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Elastic and inelastic scattering of protons on unstable ^{38}S nuclei has been measured in inverse kinematics by using a ^{38}S secondary beam at 39 MeV/nucleon. The excitation energy spectrum is measured up to 5 MeV. The first 2^+ state is seen at 1.2 MeV excitation energy, and strength at around 3-5 MeV is also observed. Angular distributions for inelastic and elastic scattering are shown and compared to optical potential and folding model calculations. The preliminary β_2 value extracted for the first 2^+ state is 0.38 ± 0.05.

1. INTRODUCTION

Direct reactions can provide a wealth of information on nuclear structure and interaction potentials which are fundamental problems in nuclear physics. Elastic scattering yields information on the nuclear matter distributions and on the effective nucleon-nucleon potentials, inelastic scattering gives access to the transition probabilities between the nuclear ground states and the excited states, and transfer reactions can be used to directly investigate the wave functions of specific nuclear states. Such studies have been performed extensively on stable nuclei and form the foundation of our current understanding of nuclear systems. However, the valley of β-stability is only a very limited area of the nuclear chart, and the investigation of nuclear structure outside this region has recently blossomed through the availibity of unstable nuclear beams.

We have recently undertaken a study of neutron rich sulfur isotopes using elastic and inelastic scattering of protons in inverse kinematics. Neutron rich sulfur isotopes are of special interest since their properties may yield a clue for understanding the anomalies in isotopic abundances observed in this mass region. The half lives for neutron rich sulfur isotopes were measured and found to be shorter than predicted by straightforward shell model calculations assuming spherical shapes, indicating a deformation for these nuclei located close to the N=28 neutron shell closure [1]. This deformation was confirmed recently by a coulomb excitation experiment which found abnormally low energies for the first 2^+ states of ^{40}S and ^{42}S [2]. Strong deformation effects in these isotopes are predicted by very recent shell model calculations of B. A. Brown using the full 0f1p space [3]. Selfconsistent relativistic mean-field calculations by Werner et al. [4] also predict deformed neutron rich sulfur isotopes.

Low and medium energy proton elastic scattering has been extensively analysed in the framework of the folding model to extract information on the nucleon-nucleon interaction and the nuclear matter distribution [5]. Inelastic proton scattering probes the transition probabilities B(EL) to low lying collective states. These transition probabilities are directly related to nuclear deformations. The comparison of deformation parameters, β_2, measured with proton scattering and electromagnetic excitation allows the determination of the ratio between the neutron and proton multipole matrix elements M_n/M_p [6].

In the case of unstable nuclei, proton scattering experiments must be performed by using inverse kinematics, either by detecting the heavy ejectile in a high resolution spectrometer or by measuring the angle and energy of recoiling protons. Recently several inverse kinematics proton scattering experiments were performed. Elastic scattering of ^{6}He on a CH_2 target was measured at GANIL by using the energy loss spectrometer SPEG [7]. A pioneering experiment of inelastic proton scattering by measuring recoiling protons was performed at GSI [8]. In this experiment the B(E2) value was measured for the first 2^+ state in ^{56}Ni. Elastic proton scattering was measured for the short-lived high spin isomer $^{18}F^m$ [9]. The neutron rich unstable nuclei ^{11}Li, ^{8}He, and ^{12}Be were studied at RIKEN by elastic and inelastic proton scattering using silicon strip-detectors to measure the recoiling protons [10].

In this paper we present preliminary results for elastic and inelastic scattering of protons on ^{38}S at 39 MeV/nucleon. Excitation energy spectra and elastic and inelastic angular distributions were obtained through the measurement of the angle and energy of recoiling protons. The experiment was performed at the National Superconducting Cyclotron Laboratory at Michigan State University.

