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Proton scattering on the unstable ^{38}S nucleus: Isovector contribution to the 2_1^+ state

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A 39*A* MeV ^{38}S radioactive beam was used with inverse kinematics to measure angular distributions for elastic and inelastic proton scattering from a CH_2 target. Optical potential and folding model calculations are compared with the elastic distribution. Using coupled channel calculations, the β_2 value for the 2_1^+ state is determined to be 0.35 ± 0.04. This value, when compared with the corresponding result from a Coulomb excitation measurement, leads to $M_n/M_p=(1.5\pm0.3)N/Z$, indicating an isovector contribution to the 2_1^+ state of ^{38}S. [S0556-2813(97)50309-8]

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Nuclei are generally treated as having an inert closed shell core coupled to valence protons and neutrons, which primarily determine the nuclear structure. However, evidence suggests that the ''magic number'' shell closures do not always persist in nuclei outside the valley of stability. Therefore it is of paramount importance to investigate the evolution of nuclear structure when moving towards the drip lines. The use of multiple experimental probes allows us to disentangle the effects due to protons and neutrons in the nucleus.

Great current interest is focused on neutron rich nuclei near the $N=28$ magic number for which theoretical calculations predict the onset of deformation [1,2]. Advances in beam currents available at a number of radioactive nuclear beam facilities have recently extended the region of nuclei accessible for direct study. In the $N=28$ region, β-decay measurements of the nuclei ^{43}P, ^{44}S, and ^{45}Cl indicate deformation in these neutron ''magic number'' nuclei [3]. The excitation energy and $B(E2)$ values of the 2_1^+ states in ^{38,40,42,44}S [2,4] have been measured through Coulomb excitation.

More detailed information on nuclear structure can be revealed through elastic and inelastic proton scattering. Low lying 2^+ and 3^- states are generally well represented by an isoscalar collective model with equal neutron and proton deformation, yielding a ratio of the neutron and proton multipole transition matrix elements $M_n/M_p=N/Z$ [5]. However, comparisons of transition probabilities measured with different probes as well as measurements with a single probe exhibiting an interference between Coulomb and nuclear amplitudes have been used to detect deviations from the simple isoscalar picture, particularly in single closed shell nuclei, where the valence nucleons drive the oscillations [6,7]. In this sense, an experimental determination of M_n/M_p gives indications about the nature of the excitation and about shell structure effects. At energies of a few tens of MeV, inelastic proton scattering is mostly sensitive to the neutrons in the nucleus, and is therefore a very suitable tool to determine M_n/M_p by a comparison with the deformation parameter obtained from electromagnetic excitation, which is only sensitive to the protons [5].

Since the advent of radioactive beam facilities, it has become possible to measure proton scattering on short lived nuclei in inverse kinematics, using a proton target. Reaction kinematics are then determined either by detecting the heavy ejectile or recoiling protons. Such studies are restricted to nuclei closer to the valley of stability than half-life or Coulomb excitation measurements, since the prerequisite of very thin targets, which preserve the kinematic characteristics of the outgoing particles, requires the availability of sizable beam currents, at least several 10^3 particles per second. Proton inelastic scattering data with unstable beams are scarce. The doubly magic nucleus ^{56}Ni was studied by (p,p') scattering in inverse kinematics at 101*A* MeV [8] and the β_2 value was extracted from cross-section measurements at only one scattering angle. Very recently, the measurement of the inelastic scattering angular distribution of an excited state in ^{11}Li has been reported [9].

This Rapid Communication presents results of elastic and inelastic proton scattering on the unstable ^{38}S nucleus in inverse kinematics, measured over a broad angular range, using large solid-angle position sensitive detectors to measure recoiling protons. The value of β_2 is extracted for the 2_1^+ state, and from a comparison with a Coulomb excitation measurement, the first experimental M_n/M_p value for the excited state of a short lived nucleus is extracted.

