PROTON SCATTERING ON ^{32,34}Si IN INVERSE KINEMATICS

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When the first excited $J^{\pi} = 2^+$ state (2_1^+) of an even-even nucleus is discussed as a collective quadrupole excitation, it is usually assumed to be isoscalar. However, it has been demonstrated that differences can occur between the amplitudes of the motions of protons and neutrons in 2_1^+ states (for a brief review, see [1]). Such differences can be measured in a particular nucleus by comparing the matrix elements connecting the 2_1^+ state to the ground state determined by two different experimental probes. Madsen, Brown and Anderson [2] found that the comparison of a low energy (10-50 MeV) (p, p') result to an electromagnetic matrix element is particularly sensitive to differences in the amplitudes of proton and neutron motion.

Differences in the proton and neutron motion are generally discussed in terms of the multipole matrix elements M_n and M_p for neutrons and protons, respectively. In a collective isoscalar state - that is, one in which the neutron and proton motions have the same amplitudes - the ratio M_n/M_p is identical to N/Z. It has been found that M_n/M_p deviates from this value for the 2_1^+ states of a number of nuclei, in particular those with a single closed shell, which have valence nucleons of one type but not the other [1].

In this context, the N = 20 isotope ^{34}Si is particularly intriguing and presents a unique challenge to nuclear models. The systematic behavior of the even-A, N = 20 isotones is remarkable because ^{32}Mg appears to be well deformed, with the energy of its 2_1^+ state below 1.0 MeV, while ^{34}Si behaves like a doubly magic nucleus with its 2_1^+ state at 3.3 MeV [3], even though it has only two protons more. Because M_n/M_p is sensitive to shell closures, the determination of this property for the 2_1^+ states of both ^{32}Mg and ^{34}Si would provide important insights on the shell structure of these two neighboring nuclei that are so surprisingly different in structure.

B.A. Brown [4] has calculated the value of M_n/M_p for ^{34}Si using the Wildenthal interaction, an interaction that has been demonstrated to have great predictive power near the line of stability. His predicted value, M_n/M_p = 0.26, deviates severely from the N/Z value of 1.43 for this nucleus. In fact, if this prediction is confirmed experimentally it will be the largest deviation of M_n/M_p from N/Z known in the entire chart of the nuclides. As such, a measurement of M_n/M_p for ^{34}Si is an important test of the Wildenthal interaction for shell model calculations in the sd shell away from the line of stability.

Quadrupole collectivity in several even-A silicon isotopes around the N = 20 shell closure has been studied by R.W. Ibbotson *et al.* [5] by using in-beam Coulomb excitation. The B(E2; $0_1^+ \rightarrow 2_1^+$) value of ^{34}Si was measured to be 85(33) e^2fm^4, from which a deformation parameter β_2 = 0.18(4) can be extracted.

The feasibility of performing proton scattering experiments (p, p') in inverse kinematics with exotic beams and intensities of around 10^4 counts/second has recently been demonstrated in a series of experiments [6,7,8]. In this report we present our results of measuring the cross section of the 2_1^+ state for ^{34}Si at 47 MeV/nucleon, as well as for its even-A neighbor ^{32}Si at 42 MeV/nucleon. The obtained β_2 values are then compared to those values extracted from the coulomb-excitation experiment [5], and thus the M_n/M_p values are deduced.

Since this was a follow-on experiment, the setup used was essentially the same as that applied in the previous experiments [6,7,8]. A primary 80 MeV/nucleon ^{40}Ar beam was provided by the K1200 cyclotron at the National Superconducting Cyclotron Laboratory, and impinged on a 367 mg/cm^2 Be target located at the production-target position of the A1200 fragment separator [9]. The resulting beam was purified by using a 233 mg/cm^2 aluminum wedge, and limited to a momentum spread of Δp/p = 1.5-3%. The beam was then traced by using two parallel-plate avalanche counters (PPACs) [10]. A 3.6 mg/cm^2 CH_2 target was placed perpendicular to the beam direction. A 0° detector, consisting of a thin and a thick fast plastic, was located downstream from the target, providing a ΔE-E separation of heavy projectile-like fragments from lighter reaction products. The final ^{32}Si and ^{34}Si beam intensities were measured to be $\sim 3\times10^4$ and $\sim 4\times10^4$, respectively.

