Sub-barrier backward quasielastic scattering: A probe of the hexadecapole deformation

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Abstract

The quasielastic scattering excitation functions for ^{16}O + ^{152}Sm, ^{170}Er and ^{174}Yb were measured with high precision at a backward angle with small energy intervals at energies near the Coulomb barriers. The hexadecapole deformation (β_4) of the target nuclei was extracted by using the lower-energy data and the obtained values agree with the available results reasonably well. This offers a sensitive method to extract β_4. This method is especially meaningful for the radioactive nuclei considering the low beam intensities.

1 Introduction

The role played by nuclear structure in near-barrier fusion reactions with heavy-ions has been observed several decades ago [1] and has been described well within the coupled-channels (CC) theoretical framework. Beside the quadrupole deformation (β_2) effect, the possible role of the hexadecapole deformation (β_4) in sub-barrier fusion has been frequently addressed [2,3]. The shape of the experimental fusion barrier distribution is equivalent to the theoretical result obtained by including classically random orientation of the deformed nucleus [4] and β_4 is expected to have a significant effect on fusion. The experimental fusion barrier distributions [5] mean that fusion reactions are very sensitive not only to β_2 but also to small β_4.

Up to now, the methods of sub-barrier α scattering [6], above-barrier α excitation [6, 7], electron scattering [8], and muonic x rays [9] have been used to determine the shape of the deformed nucleus experimentally. Usually, β_4 is difficult to extract experimentally and the obtained results are model-dependent and quite different with big errors. Theoretically, the macroscopic-microscopic method to calculate the ground-state deformation has been given in Ref. [10].

Based on the two complementary processes of fusion and backward quasielastic (QEL) scattering, we try to extract β_4 by using the lower-energy QEL data where the coupling effect to nuclear deformation is expected to be dominant. Also QEL is easier to be measured experimentally at lower-energy region. To this end, the spherical ^{16}O was selected as projectile. The nuclei of ^{152}Sm, ^{170}Er and ^{174}Yb, which can be seen as good rotors with similar β_2 but very different β_4 for the ground-state rotational band, were selected as target nuclei.

2 Experimental procedure and data analysis

The experiment was performed based on the HI-13 tandem accelerator at China Institute of Atomic Energy (CIAE). Thin targets (50-100 μg/cm^2 thick) of ^{152}Sm, ^{170}Er and ^{174}Yb with a diameter of 3 mm evaporated onto 20-25 μg/cm^2 carbon foils were used. The beam energy range is $E_{\mathrm{Lab}} =$ 40-80 MeV. The QEL particles were measured by using four silicon surface barrier detectors placed at the backward angle of $\theta_{\mathrm{Lab}} = 175°$. Another group of four silicon surface barrier detectors were placed symmetrically at the forward angle $\theta_{\mathrm{Lab}} = 41°$ relative to the beam direction as monitor detectors and also for data normalization. More details can be found in [11].

The energy window for QEL was defined to include the elastic peak and the tail corresponding to all other peripheral processes. For all reactions, the QEL counts were divided by the sum of the elastic scattering counts in the four monitor detectors, giving a quantity proportional to the ratio of the QEL cross sections to Rutherford scattering $d\sigma_{\mathrm{QEL}}/d\sigma_{\mathrm{Ru}}$, where 'Ru' denotes Rutherford scattering. The measured experimental QEL excitation functions for ^{16}O + ^{152}Sm, ^{170}Er and ^{174}Yb are shown in fig. 1 (left), where only statistical errors are given and the typical errors are smaller than 1%.

