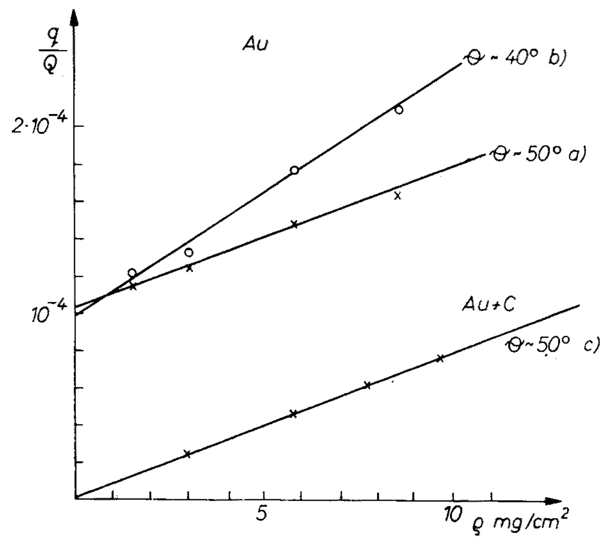

Fig. 4. The influence of the different geometries and the carbon stripper on the attenuation measurements: *a*) and *b*) — gold targets, two geometries, without carbon stripper, *c*) — gold targets, with carbon stripper

q/Q extrapolated to zero thickness is sensitive only to the properties of the target surface facing the beam stopper. We may then expect that the results of the measurements will be sensitive to the surface contamination of the target by light nuclei such as oxygen and carbon. This may explain the somewhat lower value of q/Q for Pb nuclei (see Fig. 3) as compared with the neighbour nuclei.

It was found that for the carbon target the effect of electron capture was negligible. Therefore in measurement of attenuation a thin carbon layer about 0.1 mg/cm^2 thick was placed behind the investigated target to convert the beam to the double ionized state. As can be seen from Fig. 4, this additional carbon target eliminates the effect of electron captures and the attenuation line extrapolated to the zero target thickness crosses the q/Q axis at a value very close to zero.

b) Correction for inelastic precesses

The charged reaction products correction

$$\Delta\sigma_R^{\text{inel}} = \int_0^{2\pi}\int_0^{0} d\sigma_{\text{inel}}$$

was measured in an independent experiment for all investigated targets recording spectra of the emitted charged particles by means of a rotatable semiconductor detector. The experimental details were similar to those of Ref. [7].

In the charge collection method the inelastic correction requires discrimination between the single and double charged particles. The single charge reaction products escaping from the target system give a contribution to the attenuation data because the incoming

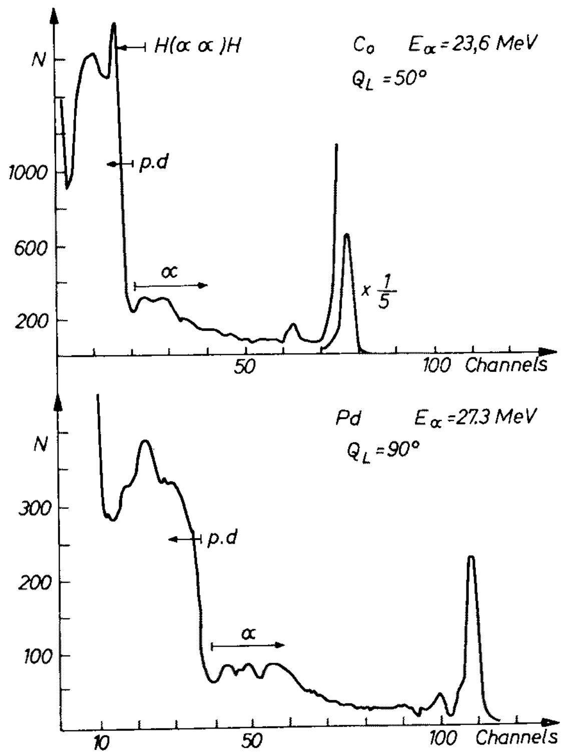

Fig. 5. The spectrum of the charged reaction products emitted from Co and Pd targets. Arrows show the energy regions where the single and the double charged particles are recorded

alpha particles bring in the double charge. Therefore in the correction for inelastic processes the proton and deuteron yields should be multiplied by the factor 0.5. In order to separate the spectra of single and double charged particles a thin counter technique was applied. The voltages on the surface barrier silicon detector were so adjusted that the thickness of the depletion layer was just sufficient to stop elastically scattered alpha particles. In this way the spectra of deuterons and protons were shifted towards lower energies. As the spectra of helium ions are concentrated mostly around the energy corresponding to the height of the Coulomb barrier, the two groups of single and double charged particles could be separated (see Fig. 5).

