QUADRUPOLE MOMENT OF THE 2_1^+ STATE IN ^{100}Mo*

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Coulomb excitation is the only experimental method that can measure quadrupole moments of short-lived excited states, thus providing information on nuclear shape. This paper presents data analysis techniques that were used to extract the diagonal matrix element of the 2_1^+ state in ^{100}Mo. Influence of various methods of data subdivision and accuracy of the beam energy on the final result is discussed. Obtained quadrupole moment of the 2_1^+ state is compared to the one determined from earlier measurements.

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1. Introduction

In the ^{100}Mo nucleus a low-lying 0^+ state is observed at energy of 695 keV, very close to the first excited 2^+ state (536 keV). Such a rare structure can be the first experimental indication of the shape coexistence phenomenon. Results of our recent Coulomb excitation measurements support this scenario. The overall deformation of ^{100}Mo in its ground and excited 0^+ states is approximately two times larger as compared to the neighbouring ^{98}Mo [1] and the shape coexistence manifests in the very different triaxiality of these states — the nucleus undergoes a transition from the maximally triaxial (0_1^+) to the prolate (0_2^+) shape [2].

Quadrupole deformation parameters of the ^{100}Mo isotope were extracted from experimentally obtained $E2$ matrix elements in a model-independent way using the rotational invariant method [3]. In order to extract the

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triaxiality parameter it was crucial to precisely determine not only the transitional $E2$ matrix elements coupling the low-lying 0^+ and 2^+ states, but also the diagonal ones, especially for the first excited state 2_1^+ [2].

In the present paper chosen aspects of Coulomb excitation analysis will be presented in terms of the sensitivity to the $\langle 2_1^+||E2||2_1^+\rangle$ matrix element.

2. Coulomb excitation of ^{100}Mo

The Coulomb excitation experiment of ^{100}Mo was carried out at the Heavy Ion Laboratory in Warsaw using the ^{32}S beam [4]. Gamma rays depopulating Coulomb excited states (Fig. 1) were detected by 12 HPGe detectors of the OSIRIS II spectrometer in coincidence with scattered projectiles. To make use of the strong dependence of Coulomb excitation cross-section on the CM scattering angle, data were collected for several ranges of scattering angles. The scattered projectiles were detected by silicon 44 PIN-diodes covering the backscattering angle from 112° to 152°.

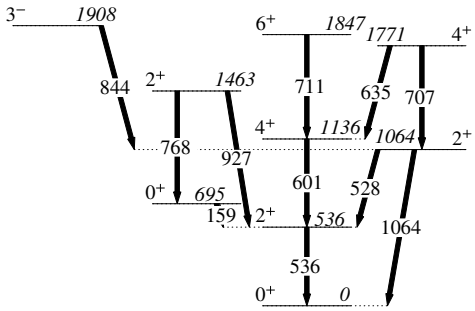

Fig. 1. Low-energy part of the level scheme for the ^{100}Mo isotope showing γ-ray transitions observed in the present Coulomb excitation experiment.

3. Determination of the quadrupole moment of the 2_1^+ state

Choosing the right strategy to subdivide the Coulomb excitation data is quite an important issue during the data analysis. A subdivision based on the projectile scattering angle makes it possible to disentangle contributions from various excitation paths. On the other hand, subdividing the data according to the relative angle between γ-ray and particle trajectories enables the observation of the γ-ray angular distribution, thus increasing the sensitivity to the M1 matrix elements.

A simulation was performed using the GOSIA code [5] to estimate the impact of various methods of Coulex data subdivision on the accuracy of the resulting diagonal $E2$ matrix element of the 2_1^+ state. The calculations were made for the same geometry as the measurement. For such a simulation, a set of matrix elements needs to be assumed, therefore the resulting values

rather indicate a trend than should be treated as absolute numbers. The obtained accuracy of the $\langle 2_1^+ \| E2 \| 2_1^+ \rangle$ matrix element for each method of data subdivision is obviously related to the γ yield used in the calculation. The intensity of the strongest transition $(2_1^+ \rightarrow 0_1^+)$ in each γ-ray spectrum collected by an individual Ge detector in coincidence with a single PIN diode was assumed to be known within 1% statistical uncertainty. Systematic errors of 5% related to efficiency calibration were assessed to all simulated γ yields. The accuracy of the $\langle 2_1^+ \| E2 \| 2_1^+ \rangle$ matrix element was determined for four different strategies of the data analysis:

1. PIN and Ge: subdivision of the data based on the particle scattering angle and γ detection angle (528 individual γ-ray spectra): **accuracy of 4%**,
2. PIN: data from all Ge detectors summed together, but subdivided according to the particle scattering angle (44 individual γ-ray spectra): **accuracy of 11%**,
3. Ge: data from all particle detectors summed together, but subdivided according to the γ detection angle (12 individual γ-ray spectra): **accuracy of 25%**,
4. no subdivision: one γ-ray spectrum resulting from summing of all data: **accuracy of 56%**.