2. EXPERIMENTAL METHOD

The ^{38}S beam was produced by fragmentation of a 85 MeV/nucleon ^{40}Ar beam, provided by the K1200 cyclotron at the National Superconducting Cyclotron Laboratory, in a 376 mg/cm^2 ^{9}Be production target. The produced fragments were identified by using the A1200 fragment separator with a standard ToF-ΔE-E detection system. In order to increase the beam purity, an aluminium wedge of 292 mg/cm^2 was placed in the second dispersive image of the A1200. The final energy of the secondary ^{38}S beam was 39 MeV/nucleon. The intensity of the beam was 3×10^5 particles per second, and the purity was higher than 99%. The angular emittance of the secondary beam was reduced by using collimators, and the momentum spread was limited to $\Delta p/p = 1\%$. This reduced the beam intensity to about 20 000 particles per second. In this way it was not necessary to use any beam tracking detectors. The ^{38}S projectiles were scattered on a very thin 2 mg/cm^2 CH_2 target in order to limit the energy loss and angular straggling of recoiling low energy protons.

Recoiling protons were measured with 5 telescopes placed at 29 cm from the target cen-

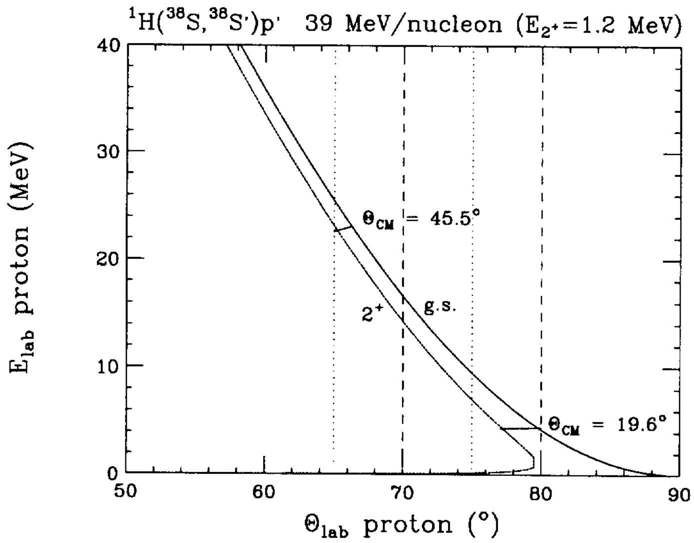

Figure 1. Kinematics for recoiling protons. The dashed and dotted lines indicate the angular ranges covered by the two detector arms.

tered at Θ_{lab}=75° (telescopes 1, 2, 3) and Θ_{lab}=70° (telescopes 4, 5). Each telescope consisted of a 300 μm silicon strip-detector with 16 vertical strips that were 3 mm wide. This yielded a recoiling angle measurement with an accuracy of 0.6°. Silicon strip-detectors were backed by a 300 μm (telescopes 1, 2, 3) or 500 μm (telescopes 4, 5) thick silicon PIN-diode and a 1 cm thick CsI stopping detector read out by 4 photodiodes. The active area of the telescopes was 5×5 cm covering a total angular range of 9.8°. This setup allowed us to measure protons from about 1 MeV up to 70 MeV. A ΔE-E plastic detector was placed at zero degrees behind the target in order to select elastic and inelastic scattering events and to give a start for the time-of-flight measurement. The particle identification in the recoil telescopes was performed either by a time-of-flight measurement between the Si strip-detector and the zero degree detector for particles stopped in the strip-detector or by a ΔE-E measurement for particles stopped in the Si PIN-diode or the CsI-detector. Figure 1 shows the detector positions with respect to the kinematics of recoiling protons. This detector setup allowed us to measure an excitation energy spectrum up to about 5 MeV and an angular distribution between $\Theta_{C.M.}$ = 20° and $\Theta_{C.M.}$ = 45°. An additional run with telescopes 4 and 5 at 67° was performed in order to measure the elastic angular distribution up to larger C.M. angles.

3. EXPERIMENTAL RESULTS

In order to test the experimental method, inelastic proton scattering in inverse kinematics was first measured for ^{40}Ar by using a 40 MeV/nucleon degraded ^{40}Ar incident beam. Figure 2 displays the energy vs. angle scatterplot for recoiling protons. Kinematic lines corresponding to the ground state and 2^+ and 3^- excited states of ^{40}Ar are clearly separated. After the kinematical transformation, figure 3 shows the measured excitation energy spectrum. The first 2^+ state is observed at 1.4 MeV and the 3^- state at 3.5 MeV.

