Excitation energies in ^{33}Cl via ^{32}S(p, γ)

S. Triambak,[1] A. García,[1] D. Melconian,[1] M. Mella,[2] and O. Biesel[1]
[1]*Physics Department, University of Washington, Seattle, Washington 98195-1560, USA*
[2]*Physics Department, University of Northern Colorado, Greeley, Colorado 80639, USA*
(Received 31 July 2006; published 15 November 2006)

We populated states in ^{33}Cl that are useful for an accurate calibration of the β-delayed proton spectrum from ^{33}Ar using ^{32}S(p, γ) resonances and obtained precise values for excitation energies by measuring the energies of the de-excitation gamma rays. In addition, we obtained an upper limit of 0.3 keV on the width of the second excited $J^\pi = 3/2^+$ state in ^{33}Cl, which removes an apparent discrepancy with the width observed in ^{33}Ar decay. Our results may play an important role in determining the e^+-ν correlation from ^{32}Ar β decay.

DOI: 10.1103/PhysRevC.74.054306 PACS number(s): 23.20.Lv, 24.30.−v, 27.30.+t, 29.30.Kv

I. INTRODUCTION

The energy calibration of the β-delayed proton spectrum from ^{33}Ar is based on the excitation energies in ^{33}Cl determined from ^{32}S(p, γ). This energy calibration is used to determine the energies of β-delayed proton groups from ^{31}Ar and ^{32}Ar as well because ^{33}Ar can be produced with larger intensities and, at on-line radioactive-beam facilities, it is simple to switch from one mass to the next. The energy calibration of the delayed-proton spectrum is important in determining the e^+-ν correlation from ^{32}Ar β decay [1].

This paper primarily reports a precision measurement of the energies of states in ^{33}Cl that play an important role in the energy calibration of the protons from ^{33}Ar. The states were populated via $p + {}^{32}$S resonances and the corresponding γ transitions were observed using a 50% HPGe detector. In addition, prior to this work, there were indications that the width of the (p, γ) resonance of the $E_x \approx 3971$ keV state was larger than that observed from its corresponding β-delayed proton group. The width of the resonance was reported as $\Gamma = 5 \pm 3$ keV [2] whereas the observed width for the state in the decay of ^{33}Ar was $\Gamma < 2$ keV [3] and $\Gamma < 0.2$ keV [4]. The importance of this state for the energy calibration motivated us to measure the excitation function around this particular resonance ($E_p \approx 1748$ keV) and to determine the width of the state. As a byproduct of this work we obtained the relative γ branches from the state at $E_x \approx 3971$ keV, which we found to be in significant disagreement with the results of Ref. [2].

II. EXPERIMENTAL PROCEDURE

We initially produced two Ag_2S targets by heating S next to a heated Ag backing, using the procedure described in Ref. [5]. One of the targets was $\approx$2 mg/cm^2 and the other $\approx$0.13 mg/cm^2. These targets were satisfactory for γ-ray energy measurements. To measure excitation functions, we made an additional target by evaporating $\approx$200 Å of Sm_2S_3 on a $\approx$300 μg/cm^2 thick Au foil using an electron beam. The energy loss for the protons in this target was $\leqslant 1$ keV at $E_p = 1748$ keV.

For the γ-ray energy measurement the targets were mounted on a movable target ladder in a vacuum chamber that allowed for direct water cooling on the backings. For the measurement of the width of the state at $E_x = 3971$ keV, the Sm_2S_3 target was mounted on the front of the target ladder such that most of the beam passed through the Au foil and deposited itself on a water-cooled, 0.5-mm-thick Au backing. This minimized local heating of the target to avoid tails in the excitation function from diffusion. The experiment was performed using the University of Washington FN tandem accelerator operating as a single-ended machine with the ion source at the terminal. The $\approx$3-μA proton beam was bombarded on the target of interest after being tuned through the 90° analyzing magnet with the object and image horizontal slits at $\approx$0.8 mm. The spread in the beam profile was calculated to be $\approx$1.8 keV for such slit settings. γ rays were registered using a 50%-efficient, high-purity Ge detector positioned at 0° to the beam. This gave the least sensitivity to target ladder-detector misalignments. Figure 1 shows the experimental setup.