The angular distributions for charged reaction products were measured from 10° to 90° in LAB system. For angles smaller than 10° the necessary cross-sections were obtained by extrapolation of the experimental data. The corrections for single and double charged products were calculated by integration of the angular distributions of these two kinds of reaction products over the angle region of the exit port of the target system. Because of the small value of the solid angle of the entrance port the correction connected with the escape of reaction product through it was negligible.

In this way the correction for inelastic processes was obtained for medium weight nuclei. For heavy nuclei only its upper limit was determined, since the charged reaction products were lost in the large background in spectra coming from slit scatterings. However, in this case the correction for inelastic processes is less significant because the cross-sections for the emission of charged particles are small.

c) Correction for elastic scattering

The correction for elastic scattering of alpha particles

$$\Delta\sigma_R^{el} = \int_0^{2\pi}\int_\Theta^{\pi} d\sigma_{el}$$

was calculated from the measured elastic scattering angular distributions for the same energies of alpha particles.

4. *Results and discussion*

Results for the total reaction cross-section together with the relevant corrections are shown in Table I.

Although the aim of this work was to measure the total reaction cross-sections in the vicinity of the Coulomb barrier some lighter nuclei, such as Co, Ni, and Cu, were also included in order to check the reliability of the charge collection method by comparison with the existing data for these nuclei obtained by means of the conventional transmission method. As can be seen from Table I, the agreement is very good within the limits of experimental errors.

In order to test the selfconsistency of the experimental procedure measurements were made with two target system geometries. These two geometries differed by the angle Θ (see Fig. 1) which determined the elastic and inelastic corrections to the measured attenuation. Two exit ports of the target system were used corresponding to the angles $\Theta_1 = 48.8°$ and $\Theta_2 = 69.8°$. For heavy nuclei the elastic scattering correction is very large so that the 70° geometry is more favourable. As can be seen from Table I the two geometries led to the same results for the total reaction cross-sections within the experimental errors.

