Coulomb nuclear interference as a tool to investigate the nuclear potential

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The sub-barrier excitation function of the octupole vibrational state at 2.615 MeV in ^{208}Pb is analyzed within the coupled-channels framework. It is shown that the position of the minimum in the excitation function, which is due to the destructive interference of the Coulomb and nuclear scattering amplitudes, is very sensitive to the nuclear potential for both the ground state and the octupole state. A different nuclear potential for the 3^- state may arise from changes in the matter distribution of ^{208}Pb due to the particle-hole excitations. The present analysis places a strong limit on the 3^- nuclear potential diffuseness, giving a difference of only $\Delta a_0 = 0.011 \pm 0.004$ fm between the ground state and 3^- state diffuseness.

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I. INTRODUCTION

The nuclear potential has been extensively used as a construct allowing many-body nucleonic interactions to be handled in models describing nuclear collision dynamics. Within the successful coupled-channels model, a Woods-Saxon parametrization of the nuclear potential is commonly adopted. The diffuseness parameter a_0 of the Woods-Saxon potential is one of the key parameters determining many of the model predictions.

Because of the doubly magic nuclei involved, the reaction $^{16}O + {}^{208}Pb$ has been studied in great detail, and a range of high-precision experimental data for various near-barrier processes is available. Measurements of elastic scattering, quasielastic scattering, and fusion cross sections have been analyzed, using both the optical model and the coupled-channels model. Earlier optical-model analyses of the elastic scattering excitation function required diffuseness values between 0.4 and 0.7 fm [1,2]. A recent analysis of the total quasielastic scattering excitation function within the coupled-channels framework (taking into account couplings to low-lying collective excitations in ^{208}Pb) resulted in a diffuseness of $a_0 = 0.67 \pm 0.02$ fm [3]. On the other hand, calculations describing fusion cross-section measurements of $^{16}O + {}^{208}Pb$ required diffuseness values of $a_0 \sim 1.18$ fm and $a_0 \sim 1.56$ fm to reproduce above- and below-barrier cross sections, respectively [4,5].

The large values of diffuseness required to fit the fusion data, and the difference in the diffuseness values derived from above- and deep–sub-barrier data, have recently sparked investigations into the most appropriate physical basis (for example a sudden or adiabatic approach) for determining the form of the nuclear potential [6–9]. Experimental confirmation of the shape of the nuclear potential in the outer region, and the value of the diffuseness in particular, is therefore of importance. Peripheral processes such as elastic and quasielastic scattering below the fusion barrier have already proven to be a sensitive measure of the diffuseness of the nuclear potential in the outer region [3,10–12]. Similar to other fields of physics, interference phenomena in nuclear scattering have also been recognized as a sensitive method for such studies. An analysis of the interference pattern in the quasielastic Mott scattering cross section as a function of the scattering angle for $^{58}Ni + {}^{58}Ni$ gave a diffuseness of $a_0 = 0.62 \pm 0.04$ fm [13]. Furthermore, the interference between the complex Coulomb and nuclear scattering amplitudes of collective excitations has been recognized (and exploited) in inelastic scattering measurements [14–18]. This Coulomb nuclear interference (CNI) typically causes a minimum in the excitation function of low-lying collective states. The position of the minimum is determined by the relative phase between the Coulomb and nuclear amplitudes and, therefore, provides a sensitive measure of the nuclear interaction.

In this work, the excitation function of the 3^- state at an energy of $E_x = 2.615$ MeV in ^{208}Pb has been interpreted within the coupled-channels framework to test the consistency of the nuclear potential diffuseness value, constrained by results from a recent analysis of the total quasielastic excitation function [3].

