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Nuclear Shapes From Heavy Ion Inelastic Scattering

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ABSTRACT

Earlier inelastic scattering experiments at energies above the Coulomb barrier have shown that angular distributions for the ground state and strongly coupled excited states can provide an accurate determination of a number of nuclear deformation parameters. An inelastic scattering experiment of ^{24}Mg on ^{208}Pb indicates that indeed this is a viable technique.

I. INTRODUCTION

Nuclear deformations have been investigated through a variety of techniques, ranging from Coulomb excitation to nuclear excitation with neutrons and light ions (Ref. 1 and references therein). In the s-d shell region in particular, a number of nuclei have been investigated with the above methods. The various experiments give a consistent value for the quadrupole deformation of the nuclei involved. The values however for the hexadecapole deformation vary appreciably and in a number of cases, the technique involved is unable to produce a value for it.For example, in the case of ^{24}Mg, [1] the β_4 values obtained through the different experimental probes, vary between +0.05 to -0.06.

Inelastic scattering of heavy ions at energies higher than the Coulomb barrier has been shown to be sensitive to the deformation parameters. Scattering of ^{20}Ne[2] and of

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$^{28}Si^{3}$ from ^{208} Pb at energies of 132 MeV and 225 MeV respectively, have shown that the angular distributions for the ground state and the strongly coupled excited states contain adequate information to accurately determine a number of the nuclear deformation parameters. Coupled-channel analysis of the data using the rotational model formalism can simultaneously determine the B(E2) value, the quadrupole charge deformation parameter, β_2^c, the hexadecapole charge deformation parameter, β_4^c, and the quadrupole moment Q_2. In comparison with the other probes used for obtaining nuclear deformations, heavy ion inelastic scattering is the only technique that permits the simultaneous determination of the above parameters.

Due to the collective nature of the states involved, it is important to obtain angular distributions not only for the first excited state (2^+) of the deformed nucleus, but also for the second excited state (4^+) and any other collective state in the vicinity that could be strongly excited. For most of the deformed nuclei in the s-d shell, due to the existence of a number of overlapping excited states in both target and projectile, particle-gamma coincidence techniques are required. In order to test the heavy ion method as a viable method for obtaining nuclear deformation parameters, an experiment of inelastic scattering of ^{24}Mg on ^{208}Pb using the particle-gamma coincidence technique was performed. Since deformations of ^{24}Mg have been investigated with many other probes, the present experiment could help remove some of the uncertainties, and in particular, assist in establishing the size and sign of the hexadecapole deformation.

II. EXPERIMENTAL PROCEDURE AND RESULTS

A 200 MeV beam of ^{24}Mg, produced by the 25 MV Folded Tandem accelerator at HHIRF of Oak Ridge National Laboratory, was incident on a 400 μg/cm^2 ^{208}Pb foil, evaporated on a 20 μg/cm^2 carbon foil. Scattered particles were detected with two position sensitive detectors (PSD), a 4.8 cm x 0.8 cm detector spanning the angles $\theta_{c.m.} = 32.8^\circ - 56.2^\circ$ and a 2.9 cm x 0.8 cm detector spanning the angles $\theta_{c.m.} = 20.5^\circ - 33.7^\circ$. The PSD's were placed in a 35 cm diameter scattering chamber surrounded by 72 NaI detectors in a 4π geometry, comprising the Spin Spectrometer of HHIRF. The NaI detectors were used in detecting the γ-rays accompanying the inelastically scattered particles. The data were accumulated on an event by event mode on a PERKIN-ELMER computer.

For the precise determination of the angles covered by the PSD's, a separate run was performed in a 1.6 m scattering chamber. Elastic scattering of ^{24}Mg on ^{208}Pb was performed under the same experimental conditions as the spin spectrometer experiment. A mask with 13 slits was placed in front of the small PSD detector and precise angle determination and detector efficiency were established.