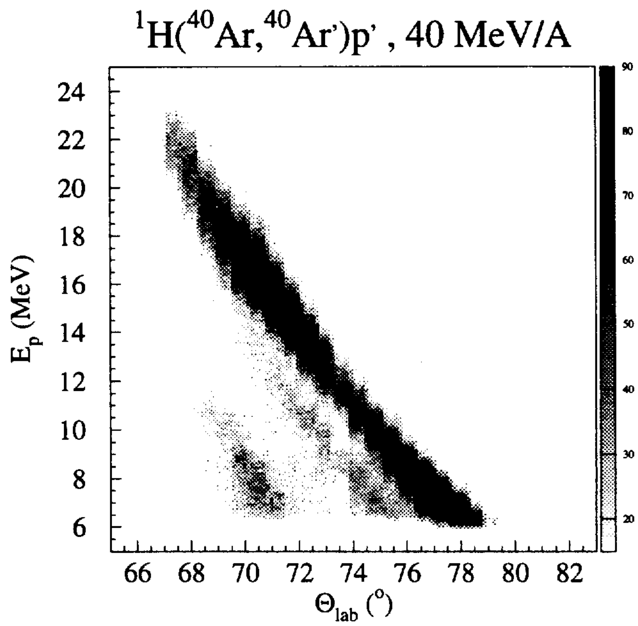

Figure 2. Energy vs. angle scatterplot for recoiling protons.

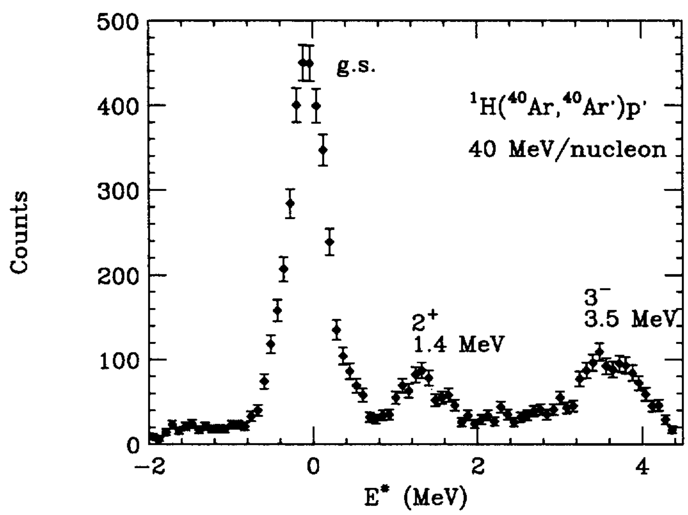

Figure 3. Excitation energy spectrum measured for ^{40}Ar scattering on protons at 40 MeV/nucleon.

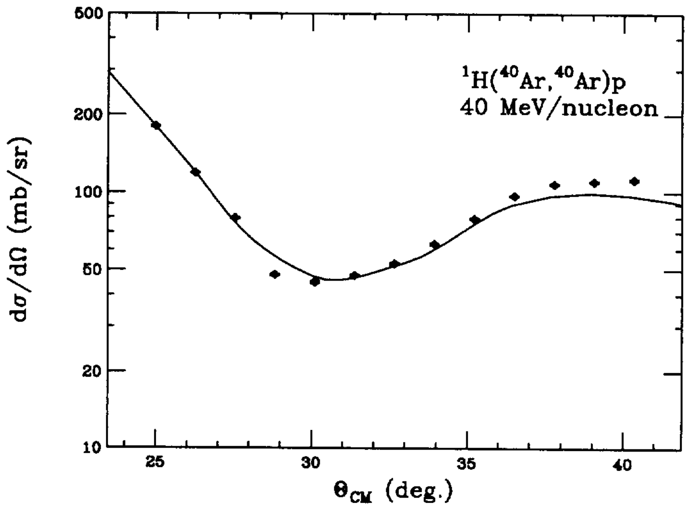

Figure 4. Comparison of ^{1}H(^{40}Ar,^{40}Ar)p at 40 MeV/nucleon (points) to a optical model calculation (solid line) that allowed to reproduce the data measured for ^{40}Ar(p,p)^{40}Ar at 40.7 MeV. The data points are arbitrarily normalized to the calculation at small angles.