The simulations show that the highest accuracy of the 2_1^+ diagonal matrix element results from the possibly highest subdivision of data, based both on the angles of the projectile scattering and the γ-ray emission. However, the level of statistics obtained in a typical Coulex experiment is usually too low to analyse individual PIN–Ge spectra. Since summing of data from some detectors cannot be avoided, the best strategy is to sum over all Ge detectors while keeping the division according to the projectile scattering angle. While the summing over all particle detectors increases the number of counts in the analysed γ-ray spectra, it also smooths out the effects, which allow determination of the contribution of concurrent excitation paths.

To demonstrate how the relative population of a state depends on the scattering angle, the example of the 0_2^+ state in ^{100}Mo is shown in Fig 2 (left). The 0_2^+ state can be populated only via two-step Coulomb excitation. The probability of the two-step process with respect to the one-step excitation of the 2_1^+ state in ^{100}Mo increases with the projectile scattering angle. In addition it is clearly visible that population of the 0_2^+ state excited via two step Coulomb excitation: $(0_1^+ \rightarrow 2_1^+) \otimes (2_1^+ \rightarrow 0_2^+)$ is sensitive to the quadrupole moment of the intermediate 2_1^+ state.

To determine the $\langle 2_1^+ \| E2 \| 2_1^+ \rangle$ matrix element from the Coulomb excitation data properly it is important to know precisely the energy of the beam. As illustrated in Fig. 2, the population of the 2_1^+ state measured experimentally can be reproduced by various combinations of the mean effective

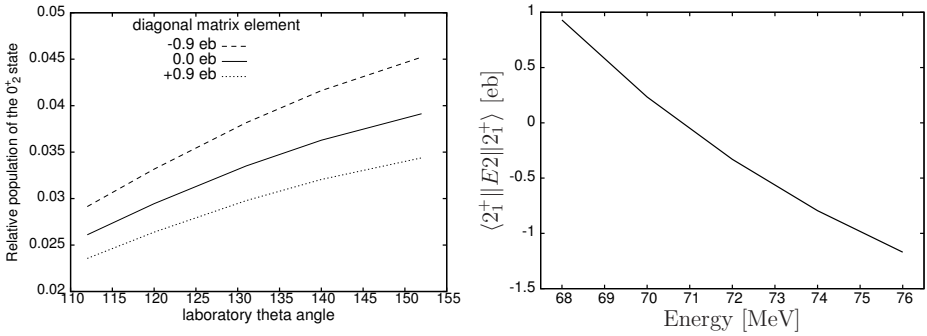

Fig. 2. Left: relative population of the 0_2^+ state (normalized to the population of the 2_1^+ state) as a function of the projectile scattering angle, calculated for three values of the 2_1^+ diagonal matrix element: -0.9 eb (dashed curve), 0.9 eb (dotted curve), 0.0 eb (solid curve); the 0.9 eb value corresponds to the rotational limit. Right: the diagonal matrix element of the 2_1^+ state, extracted from the measured population of this state, as a function of the assumed effective energy of the ^{32}S beam.

beam energy and the diagonal matrix element of this state. As one can see, slightly improper beam energy determination may lead to significant systematic error of the $\langle 2_1^+ \| E2 \| 2_1^+ \rangle$ value.

When analysing the data from the Coulomb excitation experiment of ^{100}Mo with the ^{32}S beam, it was decided to sum the spectra from individual Ge detectors, thus increasing the number of counts in observed γ lines to a level sufficient to subdivide the data according to the projectile scattering angle. Three ranges of the ^{32}S scattering angle were used: 112°–124°, 127°–131°, 135°–152°.

As a result of the data analysis, the diagonal $E2$ matrix element of the 2_1^+ state in ^{100}Mo was determined. The obtained value is $-0.33(10)$ eb which corresponds to the spectroscopic quadrupole moment, eQ, of $-0.25(7)$ eb. The obtained magnitude of the quadrupole moment is smaller compared to the one resulting from an earlier reorientation measurement with the ^{4}He and ^{16}O beams, $-0.39(8)$ eb [6], but both values agree within the error bars.

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