III. DATA ANALYSIS

Peak centroids and areas were extracted by fitting the data with an analytical function that is the convolution of a Gaussian with two low-energy exponential tails plus a delta function and a flat background. The line-shape function is of the form

$$L(E;E') = \sum_{i=1}^{2} \frac{\alpha_i}{2\lambda_i} \exp\left[\frac{(E-E')}{\lambda_i} + \frac{1}{2}\left(\frac{\sigma}{\lambda_i}\right)^2\right] \times \operatorname{erfc}\left[\frac{1}{\sqrt{2}}\left(\frac{(E-E')}{\sigma} + \frac{\sigma}{\lambda_i}\right)\right] + G(E;E'), \quad (1)$$

where E and E' are the nominal and observed energies, respectively, $G(E;E')$ is a Gaussian normalized to unit area, σ is the Gaussian width, λ_i is a decay length, and α_i is the relative area of the tail with respect to the pure Gaussian. With the appropriate normalization, the fitting function then takes the form

$$F(E;E') = \frac{A}{1+\alpha_1+\alpha_2} L(E;E') + B, \quad (2)$$

where A is the area parameter and B is the background parameter. Peak centroids and areas were obtained by varying

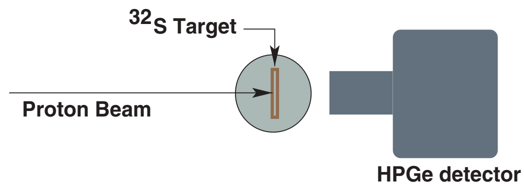

FIG. 1. (Color online) Top view of the experimental setup used for the $^{32}S(p,\gamma)$ data.

the various parameters and minimizing the χ^2 using the method of maximum likelihood. The formalism is explained in greater detail in Ref. [6].

IV. RESULTS

A. Systematic effects

The systematic uncertainties that affect the determination of γ-ray energies in this measurement are similar to those described in Ref. [6]. They were corrected for and avoided in a similar manner. The uncertainties are dominated by uncertainties in the response function, the detector solid angle, and possible misalignments.

B. Excitation energies in ^{33}Cl

To obtain the ^{33}Cl excitation energies of interest we made three independent measurements at different times. In the first measurement the thicker Ag_2S target was used and the γ rays were registered using the Ge detector placed 11.2 cm from the target, at 0°. The energy calibration was done using a ^{56}Co source that provided calibrations up to 3.5 MeV. In the second measurement, the thinner Ag_2S target was used with the Ge detector positioned at 14.5 cm from the target. The energy calibration lines were obtained from both ^{56}Co and $^{27}Al(p,\gamma)$ lines [6]. In the third measurement we concentrated only on the $E_x = 3971$ keV resonance, obtaining the excitation energy using the ≈200 Å-thick target and a ^{56}Co source, with the target-detector distance set at 9.6 cm. Measurements from all sets were in good agreement within uncertainties. Figure 2

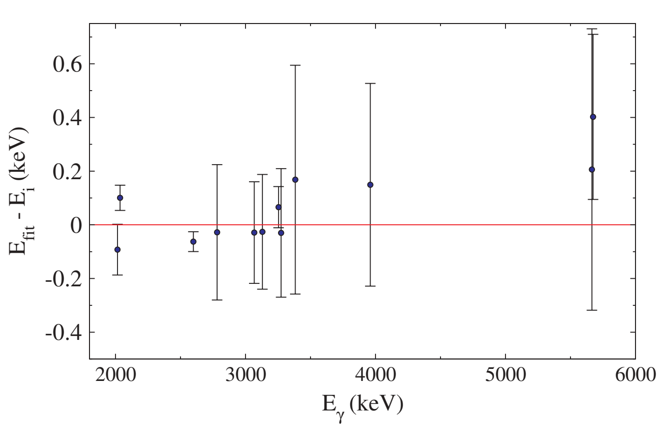

FIG. 2. (Color online) Residuals of linear fit to ^{56}Co and $^{27}Al(p,\gamma)$ lines to obtain γ-ray energy calibration.