TABLE I

Element	Geometry	Energy MeV	Attenuat. data σ mb	Elastic correction σ_{el} mb	Inelastic correction σ_{in} mb	σ_R mb	σ_R averaged mb	σ_R other data mb
Co	50°	23.14	1271 ± 51	20 ± 5	90 ± 15	1341 ± 53	1322 ± 37	1313 ± 36[7]
	70°	23.07	1156 ± 46	3 ± 1	150 ± 25	1303 ± 52		E_α = 24.7 MeV
Ni	50°	23.18	1124 ± 45	25 ± 5	197 ± 30	1296 ± 53		1305 ± 53[7]
								E_α = 24.7 MeV
Cu	50°	23.2	1255 ± 50	27 ± 5	112 ± 25	1350 ± 56		1393 ± 33 [7]
								E_α = 24.7 MeV
	50°	23.10	1470 ± 59	189 ± 19	69 ± 30	1350 ± 69	1346 ± 44	
Nb	70°	23.01	1300 ± 52	29 ± 3	72 ± 20	1343 ± 56		
	50°	27.59	1446 ± 58	59 ± 6	95 ± 42	1482 ± 72		
	70°	27.63	1367 ± 53	7 ± 1	102 ± 28	1462 ± 60	1470 ± 46	
	50°	23.27	1463 ± 58	278 ± 28	25 ± 5	1210 ± 65	1260 ± 42	
	70°	23.27	1289 ± 52	36 ± 4	40 ± 8	1293 ± 53		
Pd	50°	27.80	1467 ± 59	57 ± 6	48 ± 15	1458 ± 61	1433 ± 42	
	70°	27.84	1352 ± 53	7 ± 1	71 ± 22	1416 ± 57		
	50°	23.21	1548 ± 62	338 ± 34	30 ± 7	1240 ± 71	1292 ± 44	
	70°	23.14	1330 ± 53	50 ± 5	47 ± 12	1327 ± 55		
Ag	50°	27.66	1470 ± 59	66 ± 7	60 ± 15	1461 ± 61	1443 ± 42	
	70°	27.70	1341 ± 54	6 ± 1	88 ± 22	1423 ± 58		
	50°	23.26	1640 ± 66	350 ± 35	32 ± 10	1322 ± 75	1336 ± 46	
	70°	23.16	1341 ± 54	46 ± 5	49 ± 16	1344 ± 57		
In	50°	27.76	1496 ± 60	33 ± 10	76 ± 15	1479 ± 63	1474 ± 44	
	70°	27.80	1365 ± 55	8 ± 1	112 ± 23	1469 ± 60		
	50°	23.23	1597 ± 64	354 ± 36	43 ± 12	1286 ± 74	1367 ± 47	
	70°	23.26	1401 ± 56	50 ± 5	67 ± 17	1418 ± 59		
Sn	50°	27.79	1521 ± 61	93 ± 10	90 ± 20	1518 ± 65	1509 ± 45	
	70°	27.82	1378 ± 55	9 ± 1	132 ± 30	1501 ± 63		
	50°	23.23	3200 ± 128	2651 ± 106	< 10	549 ± 166	647 ± 61	
	70°	23.25	1432 ± 57	769 ± 31	< 10	663 ± 66		
Ta	50°	27.74	2052 ± 82	1096 ± 42	20 ± 10	976 ± 93	1068 ± 47	
	70°	27.78	1208 ± 48	142 ± 5	30 ± 15	1096 ± 50		
	50°	23.20	3705 ± 160	3294 ± 132	< 10	411 ± 208	681 ± 78	
	70°	23.21	1793 ± 72	1068 ± 42	< 10	725 ± 84		
Pt	50°	27.72	2554 ± 102	1397 ± 51	< 10	1157 ± 114	1089 ± 48	
	70°	27.76	1282 ± 51	208 ± 8	< 10	1074 ± 52		
	70°	23.10	1809 ± 72	1229 ± 49	< 10	580 ± 87		250 [11]*
Au	50°	27.72	2521 ± 101	1664 ± 66	< 10	857 ± 121	996 ± 48	635 [11]*
	70°	27.76	1251 ± 50	230 ± 9	< 10	1021 ± 51		

TABLE I (continued)

Element	Geometry	Energy MeV	Attenuat. data σ mb	Elastic correction σ_{el} mb	Inelastic correction σ_{in} mb	σ_R mb	σ_R averaged mb	σ_R other data mb
	70°	23.20	1725 ± 69	1267 ± 51	8 ± 1	466 ± 86		
Pb	50°	27.90	2642 ± 106	1866 ± 72	2 ± 0.5	778 ± 130	801 ± 44	
	70°	27.95	1105 ± 44	305 ± 12	4 ± 1	804 ± 46		
	70°	23.27	1770 ± 71	1530 ± 61	25 ± 3	265 ± 94		377 ± 16.3 [10]
Bi	50°	27.77	2730 ± 109	1864 ± 75	4 ± 0.5	870 ± 132	804 ± 44	E_α = 23.65 MeV
	70°	27.82	1088 ± 44	300 ± 12	8 ± 1	796 ± 46		760 ± 44
								E_α = 27.5 MeV

* interpolated from reference of [11].

The inelastic corrections for heavy nuclei are in general negligible. However, in the case of Bi and Pb nuclei the reaction products of the ^{209}Bi(α, n), ^{209}Bi(α, 2n), and ^{208}Pb(α, n) reactions are alpha-radioactive. The alpha particles from the alpha-decay can escape through the entrance and exit ports of the target system which will decrease the measured attenuation. In the case of the ^{209}Bi(α, 2n) reaction the alpha-radioactive ^{211}At nuclei are formed which have the half-life time 7.2 hr. This time is sufficiently long as compared with the time of the attenuation measurement (3 min) so the effect of the alpha-activity can be neglected. In the case of the ^{208}Pb(α, n) and ^{209}Bi(α, 2n) reactions the residual nuclei have half-life times much shorter than the time of the attenuation measurement. In these cases the corrections for the escaped alpha particles were calculated from the known cross-sections for the corresponding reactions [9, 10]. The corrections connected with the formations of the alpha-radioactive residual nuclei were then taken into account in the determination of the total reaction cross-sections.

Since the (α, n) and (α, 2n) reactions are predominant for heavy nuclei in our energy region, the σ_R value can be obtained by summing these two cross-sections. Thus obtained values for the Bi nucleus are also given in the last column of Table I.

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