II. EXPERIMENTAL DETAILS AND RESULTS

Experimental data from Ref. [3] were supplemented by additional measurements using ^{16}O beams provided by the 14UD tandem accelerator of the Australian National University. Energies ranged from below to above the fusion barrier V_B ($0.8 < E_{cm}/V_B < 1.1$). They were incident on a ^{208}PbS target of thickness 100 μg/cm^2, mounted perpendicular to the beam axis. To resolve the different peripheral reaction processes and minimize background events, the scattered particles were detected using a gas-Si $\Delta E - E$ telescope, which was mounted at $\theta_{lab} = 161^\circ$. Two Si surface barrier detectors (monitors) placed symmetrically around the beam axis at angles of $\pm 30^\circ$ were used for normalization. A typical recorded $\Delta E - E$ spectrum is shown in Fig. 1. The three distinct bands correspond to the charge transfers $\Delta Z = 0, 1, 2$, where ΔZ indicates the number of transferred unit charges e. Using this setup, events corresponding to the excitation of

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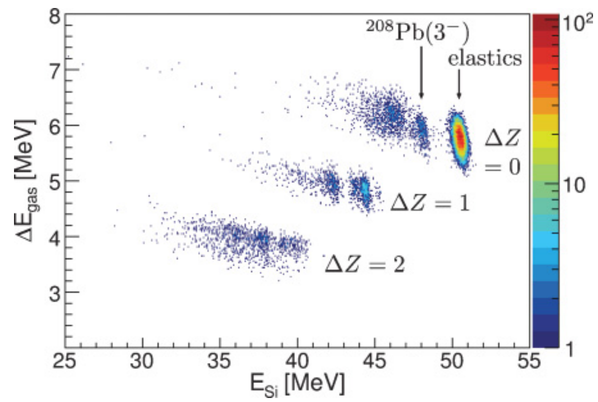

FIG. 1. (Color online) Typical spectrum recorded with the $\Delta E - E$ detector system at $E/V_B = 0.98$ for the reaction $^{16}O + ^{208}Pb$. The abscissa shows the energy deposited in the Si detector. The maximum at $E_{Si} \sim 51$ MeV corresponds to elastic scattering events. For details see text.

the 3^- state in ^{208}Pb were easily separated from the nearby elastic scattering events and events due to n transfer, at higher and lower laboratory energies, respectively. Excitation probabilities were extracted by gating on the corresponding energy region in the spectrum and dividing the resulting number of events by the sum of elastic counts in the two monitors. Overall normalization was obtained as in Ref. [3].

The extracted excitation function for the probability of exciting the octupole vibrational state at an energy of $E_x = 2.615$ MeV in ^{208}Pb is shown in Fig. 2. Earlier results [16,18] using the same accelerator were shifted in energy (by $\sim$0.3 MeV) to account for the different centrifugal potential due to different laboratory angles of the back-angle detector and are shown as open squares and triangles. The agreement between the different data sets is satisfactory, since within uncertainties both give the minimum of the CNI at $E/V_B = 0.92$.

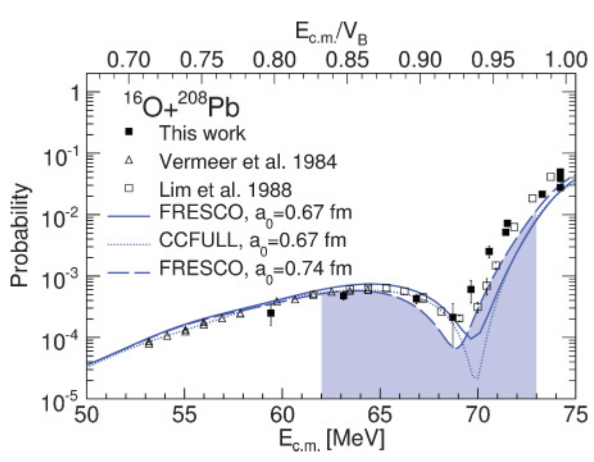

FIG. 2. (Color online) Excitation function of the 3^- state in ^{208}Pb. The solid (dashed) curve corresponds to FRESCO (CCFULL) calculations using $a_0 = 0.67$ fm; the dotted curve uses $a_0 = 0.74$ fm. The shaded area indicates the energy region used in fitting the experimental data. Experimental data from Vermeer *et al.* [16] and Lim *et al.* [18].