For detecting the scattering protons, we used a group of 6 telescopes, which were positioned 28 cm from the target. Three telescopes were mounted with their centers at laboratory-frame angles of 76° and three were centered at 70°. The whole array covered laboratory angles between 65° - 80°, corresponding to a center-of-mass angular range of approximately 20° - 45°. Each telescope had 5cm $\times$ 5cm active area and consisted of a 300 μm thick Si-strip detector followed by a second 470 μm thick PIN diode detector and a 1 cm thick stopping CsI. The strip detector comprised 16 3-mm-wide strips and was used to determine the laboratory angle of the scattered protons. Those protons stopped in the strip detectors were identified by time-of-flight. Higher-energy particles that punched through the first detector, were identified by their ΔE-E signal in Strip-PIN or PIN-CsI. Scattered protons were selected with a requirement that a heavy ejectile must survive the collision and be detected in the 0° ΔE-E plastic stopping detector.

Before measuring the ^{34,32}Si scattering, the experimental method was tested with the 35 MeV/u ^{40}Ar beam. In Fig. 1 the scattered proton data for ^{40}Ar and ^{34,32}Si are presented in the form of a lab-frame kinetic energy vs scattering angle spectra and compared to calculated kinematics curves. The energy of fast protons that punched through two Si detectors and stopped in CsI were deduced based on the energy loss in Si detectors. The abrupt structure around 10 MeV along kinematics lines is related to CsI thresholds. Scattering angles have been determined from Si-strip positions and beam tracking information. The primary source of angular uncertainty came from the angular acceptance introduced by the 3.1 mm strip size and the beam spot size. The latter, which is dominated by momentum acceptance of the beam, accounts for the obvious difference between ^{40}Ar and ^{34}Si in terms of the scattering-band widths.

The elastic-scattering angular distributions of ^{40}Ar, ^{34}Si, and ^{32}Si, Fig. 2, were obtained by projecting the contents of a contour in the excitation energy vs θ_{cm} plane. The data were normalized to coupled-channel predictions using the ECIS code [11]. In the ECIS calculation the optical-model parameters for ^{40}Ar were taken from Ref. [12] and those for ^{34}Si and ^{32}Si are adapted from ^{34}S and ^{32}S [13], respectively.

Due to low statistics and insufficient angular resolution, it was impossible to obtain the ratios of elastic scattering to inelastic scattering to the 2^+_1 states from a gaussian fit to the excitation spectra for individual angular bins. Shown in insets of Fig. 1 are the excitation-energy spectra covering a center-of-mass angular range of 4°. The angular distributions of the 2^+_1 states, Fig. 2, were obtained by selecting the 2^+_1 states in the excitation energy vs θ_{cm} plane. This process may be slightly inaccurate because of the overlap of the ground state with the 2^+_1 state distribution, see insets of Fig. 1. However, this problem was alleviated by normalizing the summed counts to those obtained from a gaussian fit to the excitation spectrum for the corresponding angular range.

The χ^2 of the coupled-channel predictions for the 2^+_1 states with respect to the experimental angular distributions was minimized to extract the β_2 values. For ^{40}Ar we obtained a β_2 value of 0.27(5) which agrees with the previous results of 0.24-0.26 [14] and 0.29(3) [6]. In case of ^{34}Si and ^{32}Si, the