A high resolution particle experiment yields accurate results for the excitation of the ground state and 1.32 MeV 2^+ state of ^{24}Mg. It becomes extremely difficult to extract the 4^+ state of ^{24}Mg at 4.12 MeV because of the second 2^+ state of ^{24}Mg at 4.23 MeV, the ^{24}Mg 2^+ and ^{208}Pb 3^- mutual excitation at 3.97 MeV and the 2^+ state of ^{208}Pb at 4.08 MeV. The γ-ray data from the Spin Spectrometer becomes essential for the identification of each state. Due to the limited resolution (approximately 7%) of the NaI detectors, the various γ-ray components in the vicinity of 4 MeV excitation could not be fully separated. Two computer enhancement techniques were utilized for the γ-ray identification:a) selective Doppler broadening correction b) γ-ray multiplicity for γ-rays detected in a pre-determined portion of the 72 NaI detectors.

Fig. 1 shows the results of the selective Doppler broadening which helps establish whether a certain γ-ray is emanating from a light nucleus (^{24}Mg) or a heavy nucleus (^{208}Pb). The spectrum contains a number of prominent peaks that have a multiplicity of one. Since the γ-rays will be Doppler broadened, a correction is applied to all 72 NaI detectors. If the correction assumes that the γ-rays are ^{24}Mg γ-rays, the lower part of the spectrum is received. If the correction assumes that they are ^{208}Pb γ-rays, the upper part is received. It is thus possible to identify in this case that one peak is a ^{24}Mg peak and the remaining are ^{208}Pb peaks.

III. ANALYSIS

For the coupled - channel calculations, the rotational model coupled - channel analysis was performed using the automatic search program ECIS-79.[4] The calculations included the $0^+ \rightarrow 2^+ \rightarrow 4^+$ couplings in ^{24}Mg and the reorientation matrix element for the $2^+ \rightarrow 2^+$ coupling. The inclusion of the second 2^+ as well as the reorientation in the 4^+ state, exerted little influence on the first 2^+ cross section. The reorientation matrix element was thus fixed at the rotational model value. Coupling of the states in ^{208}Pb with states in ^{24}Mg was not considered to be important and was