III. INTERPRETATION

Calculations were carried out using the coupled-channels codes FRESCO [19] and CCFULL [20], since not all calculations presented here could be done with one code alone. Prior to data interpretation using these codes, calculations were carried out to determine (i) the consistency between the two codes and (ii) the dependence of the position of the CNI minimum on the parameters of the nuclear potential and to transfer couplings. All calculations use a Woods-Saxon nuclear potential, generally with a depth $V_0 = 80$ MeV. For a given diffuseness, the radius parameter was adjusted to reproduce the experimental average fusion barrier energy of $V_B = 74.5$ MeV [5]. This step is a key part of the process and was carried out in the following way [3]: For the uncoupled calculations, the barrier energy is uniquely defined and was matched with the average fusion barrier energy. For calculations that include couplings, the radius parameter was further adjusted to reproduce the calculated uncoupled fusion cross section at above-barrier energies ($1.1 < E_{cm}/V_B < 1.4$), ensuring that the average barrier energy is maintained. A short-range imaginary potential was included, with depth $W = 30$ MeV, radius $r_W = 1.0$ fm, and diffuseness $a_W = 0.4$ fm, resulting in a negligible strength in the surface region. Coupled-channels calculations were therefore insensitive to reasonable variations of the imaginary potential parameters. The coupling strength to the 3^- state was the same as in Ref. [3].

The FRESCO and CCFULL calculations for the 3^- excitation function are shown in Fig. 2 for $a_0 = 0.67$ fm. Due to the isocentrifugal approximation built into CCFULL, these calculations show a deeper CNI minimum than the corresponding FRESCO calculations. The latter include couplings of the orbital angular momentum to the 3^- state, which causes a spreading in the centrifugal potentials and leads to a broadening of the CNI minimum. Despite this difference, both codes give the same position of the CNI minimum, but worse χ^2 values must be expected from the calculations using CCFULL. FRESCO itself is not able to *exactly* reproduce the probability at the bottom of the CNI minimum. This may be related to higher order couplings involving the 3^- state (e.g., multiphonon excitations and multistep transfer processes), which have not been included in the model calculations.

Both FRESCO and CCFULL calculations of the 3^- excitation function were confirmed to be independent of the depth of the nuclear potential, by varying V_0 between 80.0 and 853.0 MeV, and each time adjusting the radius parameter r_0 to reproduce V_B. The latter value for V_0 corresponds to the depth of the nuclear potential as used in Ref. [3]. For $E/V_B < 1.0$, both nuclear potentials give the same results for the 3^- excitation function, as well as for the total quasielastic scattering cross section. This outcome is expected, as both processes are only sensitive to the outer part of the nuclear potential.

To investigate the effect of transfer channels on the position and shape of the CNI minimum, FRESCO calculations were performed including couplings to the neutron transfer channel ^{208}Pb(^{16}O,^{17}O)^{207}Pb$_{g.s.}$, as well as to the proton transfer channel ^{208}Pb(^{16}O,^{15}N)^{209}Bi$_{7/2^-}$, with spectroscopic factors given in Table I. Results showed that the position and depth of

TABLE I. Spectroscopic factors of the dominant transfer channels ^{208}Pb(^{16}O,^{17}O)^{207}Pb$_{\rm g.s.}$ and ^{208}Pb(^{16}O,^{15}N)^{209}Bi$_{7/2^-}$.

Nucleus	Spectroscopic factor	Source
^{207}Pb$_{\rm g.s.}$	1.74	[21]
^{17}O$_{\rm g.s.}$	1.03	[22]
^{209}Pb$_{7/2^-}$	1.12	[23]
^{15}N$_{\rm g.s.}$	1.26	[24]

the CNI minimum were unaffected by the included transfer-channel couplings.

The sensitivity of the position of the CNI minimum to the diffuseness of the nuclear potential was investigated. Results using the diffuseness $a_0 = 0.67$ fm, which gives the best fit for the total quasielastic scattering data [3], show that the position of the CNI minimum cannot be reproduced satisfactorily (see Fig. 2). A larger value of the diffuseness parameter $a_0 = 0.74 \pm 0.01$ fm gives the best fit to the 3^- excitation function in the region $62 < E_{\rm c.m.} < 73$ MeV (dotted curve in Fig. 2). However, this is not in agreement with the quasielastic scattering data shown in Fig. 3. This discrepancy could have a physical explanation, as detailed in the following paragraphs.

