Nuclear Matter Sizes and Isoscalar Octupole Transition Rates of $^{204,206,208}$Pb from 104 MeV $\alpha$-Particle Scattering

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Differential cross sections for elastic and inelastic scattering of 104 MeV $\alpha$-particles from $^{204,206,208}$Pb were measured with high angular accuracy. The experimental results were analysed on the basis of a semimicroscopic folding model in order to determine the matter distributions at the nuclear surface and the transition densities. Using phenomenological parametrisations of the densities the analyses of elastic scattering yield rms radii of $\langle r^2 \rangle^{1/2} = 5.55 \pm 0.06$ ($^{204}$Pb), $5.57 \pm 0.06$ ($^{206}$Pb), $5.63 \pm 0.05$ ($^{208}$Pb) fm. Various sensitivities affecting the results were studied. From the inelastic cross sections for the $3_1^-$-states octupole transition probabilities and transition radii were derived by using different methods proposed in literature.

1. Introduction

Though $\alpha$-particles are complex and, in principle, interact in a more complicated way than nucleons do the strong absorption in nuclear matter restricts the interaction to the nuclear surface, in particular for scattering into the forward hemisphere. Thus, the fact that $\alpha$-particles are tightly bound and have $S=T=0$ leads to a rather uncomplicated interpretation. In recent years in addition to the wellknown purely phenomenological descriptions simple semimicroscopic reaction models represented by the first term of a multiple scattering expansion of the optical potential have been applied with great success [1]. Designated as folding models they relate in a transparent way the interaction potential to the ground state nucleon distribution and to the transition densities of simply structured collective states.

In this paper we report experimental investigations of elastic and inelastic scattering of 104 MeV $\alpha$-particles from $^{204,206,208}$Pb. The experiments were motivated by the attempt to determine the nuclear matter sizes of the even lead isotopes and to extract isoscalar transition rates from inelastic scattering cross sections. The analyses (using the coupled channels method when inelastic cross sections are included) derive the interaction potentials from a semimicroscopic folding model approach and result in information about the nucleon distributions. Part of the results, in particular with regard to neutron-proton rms radii differences have been published elsewhere [2]. Here we consider in detail the influences of various possibilities in treating phenomenologically the imaginary part of the potential and of different phenomenological parametrisations of the densities, and attempt to explore the limits of systematic uncertainties. We also compare the obtained size information with results of various different methods. Particularly $^{208}$Pb has often been discussed and studied with this aspect. From the inelastic scattering cross sections of the first $3^-$-states transition radii and isoscalar octupole transition rates are derived by applying and comparing different methods.

2. Experimental Procedure and Results

The measurements used the scattering facilities [3] at the Karlsruhe Isochronous Cyclotron. Some characteristic data of the targets used are given in Table 1. The 104 MeV $\alpha$-particle beam was energy analysed to about 50 keV FWHM and focussed to a beam spot of about 1.5 mm $\varnothing$ at the target position with an angular divergence of less than 0.3° FWHM. The angular acceptance of the detectors was 0.15° which has been conveniently attained with reasonable widths.
of the defining detector slits due to the relatively large scattering chamber (150 cm \( \varnothing \)) used. The absolute zero of the angular scale was determined with an accuracy of better than 0.1° by measuring the sharp diffraction minimum of the elastic scattering from \(^{90}\text{Zr}\) around \( \theta_{\text{lab}} = 18^\circ \). A \(^{90}\text{Zr}\) target was chosen for that purpose as for Pb the sharp diffraction minima appear at larger scattering angles where the cross sections are very small.

The scattered \( \alpha \)-particles were detected by four Si surface barrier detectors of 4 mm thickness. The detectors were mounted to the same movable arm with angular distances of 1.5° between each other. The electronic setup consisted of standard NIM-modules. Biased amplifiers selected and stretched the energy interval of about 5 MeV at the high energy end of the energy scale. The spectra were accumulated by use of a CDC 3100 computer. The overall energy resolution was about 150 keV FWHM.

Particle identification techniques were not applied as the maximum energy loss of protons, deuterons, tritons and \(^{3}\text{He}\)-particles in 4 mm silicon is 26, 37, 43 and 93 MeV, respectively. Thus these pulses were cut off by the biased amplifiers.