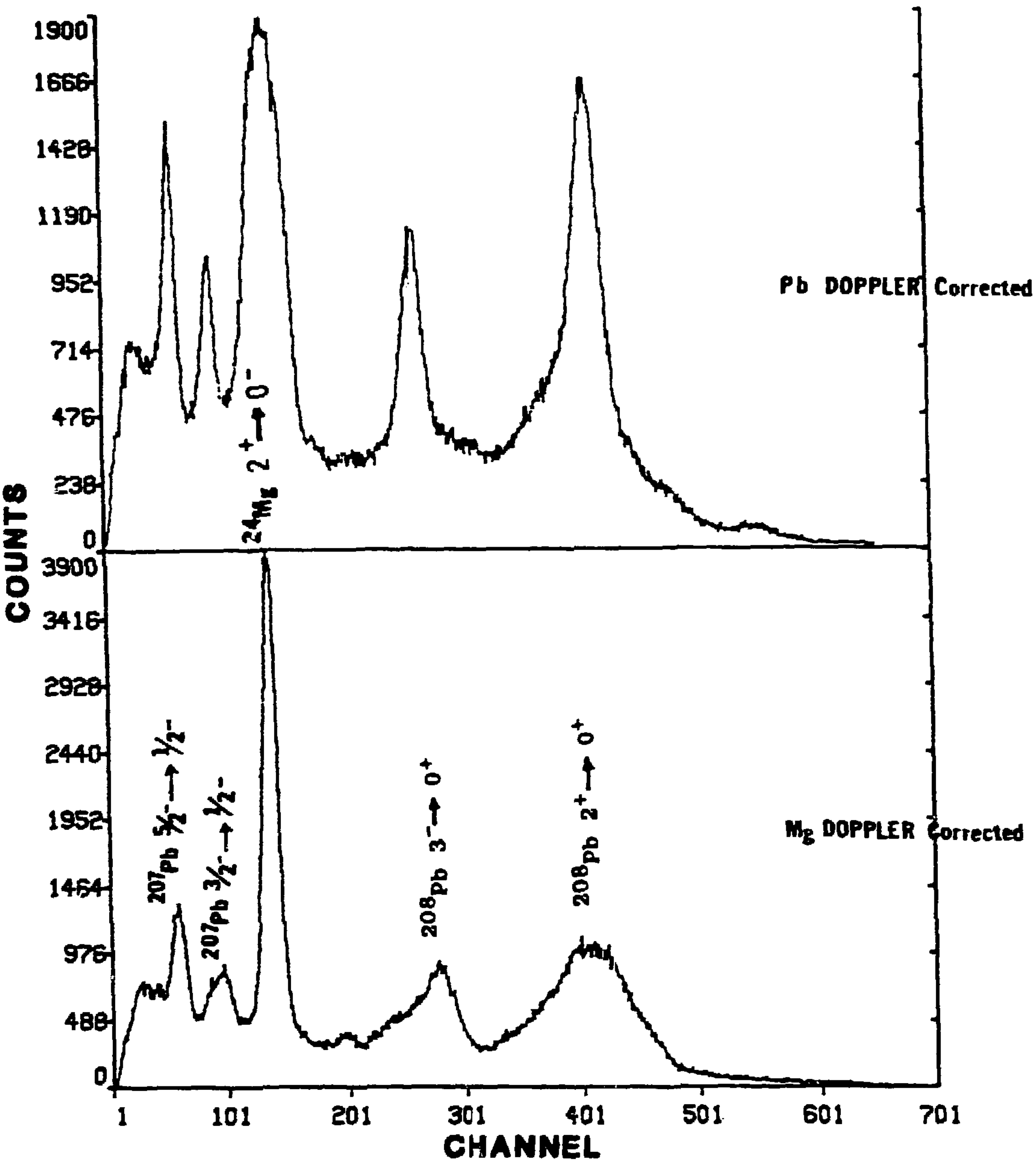

Fig. 1 Effects of selective Doppler broadening correction. Lower part of figure assumes that all peaks are Mg peaks. The Doppler correction compensates for the width of only one peak which is a Mg peak. Similar results for Pb are shown in the upper part of the figure.

not included explicitly. The excitation of the 3^- and 2^+ states of ^{208}Pb is taken into consideration through the imaginary part of the optical potential, since a simultaneous fit of the elastic and inelastic excitation of ^{24}Mg is required. The parameters used in the calculations were the six optical model parameters (V, r_v, a_v, W, r_w, a_w) and the deformation parameters β_2^c, β_4^c. In the optical model calculations, all three potentials involved (real, imaginary and Coulomb) were deformed. The charge surface of the deformed nucleus was assumed to be described by the parameter:

$$R^c(\theta) = r_o{}^c A^{1/3} [1 + \beta_2{}^c Y_2(\theta) + \beta_4{}^c Y_4(\theta) + \ldots]$$

while the nuclear surface was supposed to be created by rolling the spherical nucleus (^{208}Pb) over the deformed nucleus (^{24}Mg). The parameter that describes this surface is :

$$R^N(\theta) = r_o{}^N [A_1{}^{1/3} + A_2{}^{1/3}) (1 + \beta_2{}^N Y_2(\theta) + \beta_4{}^N Y_4(\theta) + \ldots].$$

The Coulomb and nuclear deformations β^c and β^N respectively, are not independent of each other. They are related through Hendrie's rolling model scaling procedure.[5] However, the best fits to the data were obtained by decoupling the nuclear deformations from the charge deformations.

The initial optical model parameters were those of Ref. 3 from the scattering of 225 MeV ^{28}Si on ^{208}Pb. The parameters were allowed to vary in an extended search, fitting simultaneously the ^{24}Mg elastic angular distribution and the forward ($\theta_{c.m.} < 38^o$) portion of the 2^+ angular distribution. The latter was used to determine the value of β_2^c. Table I lists the final optical model parameters used in the analysis.

TABLE I

Final optical model parameters

V (MeV)	r_v (fm)	a_v (fm)	W(Vol) (MeV)	r_w (fm)	a_w (fm)
41.0	1.15	0.9	20.0	1.24	0.59

For the 2^+ angular distribution, the fitting of the angular region around the grazing angle ($\theta_{c.m.} = 43^o$) was found to be sensitive to the value of β_4^c. By fitting simultaneously the 2^+ and 4^+ angular distributions the value of β_4^c was determined. Fig. 2 shows the angular distributions for the ground state, 2^+ and 4^+ excited states of ^{24}Mg along with the best fits obtained from the coupled - channel analysis.