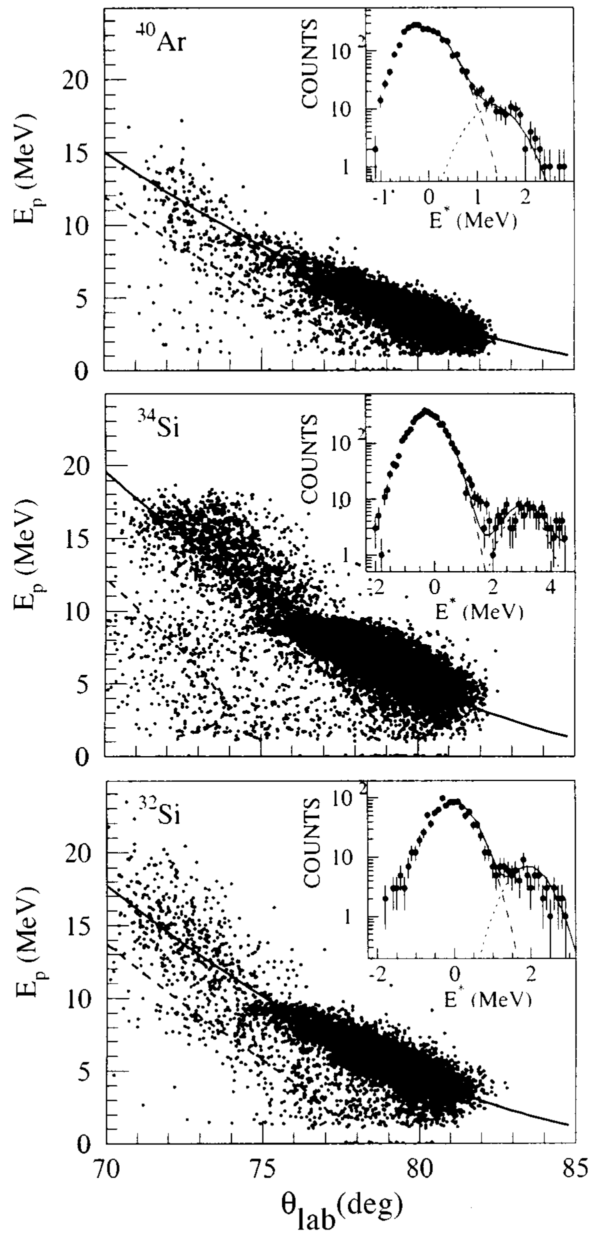

Figure 1: Scatterplot of energy vs angle for recoiling protons from ^{40}Ar(p, p') (upper panel), ^{34}Si(p, p') (middle panel), and ^{32}Si(p, p') (lower panel). The data were taken with three telescopes centered at 76^o with respect to the beam direction. The solid curves show the calculated kinematics for the ground states, the dash curves for the 2_1^+ states. In inserts are plotted the excitation-energy spectra for the center-of-mass angular range of 20.0^o-20.0^o for ^{40}Ar, 21.0^o-25.0^o for ^{34}Si, 22.0^o-26.0^o for ^{32}Si. Due to the asymmetric shapes, gaussian fits are performed to the higher excitation-energy part of the peaks.