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A beam of 85A MeV ^{40}Ar nuclei, provided by the K1200 cyclotron at the National Superconducting Cyclotron Laboratory, impinged on a 376 mg/cm^2 Be target located at the production target position of the A1200 fragment separator [10]. The resulting beam was purified by using a 292 mg/cm^2 aluminum wedge, and limited to a momentum spread of $\Delta p/p=1\%$, yielding a ^{38}S beam that was more than 99% pure.

The beam, consisting of around 2×10^5 particles per second, was then collimated sufficiently ($\Delta\theta_{\text{beam}}\leqslant0.3°$ FWHM) so that it was unnecessary to carry out event-by-event trajectory tracing. The final beam intensity was around 3×10^4 particles per second. A 1.9 mg/cm^2 CH_2 target was rotated to an angle of 34° with respect to the beam direction, thus providing an effective in beam target thickness of 4.6 mg/cm^2, while limiting the energy loss and angular straggling of low-energy protons recoiling towards the detectors. A 0° detector, placed downstream from the target, consisted of a thin and thick fast plastic. This detector covered scattering angles up to 4.7°, largely above the kinematic limit for elastic and inelastic scattering of ^{38}S from protons, and provided a ΔE-E separation of heavy projectile-like fragments from lighter reaction products, a scaler count of the ^{38}S particle flux, and a time signal.

A group of 5 telescopes, 5×5 cm active area, consisting of a 300 μm thick Si strip detector followed by a second 300 μm or 500 μm thick Si detector and a 1 cm thick stopping CsI, were positioned 29 cm from the target to measure recoiling protons. The telescopes covered laboratory angles between 62° and 88°. The first Si detector was segmented into 16 vertical strips (3.125 mm spacing or 0.6° in the lab frame). An energy signal and a time signal stopped by the 0° ΔE plastic detector was read for each strip and identified particles stopping in these detectors. The time resolution was $\sim$900 ps FWHM for 3.2 MeV protons. Higher-energy particles that punched through the first detector, were identified by their ΔE-E signal in Si-Si or Si-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. The laboratory angle of the scattered protons was determined from the strip detector and the center of mass (c.m.) angle and the ^{38}S excitation energies were calculated on an event by event basis.

Before measuring the ^{38}S scattering, the experimental method was tested with the ^{40}Ar beam degraded to 40A MeV. Figure 1(a) shows an energy vs laboratory angle scatterplot for recoiling protons scattered by the ^{40}Ar beam. The observed kinematic lines correspond to the ground state and first 2^+ and 3^- states of ^{40}Ar. The insert in Fig. 1(a) shows the excitation energy spectrum for the angular bin between 30.5° and 31.5° in the c.m. frame. The overall angular resolutions were on the order of 1.6° FWHM in the laboratory frame and 3.2° FWHM in the c.m. frame. The primary source of angular uncertainty came from the angular acceptance introduced by the 3.1 mm strip size and the $\sim$4 mm FWHM beam spot size. The excitation energy resolution, which depends largely on the laboratory angular resolution, varies from around 600 keV at low c.m. angles to 900 keV at higher c.m. angles. Because of the high beam intensity available for ^{40}Ar, the 0° ΔE-E plastic detector was not used to measure coincident projectile-like fragments. This leads to a large background, presumably resulting from central collisions of ^{40}Ar on protons and ^{12}C, and also precludes obtaining an absolute normalization. The ratio of elastic scattering to inelastic scattering to the 2_1^+ state was obtained from a Gaussian fit to the spectrum, after background subtraction. The deformation parameter β_2 was extracted for the 2_1^+ state by comparing the measured ratio to a coupled channel calculation performed with the code ECIS [11] using optical model parameters from Ref. [12]. This yields $\beta_2=0.29\pm0.03$ for ^{40}Ar; which is slightly larger, but consistent with the previous measurements of 0.24–0.26 [13], in spite of the large background.