These energies are in reasonable agreement with the adopted energies of 1.46 MeV and 3.68 MeV, respectively [11]. The excitation energy resolution is about 700 keV. This is comparable to the energy resolution obtained with the spectrometer SPEG at GANIL for a ^{40}Ar beam at 40 MeV/nucleon [12].

Figure 4 shows the measured elastic angular distribution for ^{40}Ar. The data is arbitrarily normalized to the calculation at small angles. The C.M.-angular resolution is estimated to be better than 2°. The angular distribution is compared to an optical model calculation that fit proton scattering data on ^{40}Ar at 40.7 MeV in direct kinematics [13]. The overall agreement is good giving confidence to the experimental method used in the present experiment. The small dip observed at $\Theta_{C.M.} = 28^o$ is due to the dead layer between the PIN diode and the CsI detector. The slight discrepancy between the calculation and the data for $\Theta_{C.M.} > 37^o$ is still under investigation.

Figure 5 shows excitation energy spectra measured for the reaction ^{1}H(^{38}S,^{38}S')p' at 39 MeV/nucleon. The energy resolution is about 800 keV which is almost as good as what was obtained for the stable ^{40}Ar beam. The first 2^+ state is observed at about 1.2 MeV which, within the experimental resolution, is compatible with the adopted value of 1.29 MeV [11]. Measurements of ^{36}S(t,pγ)^{38}S report a 4^+ state at 2.8 MeV [14,15] in agreement with shell model calculations. In the present data only a slight enhancement of the cross section is observed at this energy. At higher excitation energy a broad bump is observed between 3 and 5 MeV which contains at least two states. It can be fitted by two Gaussians centered at 3.8 and 4.4 MeV. Evidence for a state at 3.52 MeV has been reported from ^{38}P(β^-)^{38}S γ-decay experiment [16]. Shell model calculations of ref. [14] predict 3^- stregth near this energy. In ref. [14,15] several states are reported between 3 and 6 MeV but no clear spin assignments are given. More detailed analysis of the data, currently in progress, could bring information on the strength in this region.

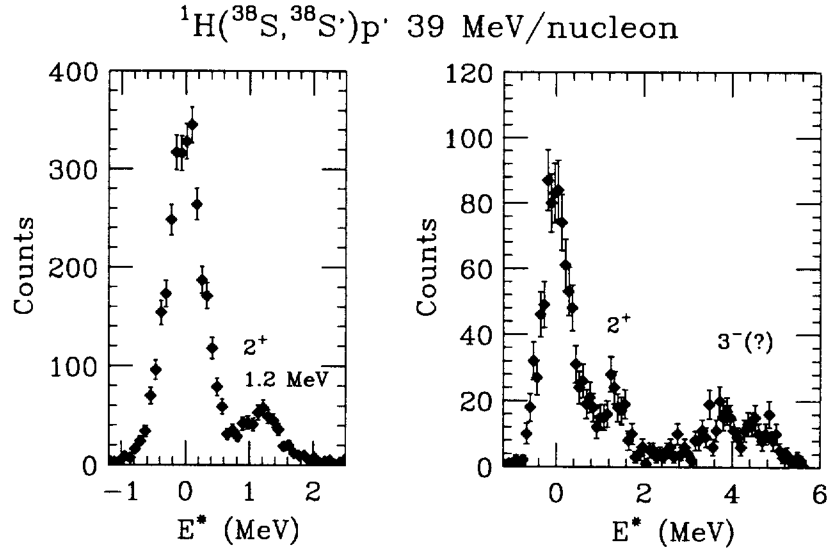

Figure 5. Excitation energy spectrum measured for ^{38}S scattering on protons at 40 MeV/nucleon. Spectrum at the left is measured with telescopes 1, 2 and 3 placed at Θ_{lab}= 75° and at right with telescopes 4 and 5 placed at Θ_{lab}= 70°.