An effective energy E_{eff} was used by considering the minor centrifugal energy E_{cent} correction, that is $E_{\mathrm{eff}} = E_{\mathrm{c.m.}} - E_{\mathrm{cent}}$, in order to compare the barrier distribution $D_{\mathrm{QEL}}(E_{\mathrm{c.m.}}, 175°)$ with $D_{\mathrm{QEL}}(E_{\mathrm{eff}}, 180°)$. The corresponding barrier distributions are shown in fig. 1 (right). Considering the
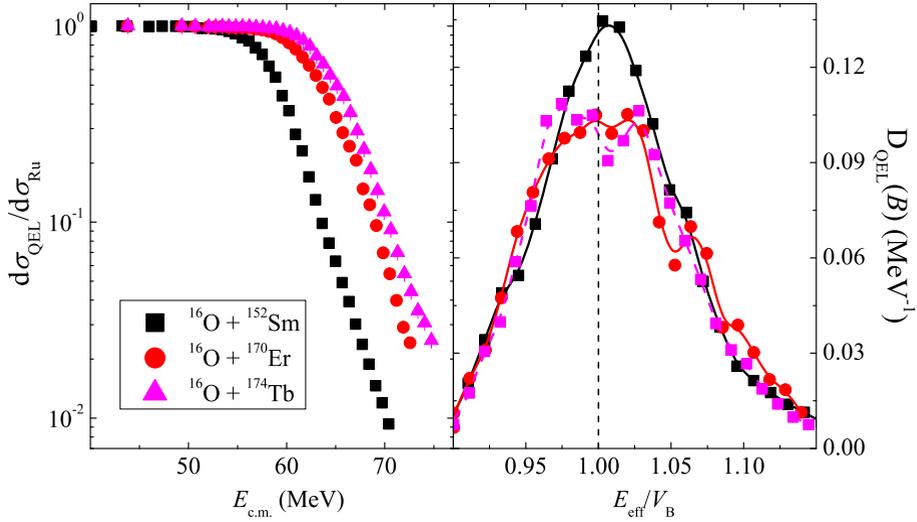
Figure 1: Experimental QEL excitation functions (left) for ^{16}O + ^{152}Sm, ^{170}Er and ^{174}Yb measured at $\theta_{\text{Lab}} = 175°$ and the extracted barrier distributions (right).

prevailing sensitivity of QEL to nuclear deformation at lower energies and to simplify the problem further by reducing the possible effect of other reaction channel couplings on the extracted β_4, only the data of $d\sigma_{\text{QEL}}/d\sigma_{\text{Ru}} > 0.7$ was used in the following analysis somewhat arbitrarily.

The CC calculations were performed with a modified version of the code CCFULL [12]. A Woods-Saxon (WS) potential with $r_0 = 1.20$ fm and $a = 0.65$ fm was used, the potential depth V was varied to reproduce the barrier heights. As usual, a short range imaginary potential with $W = 30$ MeV, $r_{0W} = 1.0$ fm, and $a_W = 0.4$ fm was used to simulate the compound nucleus formation. The used Coulomb radius parameter is $r_{0C} = 1.1$ fm, which has little influence on the calculated cross sections. The calculated results are insensitive to the parameters of the imaginary part of the potential as long as it is strong enough and well localized inside the Coulomb barrier.

Considering the coupling effect, the excitation energies of ^{16}O are high compared with the barrier curvature, so only produces an adiabatic potential renormalization, without affecting the structure of the barrier distribution [13]. This effect can be included in the potential and will not be considered explicitly in the CC calculations. Excitation states up to 10^+ in the rotational band of the target nuclei were included.

For ^{16}O + ^{152}Sm, both fusion and backward QEL have been studied

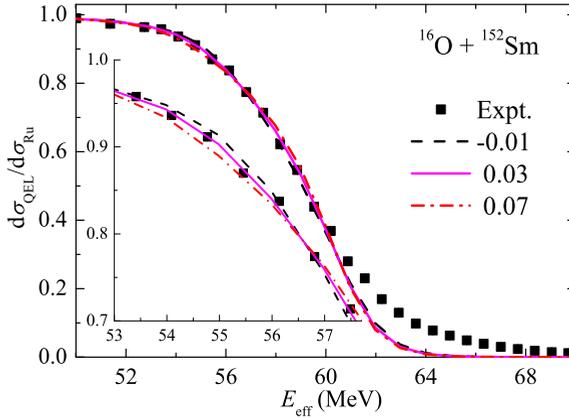Figure 2: Experimental QEL excitation function for ^{16}O + ^{152}Sm compared with the CC calculations by using different β_4.

widely [14]. Figure 2 shows the present-work backward QEL excitation function (solid squares). The lines are the CC calculations which take the permanent deformation of ^{152}Sm into account. $\beta_2 = 0.31$ [15] is used and fixed for ^{152}Sm. Different β_4-values were used in the CC calculations for getting the optimal value by comparison with the experimental data. The parameter which gives the best reproduction for the lower-energy data well is $\beta_4 = +0.037$ by using a chi-square analysis, the corresponding error is ± 0.006 by making $\chi^2_{\min}/N_{\mathrm{pt}} = 1.1$ for the optimal fit increased by 1, where 'N_{pt}' denotes the number of data points used in the fitting procedure. This means that the lower-energy backward QEL is indeed sensitive to higher order deformation β_4.

The extracted β_4-value for ^{152}Sm here is similar with both $\beta_4^N = 0.038 \pm 0.007$ extracted from 14-18 MeV α scattering [16] and 0.048 obtained from 50 MeV α scattering [7], but smaller than both the charge deformation parameter of $\beta_4^C = 0.08$ [17] and $\beta_4 = 0.07$ ($\beta_2 = 0.287$) [8] obtained from electron scattering.