The fitting of the 2^+ data includes the reorientation matrix element as defined by the rotational model i.e.

$$M(E2;2\rightarrow 2) = 1.19\ M(E2;0\rightarrow 2)$$

The reorientation matrix element $M(E2;2\rightarrow 2)$ is sensitive to the magnitude of the 2^+ cross section for angles larger than the grazing angle. Changes in the value of the matrix element result in changes on the slope and the magnitude of the angular distribution at large angles. To show the effect, the dot-dashed line in the 2^+ angular distribution in Fig. 2, is a calculation with the $M(E2;2\rightarrow 2)$ matrix element set equal to zero. The pronounced effect of the above matrix element at large angles is evident. From the fitting of the 2^+ cross section at large angles, it was determined that the rotational reorientation matrix element did not need any adjustment.

From the determined values of β_2^c and β_4^c, a value of B(E2) was calculated based on the relation :

$$[B(E2)]^{1/2} = \int \rho(r,\theta) r^2 Y_2(\theta) d\tau = 3zeR_o^2/\sqrt{5\pi}(\beta_2 + 0.36\beta_2^2 + 0.97\ \beta_2\beta_4 + ...)$$

The value of $B(E2) = 0.0405\ e^2b^2$ is in good agreement with the value of $B(E2) = 0.0425\ e^2b^2$ obtained from Coulomb excitation.[6]

To examine the accuracy in the determination of β_4^c, its value was changed in increments of 0.01 and the values of CHI square and the visual qualities of the fits to the ground state and the two excited states of ^{24}Mg were recorded. The value of β_2^c was adjusted so that the B(E2) value would remain unchanged. The parameters β_2^N and β_4^N were adjusted according to the rolling model. The error in the value of the β_4^c parameter was found to be approximately 30%. The largest contribution to this error is from the large error bars for the extracted 4^+ angular distribution of ^{24}Mg.