TABLE I. Level energies and Doppler-corrected γ-ray energies from ^{33}Cl.

J^π	E_x (keV)		E_γ (keV)[b]
	Previous work[a]	This work	
$3/2^+$	3971.5(1.1)	3971.1(2)	3970.9(2)
$5/2^-$	3980.4(1.0)	3979.1(2)	3978.8(2)
$1/2^+$	4112.9(1.2)	4112.3(2)	4112.0(2)
$1/2^+$	4438.3(1.4)	4439.1(2)	4438.7(2)
$3/2^+$	4463.6(1.8)	4464.5(4)	4464.1(4)
$1/2^+$	5547.9(8)[c]	5548.5(4)[d]	4737.6(4)
			5548.0(2.0)

[a]From Ref. [2], unless noted otherwise.
[b]Obtained as a weighted mean of different independent measurements. The systematic uncertainties from peak line shapes and the detector solid angle were added in quadrature to the statistical uncertainties.
[c]From Ref. [7].
[d]Weighted average from the two decay modes whose branches are shown in Table II.

shows the residuals from a linear fit that was used to obtain the energy calibration for the second set of the aforementioned data. The observed γ energies were corrected for Doppler shifts using Monte Carlo simulations, as described in Ref. [6]. Table I compares our results to previous work. Our results are in agreement with previous measurements, with improved precision.

We populated the lowest $T = 3/2$ state at $E_x \approx 5.5$ MeV with the proton beam at $E_p \approx 3.4$ MeV. We observed peaks in our γ spectrum corresponding to two decay modes. As shown in Fig. 3, one is a prominent peak that corresponds to the transition to the first excited ($E_x \approx 811$ keV) state; the other smaller peak corresponds to direct de-excitation to the ground state. This is to be expected based on the decays of the isobaric analog state in the mirror ^{33}S nucleus. Table II

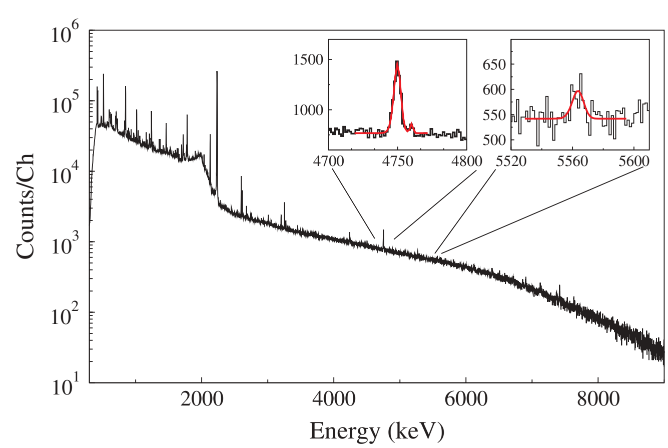

FIG. 3. (Color online) γ spectrum from $^{32}S(p,\gamma)$ taken at $E_p \approx 3.4$ MeV. The lower energy lines correspond to inelastic scattering plus the ^{56}Co calibration source. The insets show the γs corresponding to transitions from the $E_x = 5548$ keV ($T = 3/2$) state in ^{33}Cl and their corresponding fits.

TABLE II. Relative γ branches (in percentage) from the lowest $T = 3/2$, $A = 32$ states.