Similar analysis was also performed for ^{16}O + ^{170}Er and ^{16}O + ^{174}Yb. The β_4 extracted in this work are shown in fig. 3 (solid circles). Figure 3 also represents some available results for Sm, Er and Yb isotopes, which include the charge deformation β_4^C (α^C) extracted by means of the Coulomb excitation experiments [6, 17–19], nuclear deformation β_4^N (α^N) by using the interference effects [16] and inelastic scattering of α particles at energies well above the barrier [6, 7]. Also included in this plot are the β_4 of ^{152,154}Sm,
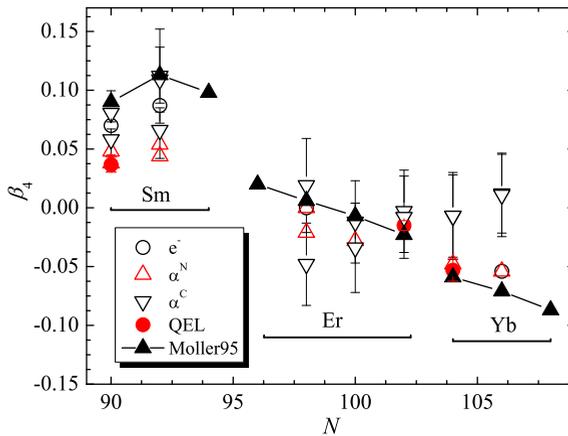
Figure 3: The variation of β_4 with neutron number N for Sm, Er and Yb isotopes by using different experimental methods and Möller's theoretical prediction [10].

^{166}Er and ^{176}Yb determined by electron scattering (e$^-$) [8]. Deformations of the nuclear ground states calculated with a macroscopic-microscopic model (Möller95) [10] are also shown in fig. 3. It can be seen that the extracted β_4-values in this work qualitatively agree with this overall trend.

3 Summary

In summary, we have measured the QEL scattering excitation functions with high precision at a backward angle and extracted the barrier distributions for ^{16}O + ^{152}Sm, ^{170}Er and ^{174}Yb. The extracted β_4-values show a transition from positive for ^{152}Sm and near-zero for ^{170}Er, to negative for ^{174}Yb, which is consistent with the available trend. This means that the backward QEL at the lower-energy region, like fusion excitation function, is indeed sensitive to the higher-order deformation and especially the sign of β_4. Of course, more precise data and more systems are needed to further check the feasibility of this method. Comprehensive data analysis is also needed in order to get a more reliable quantitative result.

Acknowledgements

References

[1] Stokstad R.G. et al., *Phys. Rev. Lett.*, **41** (1978) 465.

[2] Rhoades-Brown M.J. and Oberacker V.E., *Phys. Rev. Lett.*, **50** (1983) 1435.

[3] Dasgupta M. et al., *Annu. Rev. Nucl. Part. Sci.*, **48** (1998) 401.

[4] Nagarajan M.A., Balantekin A.B. and Takigawa N., *Phys. Rev. C*, **34** (1986) 894.

[5] Lemmon R.C. et al., *Phys. Lett. B*, **316** (1993) 32.

[6] Lee I.Y. et al., *Phys. Rev. C*, **12** (1975) 1483.

[7] Hendrie D.L. et al., *Phys. Lett. B*, **26** (1968) 127.

[8] Cooper T. et al., *Phys. Rev. C*, **13** (1976) 1083.

[9] Powers R.J. et al., *Phys. Rev. Lett.*, **34** (1975) 492.

[10] Möller P., *At. Data Nucl. Data Tables*, **59** (1995) 185.

[11] Jia H.M. et al., *Phys. Rev. C*, **90** (2014) 031601(R).

[12] Hagino K., Rowley N. and Kruppa A.T., *Comput. Phys. Commun.*, **123** (1999) 143.

[13] Hagino K. et al., *Phys. Rev. Lett.*, **79** (1997) 2014.

[14] Zhang Huanqiao et al., *Phys. Rev. C*, **57** (1998) R1047.

[15] Raman S., Nestor C.W. Jr., and Tikkanen P., *At. Data Nucl. Data Tables*, **78** (2001) 1.

[16] Brückner W. et al., *Phys. Rev. Lett.*, **30** (1973) 57.

[17] Fischer H. et al., *Phys. Rev. C*, **15** (1977) 921.

[18] Erb K.A. et al., *Phys. Rev. Lett.*, **29** (1972) 1010.

[19] Wollersheim H.J., Wilcke W. and Elze T.W., *Phys. Rev. C*, **11** (1975) 2008.