The angular distributions of the scattered \( \alpha \)-particles were measured between \( \theta_{\text{lab}} = 10.8^\circ \) and \( \theta_{\text{lab}} = 47.8^\circ \) in steps of 0.5°. Once the detectors had been set to a definite scattering angle the spectra for all three targets were measured in turn one after the other, thus improving the relative angular accuracy of the differential cross sections between the three targets. The beam currents were varied from a few nA at very forward angles up to 500 nA for larger angles. Details of the experimental arrangement and the data handling are given in Reference 4.

The measured differential cross sections for elastic scattering and for inelastic scattering from the first \( 3^-\) -states are shown in Figure 1. The error bars quoted include the angular uncertainty of \( \pm 0.1^\circ \) which has been transformed into cross section errors. Since the uncertainties of target thickness, detector acceptance, and integrated beam current determined the absolute scale only within 10% accuracy we normalized the data at small forward angles to optical model cross sections which show very small variations for any reasonable description.

### Table 1. Characteristic data of the targets used

<table>
<thead>
<tr>
<th>Target</th>
<th>Isotopic Enrichment [%]</th>
<th>Thickness [mg/cm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{204}\text{Pb})</td>
<td>99.73</td>
<td>4.08</td>
</tr>
<tr>
<td>(^{206}\text{Pb})</td>
<td>99.80</td>
<td>3.73</td>
</tr>
<tr>
<td>(^{208}\text{Pb})</td>
<td>99.22</td>
<td>8.00</td>
</tr>
</tbody>
</table>

### 3. Elastic Scattering Analyses

#### 3.1. Macroscopic Optical Model

The conventional optical model analysis of the elastic scattering using the phenomenological standard Saxon-Woods form (with volume absorption) for the nuclear potential:

\[
U(r) = -V_0 f_v(r) - i W_0 f_w(r)
\]

\[
f_{v,w}(r) = \left[ 1 + \exp \left( \frac{r - R_{v,w}}{a_{v,w}} \right) \right]^{-1}
\]

and a Coulomb potential derived from an uniformly charged sphere with \( R_c = 1.3 \cdot A^{1/3} \) fm results in the theoretical cross sections (solid lines) and parameter values shown in Figure 1. The corresponding volume integrals of the real potentials

\[
J_R = \frac{V_0}{A} \int_0^{R_c} f_v(r) r^2 dr = \frac{4}{3} \pi V_0 R_c^3 \left[ 1 + \left( \frac{\pi a_v}{R_v} \right)^2 \right] / 4A
\]

are

\[
J_R = 312.0 \text{ MeV fm}^3 \quad \text{for } \^{204}\text{Pb}
\]

\[
J_R = 312.9 \text{ MeV fm}^3 \quad \text{for } \^{206}\text{Pb}
\]

\[
J_R = 315.5 \text{ MeV fm}^3 \quad \text{for } \^{208}\text{Pb}
\]

From previous studies \([5, 6]\) it is known that a parameter set with \( V_0 = 120 \sim 130 \) MeV seems to be favored for \( \alpha \)-particle energies of about 100 MeV. In the present analyses somewhat higher \( V_0 \)-values were obtained but we did not look for alternative parameter families. In general, studies of the ambiguities require data of a larger angular range exceeding the diffraction region. This was out of the scope of our present investigation.

#### 3.2. Folding Model Analyses

##### 3.2.1. Procedures

A semimicroscopic description of the elastic scattering of \( \alpha \)-particles from nuclei starts with the intuitive expression \([1]\) for the real central interaction potential

\[
U_R(r) = \int \rho_m(r) V_{\text{eff}}(r, r) d^3 r,
\]

where \( \rho_m(r) \) is the total nucleon density distribution and \( V_{\text{eff}}(r, r) \) is an adequate effective \( \alpha \)-particle bound nucleon interaction. We used the Gaussian form of the interaction potential proposed by Bernstein \([7, 8]\)

\[
V_{\text{eff}}(r, r) = \lambda_R V_0 \exp(-|r - r|^2/\mu_0^2)
\]

with revised parameter values \( V_0 = 40 \) MeV and \( \mu_0 = 1.95 \) fm which are based on a more recent value of the \( \alpha \)-particle's rms radius \([9]\). The energy dependent "renormalization" parameter \( \lambda_R \) was phenomenologically determined to be \( \lambda_R = 0.996 \) by studies of elastic \( \alpha \)-particle scattering from light nuclei, particularly from \(^{40}\text{Ca}\) \([4, 10]\). Exchange effects play a minor role.