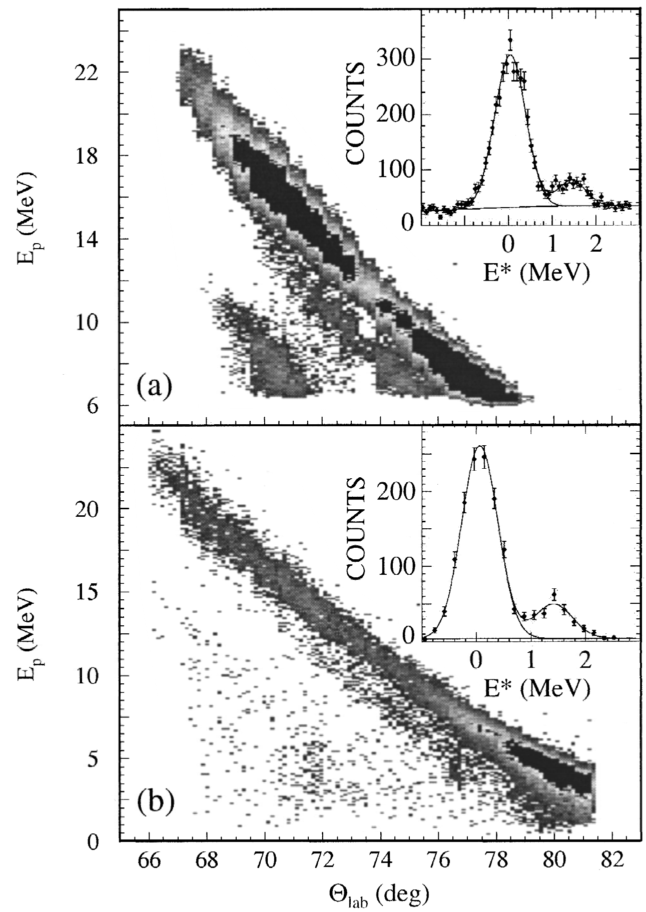

FIG. 1. (a) Energy vs angle scatterplot for recoiling protons from 40A MeV ^{40}Ar(p,p') in inverse kinematics. Insert: the excitation energy spectrum for the center of mass angular range of 30.5°–31.5°. The solid lines correspond to Gaussian fits (see text). (b) Same as (a) for 39A MeV ^{38}S(p,p'). Inset: the excitation energy spectrum for the center of mass angular range of 27°–30°. The solid lines correspond to Gaussian fits (see text).

In the case of ^{38}S, several states, including the first 2_1^+ state located at 1.29 MeV, of ^{38}S are known from extensive ^{36}S(t,p) [14] and ^{36}S$(t,p\gamma)$ [15] studies. Figure 1(b) displays a scatterplot of laboratory energy vs angle for recoiling protons from the ^{38}S scattering. Despite lower statistics than in the ^{40}Ar test case, elastic scattering and inelastic scattering to a state at 1.2 MeV, which can be identified as the 2_1^+ state, are clearly separated. Indications for the presence of higher lying states are also observed. The inset shows the excitation energy spectrum for an angular bin between 27° and 30° in

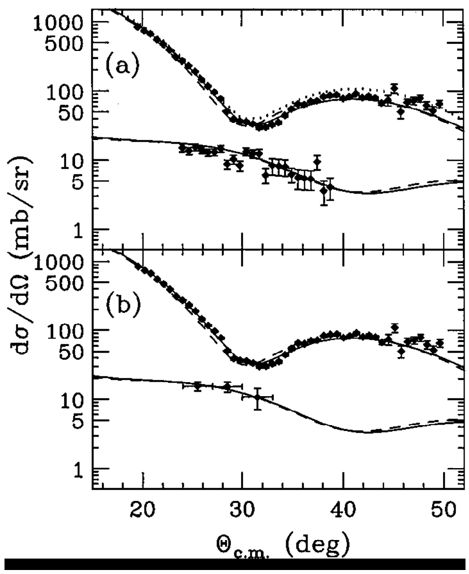

FIG. 2. (a) Angular distributions for the ground state and the 2_1^+ state in the ^{38}S(p,p') reaction at 39*A* MeV, obtained by projecting the contents of contours (see text). (b) The elastic scattering data and calculations are the same as in (a). The 2^+ data is obtained by the Gaussian fit method (see text). In both (a) and (b) the calculations are coded as follows; dashed line: coupled channel calculation with Becchetti-Greenlees potential; solid line: coupled channel calculation with ^{40}Ar(p,p') potential; dotted line: folding model calculation; for details see text.