Final state (MeV)	Relative branches	
	^{33}S[a]	^{33}Cl[b]
0.8	85(5)	88(3)
0	15(5)	12(3)

[a]From Ref. [8].
[b]This work. See text in Sec. IV D to determine the γ branches.

shows the good agreement between relative branches from the isobaric analog states of the two mirror nuclei, confirming our identification of the γ-ray peaks. Our value for the excitation energy is in good agreement with the recent determination of Ref. [7] that showed the energy of the lowest $T = 3/2$ state in ^{33}Cl to be $\approx$5 keV higher than that determined in Ref. [9]. We tested the isobaric multiplet mass equation (IMME) [10,11] for the $A = 33$, $T = 3/2$ quartet using our measured value for the excitation energy of the lowest $T = 3/2$ state in ^{33}Cl. Table III shows the best available results for the masses and the corresponding IMME fit. We find excellent agreement with the IMME prediction, with $Q(\chi^2, \nu) = 0.73$.

C. Width of the $E_x = 3971$ keV state

The width of the $E_x = 3971$ keV state was obtained by varying the proton energy in steps of $\approx$0.5 keV and measuring the γ yield. We obtained the centroid and the (γ-detector response) width of the γ peak by fitting it on resonance. We then obtained the rest of the excitation function data by minimizing the χ^2 and assuming a fixed line shape, allowing only the area and the background to vary. Figure 4 shows the excitation function around the $E_x = 3971$ keV resonance. For comparison, we also show the excitation function around the $E_x = 3979$ keV resonance, which has a narrow width [2]. We fitted the yields for the 3971- and 3979-keV resonances separately, by assuming a common function to describe the combined effects of beam-energy resolution and target nonuniformities. This function was the same as the one described by Eq. (1). The resonances were assumed to arise from the interference of a Breit-Wigner resonance and a constant nonresonant background. The data were fitted by allowing the Breit-Wigner parameters and the nonresonant background to vary. The resulting fits are shown in Fig. 4. The fits indicate that both these states have $\Gamma \leqslant 0.3$ keV.

TABLE III. Comparison of the measured mass excesses of the lowest $T = 3/2$ quartet in $A = 33$ with a fit to the IMME [$Q(\chi^2, \nu) = 0.73$].[a]

Isobar	T_z	M_{Exp} (keV)[b]	M_{IMME} (keV)
^{33}P	$-3/2$	$-26337.5(1.1)$	$-26337.69(95)$
^{33}S	$-1/2$	$-21106.29(17)$[c]	$-21106.28(17)$
^{33}Cl	$1/2$	$-15454.9(6)$[d]	$-15455.07(35)$
^{33}Ar	$3/2$	$-9384.08(44)$[e]	$-9384.05(43)$

[a]$Q(\chi_0^2, \nu)$ is the probability of obtaining a set of data with $\chi^2 \geqslant \chi_0^2$, given that the model is correct.
[b]Unless noted otherwise, ground-state masses are from Ref. [12].
[c]Using $E_x = 5479.7(1)$ keV from Ref. [13].
[d]Using E_x from this work.
[e]Blaum *et al.* [10].

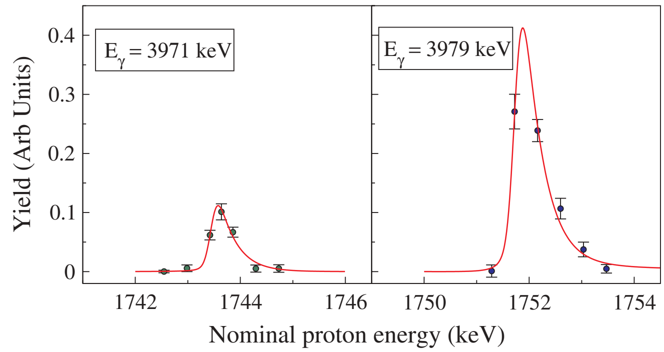

FIG. 4. (Color online) Excitation functions around the $E_x = 3971$ keV and the $E_x = 3979$ keV resonances. See text for description of the fits.