Preliminary angular distributions extracted for the ground state and the first 2^+ state are presented in figure 6. The dotted line corresponds to a coupled channel calculation performed with the code ECIS [17] using optical potentials from ^{34}S(p,p')^{34}S' scattering at 30 MeV [18]. The elastic scattering data is arbitrarily normalized to the calculation at small angles. In order to obtain better agreement with the data the absorption was reduced by 35% (solid line in figure 6). However, even with lower absorption the elastic scattering data at large angles is still above the calculation. The use of an optical potential obtained for ^{40}Ar [19] gave similar results to those of ^{34}S. The change in absorption affects mainly large scattering angles, while the region below $\theta_{C.M.}$=25° is rather independent of small changes in optical potential. The elastic scattering data is also compared to a folding model calculation (dashed line in figure 6). This was performed by using nuclear densities calculated by B. A. Brown [3] and JLM nucleon-nucleon potential [20]. This calculation is very similar to the optical potential calculation again underestimating the cross section at large angles. These results are still preliminary, and further analysis of the elastic scattering data is in progress.

A preliminary β_2 value for the first 2^+ state was extracted by comparing the experimental 2^+ data to the optical model calculation with reduced absorption. This was done at small angles ($\Theta_{C.M.} < 25°$) where the cross section is rather independent of the absorption. The normalisation was obtained from the elastic scattering data as discussed above. The best fit value is $\beta_2 = 0.38 \pm 0.05$, the corresponding calculation is shown in figure 6. This value is higher than the β_2 value of 0.28 measured for ^{34}S through (p,p') scattering. The value measured for ^{40}Ar, which has the same neutron configuration as ^{38}S, is 0.24 [19].

These deformation parameters extracted from (p,p') scattering cannot directly yield the

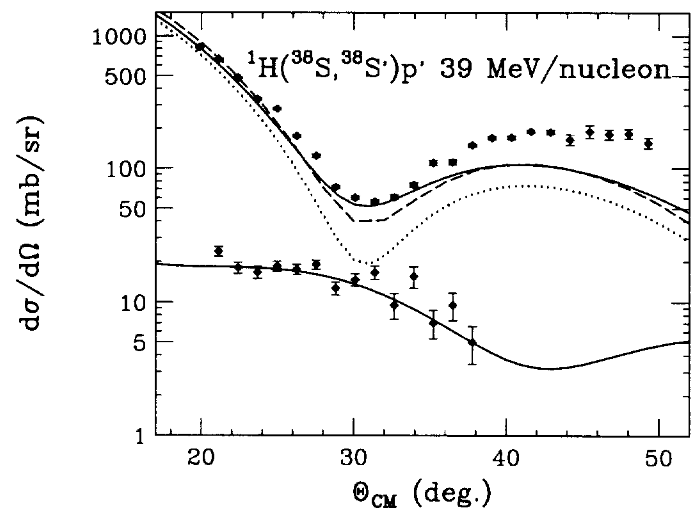

Figure 6. Angular distributions for the ground state and the 2^+ state excited in the $^{1}H(^{38}S,^{38}S')p'$ reaction at 39 MeV/nucleon. The solid lines correspond to an optical model calculation with a value of $\beta_2 = 0.38$ for the 2^+ state. The dotted line is the same calculation with higher absorption, and the dashed line a folding model calculation (see text). Experimental data is arbitrarily normalized to calculations at small angles.

reduced electromagnetic matrix element B(E2) since incident low energy protons interact more strongly with neutrons in the nucleus than with other protons, while electromagnetic probes see only the protons in the nucleus. It will be very interesting in the future to use these characteristics of different probes to extract information about the differences of neutron and proton deformations in nuclei far from stability.

4. CONCLUSIONS

We have measured for the first time elastic and inelastic proton scattering on the unstable nucleus ^{38}S. The ground state and 2^+ state at 1.2 MeV of ^{38}S are clearly separated and strength at higher excitation energies is also seen. A preliminary β_2 value of 0.38 ± 0.05 is extracted for the 2^+ state. The measurement of the angle and energy of the recoiling protons using silicon strip telescopes is proven to be a powerful and general method for the study of such reactions. Recently, measurements of proton scattering on the unstable nuclei ^{18}Ne, ^{20}O, and ^{40}S have been performed at the NSCL with the same experimental set-up, and the data are currently under analysis.

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