the c.m. frame. Note that in the case of the 39*A* MeV ^{38}S beam, the background is strongly suppressed by requiring that a heavy ejectile be observed in the 0° ΔE-E detector in coincidence with scattered protons. The energy and angular resolutions are similar to those obtained in the ^{40}Ar test case.

The elastic scattering angular distribution of ^{38}S, Fig. 2(a), is obtained by projecting the contents of a contour in the excitation energy vs $\theta_{\mathrm{c.m.}}$ plane. Coupled-channels predictions using the ECIS code [11] are shown in comparison with the data. Note that no arbitrary normalization is involved here. A calculation based on the Becchetti-Greenlees parameterization [16], which was developed for (p,p) scattering on $A \geqslant 40$ nuclei, is shown by the dashed line in Fig. 2. A second calculation, shown as the solid line in Fig. 2, uses optical model parameters for ^{40}Ar(p,p) [12] and gives slightly better agreement with the measured ground state distribution, in particular at small angles.

In a microscopic approach, folding model calculations using the nucleon-nucleon potential proposed by Jeukenne, Lejeune, and Mahaux (JLM) [17] have had success at describing nucleon nucleus scattering, provided the imaginary potential is adjusted by a normalization factor typically around 0.8 [18]. The present elastic scattering data is also well reproduced by a folding model calculation (dotted line in Fig. 2), which folds nuclear densities with the JLM nucleon-nucleon potential. The densities were calculated in a shell model using the full $0f1p$ space [19,20]. The analysis of the elastic scattering, using both macroscopic and microscopic potentials, reveals no appreciable deviation, in the angular range studied, with respect to the systematics obtained for stable nuclei.

The cross section of the 2_1^+ state was obtained using two methods. First, the 2_1^+ state was selected in the excitation energy spectrum, and the angular distribution was obtained, Fig. 2(a), in the range where the ground state and 2_1^+ distributions are resolved (24°–39°). This process may be slightly inaccurate because of a small overlap of the ground state with the 2_1^+ distribution, see insert of Fig. 1(b); however the shape of the inelastic scattering distribution can be compared in Fig. 2(a) with the coupled channel ECIS calculation using the β_2 value extracted below. The shape of the experimental angular distribution is in full agreement with the calculation.

In order to extract the value of β_2, Gaussian distributions were fit to the ground state, the 2_1^+ state, and the very low background as shown in the insert of Fig. 1(b), for three angular bins. The χ^2 of the coupled-channels prediction for the 2_1^+ state was minimized to obtain the measured deformation parameter. The extracted cross sections and the calculations are shown in Fig. 2(b). Using the Becchetti-Greenlees parameterization (dashed line) [16], the cross sections extracted from the Gaussian fits yield $\beta_2 = 0.35 \pm 0.04$, while the ^{40}Ar optical parameters of Ref. [12] (solid line) give $\beta_2 = 0.36 \pm 0.04$. In the following we will adopt the value $\beta_2 = 0.35$. The validity of the use of a macroscopic model to extract deformation parameters in the case of hadronic probes has been discussed in Ref. [21]. Differences between macroscopic and microscopic analyses are shown to increase with increasing transition multipolarity and the macroscopic analysis of $L = 2$ transitions has been deemed reliable.