The collective octupole vibration results from the mixing of many particle-hole excitations [25]. These excitations should in principle lead to a change in the nuclear-matter distribution, resulting in a different nuclear potential for the collective excited state compared to the ground state. Traditionally, within the coupled-channels framework, both vibrational and rotational excitations use the same nuclear potential as the elastic (ground-state) channel. Introducing a different nuclear potential for the 3^- state in ^{208}Pb will cause a change of the relative phase between the ^{208}Pb(g.s.) and ^{208}Pb(3^-) channel wave functions, which effectively can lead to an energy shift of the CNI minimum.

The coupled-channels code CCFULL was modified, because it more readily accommodates the input of different

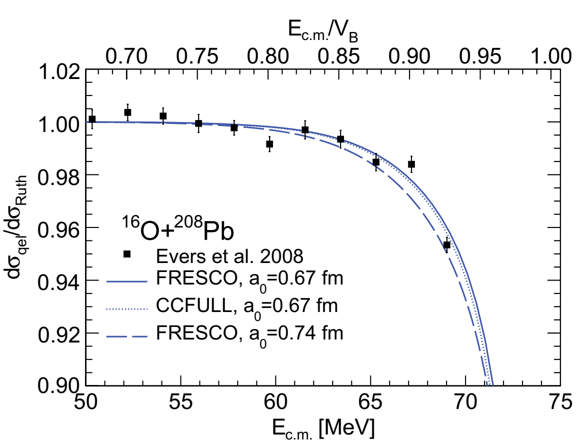

FIG. 3. (Color online) Total quasielastic scattering excitation function $d\sigma_{\rm qel}/d\sigma_{\rm Ruth}$. The solid (dashed) curve corresponds to FRESCO (CCFULL) calculations using $a_0 = 0.67$ fm; the dotted curve uses $a_0 = 0.74$ fm. Experimental data from Evers *et al.* [3].

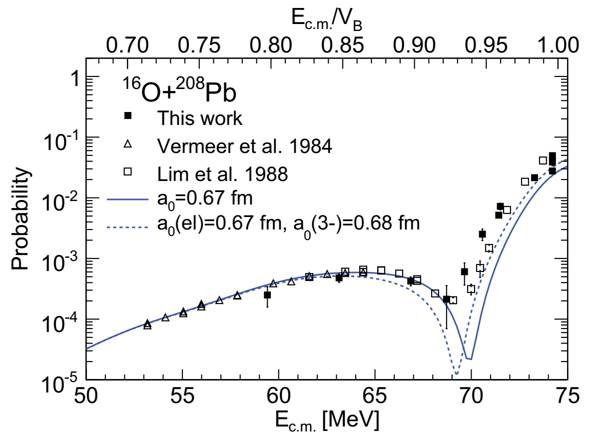

FIG. 4. (Color online) Excitation function of the 3^- state in ^{208}Pb. The solid curve uses a single diffuseness parameter $a_0 = 0.67$ fm for both the ground state and the 3^- state, and the dashed curve uses a value of $a_0^{3^-} = 0.682$ fm for the 3^- potential diffuseness. Experimental data are same as in Fig. 2.

nuclear potentials for each channel separately. The same real and imaginary nuclear potential parameters as in the FRESCO calculations were used for the elastic channel, with a diffuseness of $a_0^{\rm el} = 0.67$ fm for the ground-state nuclear potential, while the diffuseness of the 3^- nuclear potential $a_0^{3^-}$ was kept as the only free parameter. Fitting the coupled-channels calculations to the experimental data in the region $62 < E_{\rm c.m.} < 73$ MeV thus gave the best-fitting diffuseness parameter for the nuclear potential of the octupole vibrational state.

Figure 4 shows that the position of the CNI dip is very sensitive to small variations of the ^{208}Pb(3^-) diffuseness parameter. By minimizing the $\chi^2_{\rm dof}$ value as a function of $a_0^{3^-}$, the best-fitting value for the 3^- diffuseness parameter including its uncertainty is obtained, as shown in Fig. 5. This