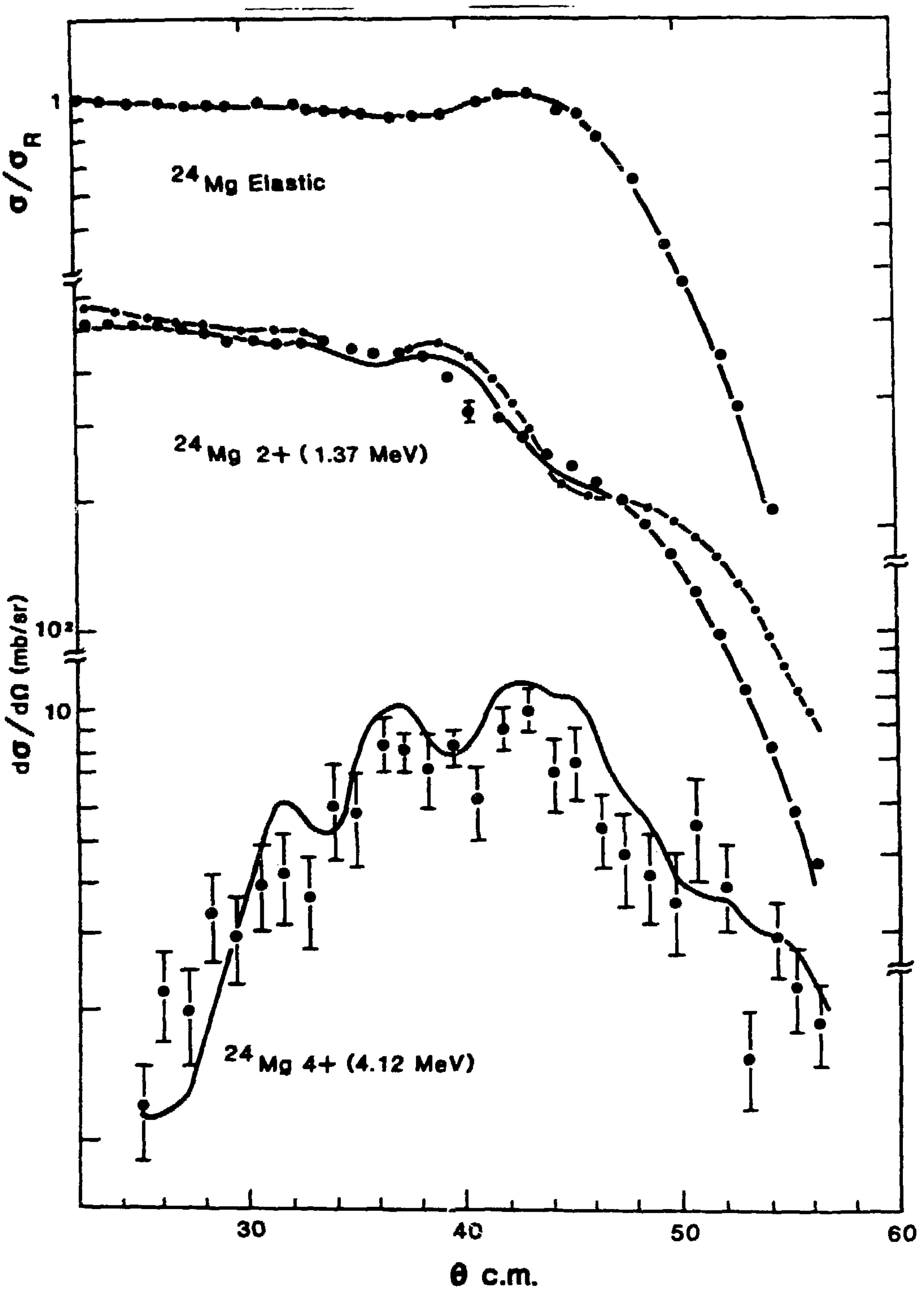

Fig. 2 Angular distributions for the 0^+, 2^+ and 4^+ states of ^{24}Mg. For the elastic and 2^+ angular distributions, the large dots are the experimental points and the error bars are smaller than the dot size. Solid lines are coupled-channel calculations. The small dot-dash line for the 2^+ angular distribution is a coupled-channel calculation with the $2^+ \rightarrow 2^+$ reorientation matrix element set equal to zero.

Since no adjustment was necessary to the reorientation matrix element, the spectroscopic quadrupole moment Q_2 is given by the rotational model as:

$$Q_2=(16\pi/5)^{1/2}\, x 2/7 x [B(E2)]^{1/2}$$

We thus obtain a value for the spectroscopic quadrupole moment for ^{24}Mg Q_2 =-0.18 eb. The measured value of Q_2 with the reorientation effect in heavy ion Coulomb excitation is approximately 30 % larger.[6] Table II contains the various deformation parameters measured in this experiment in comparison to those derived from other experiments.

TABLE II

Results for the quadrupole moment and deformation parameters of ^{24}Mg

Projectile	B(E2) (e^2b^2)	Q_2 (eb)	β_2^c	β_4^c	Ref
CE	0.0425	-0.24	0.46		6
e,e′			0.45	-0.06	7
n,n′	0.0357		0.51	0.0	1
p,p′			0.47	+0.05±0.04	8
H I	0.0405	-0.18	0.52	-0.07	this work

IV. CONCLUSIONS

The results of the present experiment indicate that heavy ion inelastic scattering is a viable method for the determination of collective shape parameters in deformed nuclei. In particular, the rotational model coupled-channel analysis shows that different parts of the angular distributions are sensitive to different collective parameters. The fall-off part of the elastic angular distribution is sensitive to the values of W and a_w ; the forward part of the 2^+ angular distribution is sensitive to the value of β_2^c ; the fall-off part of the same angular distribution is sensitive to the

M(E2;2→2) reorientation matrix element, while the grazing angle portion of the angular distribution is sensitive to the value of β_4^c. Through such an experiment is is possible to simultaneously determine:

a) the β_2^c and β_4^c charge deformation parameters
b) the β_2^N and β_4^N nuclear deformation parameters
c) the spectroscopic quadrupole deformation Q_2
d) the B(E2) value

Given adequate experimental resolution, it is thus possible to determine in a single experiment more collective parameters than other techniques.

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