The β_2 value extracted here is larger than the electromagnetic $\beta_2 = 0.25 \pm 0.016$ measured by Coulomb excitation [4] which itself is in good agreement with the shell model predictions of Ref. [15]. This 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 ratio was calculated using the formula derived in Ref. [5]:

$$\frac{M_n}{M_p} = \frac{b_p}{b_n}\left[\frac{\delta}{\delta_{\mathrm{e.m.}}}\left(1 + \frac{b_n}{b_p}\frac{N}{Z}\right) - 1\right],$$

where b_p and b_n are the interaction strengths of protons with protons and neutrons, respectively, δ is the deformation length from (p,p') and $\delta_{\mathrm{e.m.}}$ is the electromagnetic deformation length ($\delta = \beta_2 r_0 A^{1/3}$). An r_0 value of 1.17 fm corresponding to the optical parameters of the Bechetti-Greenlees systematics was used for (p,p') scattering, while $r_0 = 1.20$ fm was taken for electromagnetic excitation. The b_p and b_n values were taken as 0.3 and 0.7, respectively [6]. This yields $M_n/M_p = 2.0 \pm 0.4$ for the 2_1^+ state in ^{38}S, and thus $M_n/M_p = (1.5 \pm 0.3)N/Z$, which is incompatible with the value of N/Z expected for a pure isoscalar collective excitation.

It is interesting to observe the trend of β_2 and M_n/M_p values for the 2_1^+ state as a function of neutron number in the sulfur isotopes, which are displayed in Table I. All the β_2 values from low-energy ($E < 50$ MeV) proton scattering experiments displayed in the table were extracted from a macroscopic analysis similarly to this work, allowing meaningful comparisons. The M_n/M_p values were calculated from the experimental β_2 values using the procedure described above. One should first note the very low β_2 values and high-

TABLE I. Compilation of 2_1^+ states for sulfur isotopes. Energies and β_2(e.m.) values are from Ref. [22]. $\beta_2(p,p')$ values are from Refs. [23] (^{32}S), [24] (^{34}S), [25] (^{36}S) and from this work (^{38}S).

	E (MeV)	$\beta_2(p,p')$	β_2(e.m.)	$(M_n/M_p)/(N/Z)$
^{32}S	2.23	0.28	0.31	0.84
^{34}S	2.12	0.28	0.25	1.12
^{36}S	3.29	0.18	0.16	1.12
^{38}S	1.29	0.35	0.25	1.5

excitation energy of the 2_1^+ state in ^{36}S, as well as the M_n/M_p value compatible with N/Z. Therefore ^{36}S exhibits features akin to those of a well closed nucleus. When moving away from ^{36}S, the measured β_2 values increase and a large difference in M_n/M_p values is observed between ^{32}S and ^{38}S, showing a rapid change of the structure as a function of neutron number. The large M_n/M_p value for ^{38}S can be qualitatively understood by considering the ^{38}S nucleus as a ^{36}S core plus two valence neutrons. In this case, the two neutrons drive the oscillation and the core polarization is not sufficient to restore the isoscalar character of the excitation. In previous studies of stable nuclei, similar behavior was observed in the case of ^{18}O which can be described as a ^{16}O core and two valence neutrons [5]. In that respect our result on ^{38}S is not completely unexpected. On the other hand, ^{58}Ni, which has again two neutrons outside a closed shell, exhibits an M_n/M_p value consistent with N/Z [5]. These discrepancies may be due to core polarization effects and call for more theoretical developments.

We have measured extensive angular distributions for elastic scattering and for inelastic scattering of protons on the unstable nucleus ^{38}S. The use of a large array of silicon-strip telescopes to measure recoiling protons in inverse kinematics proved to be a powerful and straightforward method to measure excitation energy spectra and angular distributions for unstable nuclei with reasonable resolution and low background. Elastic scattering data shows no appreciable deviation from the systematics obtained for neighboring stable nuclei. The measured inelastic cross section for the first 2_1^+ state yields $\beta_2=0.35\pm0.04$. A comparison with electromagnetic excitation allows us to extract $M_n/M_p=(1.5\pm0.3)N/Z$, indicating a significant isovector contribution to the 2_1^+ state. This suggests that ^{38}S can be considered as a ^{36}S core and two valence neutrons. It would now be interesting to investigate the persistence of such a structure for larger neutron numbers, for which the neutron skin effects may be more pronounced. In this aim, a similar experiment has recently been performed for ^{40}S.

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