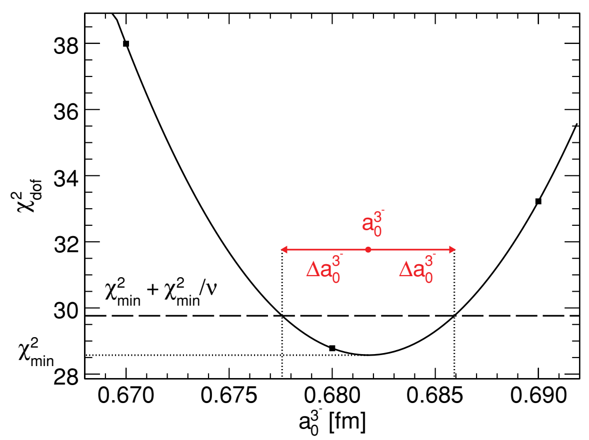

FIG. 5. (Color online) Illustration of the determination of the uncertainties for the 3^- diffuseness parameter. $\chi^2_{\rm min}$ is the $\chi^2_{\rm dof}$ value corresponding to the best value for $a_0^{3^-}$; ν corresponds to the number of degrees of freedom (dof). The large values of $\chi^2_{\rm dof}$ are due to the small errors in the 3^- excitation function and the fact that CCFULL cannot reproduce the probability at the bottom of the CNI minimum, see text.

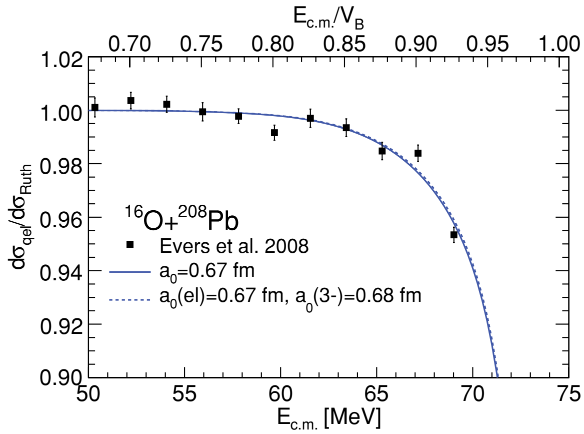

FIG. 6. (Color online) Total quasielastic scattering excitation function $d\sigma_{\mathrm{qel}}/d\sigma_{\mathrm{Ruth}}$. Curves have the same meaning as in Fig. 4. Experimental data are the same as in Fig. 3.

procedure is identical to the one described in Ref. [3]. A 1.6% larger value, $a_0^{3^-} = 0.682 \pm 0.004$ fm, gives the best fit to the excitation function whilst having a negligible effect on coupled-channels calculations of the total quasielastic scattering excitation function, as shown in Fig. 6. This analysis of the experimental data indicates a small difference in diffuseness between the ground state and the 3^- state of $\Delta a_0 = a_0^{3^-} - a_0^{\mathrm{el}} = 0.011 \pm 0.004$ fm.

IV. CONCLUSION

Coulomb nuclear interference (CNI) should be a very sensitive measure of the nuclear potential in the surface region. It has been shown, using coupled-channels calculations, that the CNI minimum in the excitation function of the octupole vibrational state in ^{208}Pb is sensitive to both the diffuseness of the ground-state potential and that associated with the 3^- state in ^{208}Pb. It was, however, insensitive to other parameters such as transfer couplings and the depth of the nuclear potential.

The diffuseness of the ground-state potential, and that associated with the 3^- state in ^{208}Pb, should in principle differ due to changes in the matter distribution associated with the collective excitation. Coupled-channels calculations show that the position of the CNI minimum is much more sensitive to the difference between the two diffuseness values than to the absolute value of the diffuseness. This means that fitting the CNI data alone, using a common potential diffuseness, may give misleading results. Thus, the CNI data were fitted by adjusting only $a_0^{3^-}$ while keeping a_0^{el} fixed at the value of 0.67 fm, determined from quasielastic scattering. This constraint placed a strong limit on the difference between the ground-state and 3^- state diffuseness, $\Delta a_0 = a_0^{3^-} - a_0^{\mathrm{el}} = 0.011 \pm 0.004$ fm. This negligible difference means that strong coupling to the 3^- state cannot be the cause of the difference in the diffuseness parameters required to reproduce the quasielastic and fusion measurements. Efforts should thus be directed toward investigations of unambiguous experimental probes of the potential shape at and inside the fusion barrier radius.

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