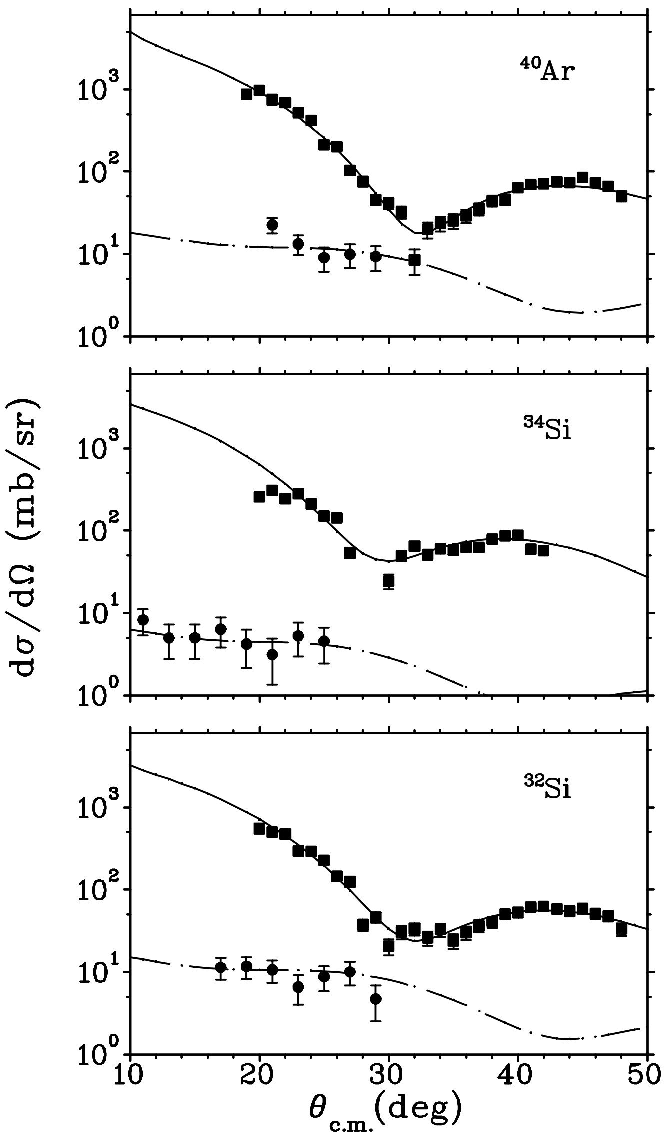

Figure 2: Angular distributions for proton scattering off the ground state and the 2_1^+ state for ^{40}Ar(p, p') (upper panel), ^{34}Si(p, p') (middle panel), and ^{32}Si(p, p') (lower panel). The solid squares and the solid triangles represent the elastic-scattering data extracted from the three telescopes centered at 76° and 70° with respect to the beam direction, respectively. The solid circles show the inelastic-scattering data drawn from the three telescopes centered at 76° with respect to the beam direction. The coupled-channel calculations for elastic scattering (solid lines) and inelastic-scattering (dash-dotted lines) are plotted for comparison.

Table 1: The 2_1^+ states for ^{40}Ar, ^{34}Si, and ^{32}Si. The excitation energies are adopted from Ref. [15]. The β_2(e.m.) values are from Ref. [5]. The β_2(p,p') values are from this work.

Isotope	E (MeV)	β_2(p,p')	β_2(e.m.)	(M_n/M_p)/(N/Z)
^{40}Ar	1.46	0.27(5)	0.27(2)	0.97(19)
^{34}Si	3.33	0.20(3)	0.18(4)	1.11(30)
^{32}Si	1.94	0.31(4)	0.26(4)	1.22(24)

β_2 values of 0.20(3) and 0.31(4), respectively, were extracted, which is the first time these values were measured by using a (p, p') method.

In Table 1 we compile deformation parameters for ^{40}Ar, ^{34}Si and ^{32}Si. Note that within experimental uncertainties the β_2 values obtained from (p, p') reaction are in agreement with those values extracted from coulomb excitation. As mentioned above, a difference between electromagnetic and hadronic values can be related to different proton and neutron vibration amplitudes through the study of multipole-transition matrix elements M_n/M_p. The M_n/M_p ratios were calculated using the formula derived in Ref. [1]. They are presented in Table 1 with respect to N/Z ratios. For the three isotopes studied here, within experimental uncertainties, the M_n/M_p values are identical to the N/Z ratios. This can be accounted for in an isoscalar model where protons and neutrons participate equally in the excitation of the nucleus.

Since ^{34}Si has a shell closure of N = 20, it is interesting to compare the experimental result to a model calculation. The shell-model calculation [4] using the Wildenthal interaction, which predicts a Mn/Mp value of 0.26, is obviously not valid here. However, the calculation expects a β_2 value of 0.16 associated with proton-scattering experiment, which agrees with the value we measured. What can cause the problem, is that the Wildenthal interaction yields an electromagnetic β_2 value which is too large. It is interesting to note that Kelley *et al.* [6] compiled the deformation parameters for ^{36}S, the N = 20 isotone of ^{34}S. They noticed that in view of the low β_2 value and high excitation energy of the 2_1^+ state of ^{36}S, ^{36}S exhibits features akin to those of a well closed nucleus. Our work indicates that this conclusion applies to ^{34}Si as well.

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