D. Relative γ branches from the $E_x = 3971$ keV state

To determine the relative γ branches, we obtained relative γ-ray detection efficiencies using a PENELOPE Monte Carlo simulation [14]. Simulations were done in the range $810 \leqslant E_\gamma \leqslant 4175$ keV in steps of 25 keV and then fitted to a polynomial,

$$\ln \epsilon_i(E_{\gamma_i}) = \sum_{j=0}^{3} a_j \, (\ln E_{\gamma_i})^j, \tag{3}$$

to obtain a relative efficiency curve. Furthermore, we replaced the ^{32}S target with a ^{56}Co calibration source to experimentally obtain the relative efficiencies. Figure 5 shows the excellent agreement between the calibration points and the model based

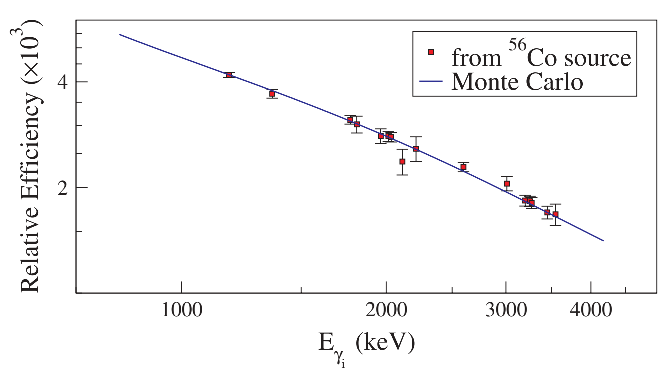

FIG. 5. (Color online) Relative efficiency curve for the Ge detector. The calibration points are normalized to the point at $E_\gamma = 1175$ keV.

TABLE IV. Relative γ branches (in percentage) from the $E_x = 3971$ keV state. Excitation energies are in MeV.

Final state		^{33}S Ref. [13]	^{33}Cl	
J^π	E_x		Ref. [2]	This work[a]
$3/2^+$	0	61(3)	31(4)	50(3)
$1/2^+$	0.8	16(2)	40(4)	18(2)
$5/2^+$	2.0	12(2)	16(3)	16(2)
$3/2^+$	2.3	5(3)	5(2)	8(2)
$5/2^+$	2.8	6(1)	8(1)	8(4)

[a]We assumed a 5% uncertainty in the ratio of γ detection efficiencies.

on the simulated efficiencies. Table IV shows the relative γ branches from the $E_x = 3971$ keV state and compares our results to previous work. We find significant disagreement with the results of Ref. [2]. Our result for the branch to the ground state is $\approx 3\sigma$ smaller than the corresponding branch measured from the isobaric analog state in ^{33}S.

V. CONCLUSIONS

We made precision measurements of excitation energies of states in ^{33}Cl that are important for calibrating the β-delayed proton groups from ^{33}Ar. This is important in determining the e^+-ν correlation from ^{32}Ar. In addition, we deduced an upper limit of 0.3 keV on the width of one of these states ($E_x = 3971$ keV) and solved an apparent discrepancy from previous measurements. We also determined the relative γ branches from the 3971-keV state that significantly disagree with the previously measured values.

ACKNOWLEDGMENTS

We thank Eric G. Adelberger for thoughtful comments, Greg Harper for help with accelerator operation, Doug Will for his assistance in target preparation, and Bob Vandenbosch for providing us with gold foils. MM acknowledges support from the NSF REU program at the University of Washington. This work was supported by the U.S Department of Energy.

[1] E. G. Adelberger, C. Ortiz, A. García, H. E. Swanson, M. Beck, O. Tengblad, M. J. G. Borge, I. Martel, H. Bichsel, and the ISOLDE Collaboration, Phys. Rev. Lett. **83**, 1299 (1999).

[2] M. M. Aleonard, P. Hubert, L. Sarger, and P. Mennrath, Nucl. Phys. **A257**, 490 (1976).

[3] D. Schardt and K. Riisager, Z. Phys. A **345**, 265 (1993).

[4] A. García *et al.* (in preparation).

[5] D. D. Watson, Rev. Sci. Instrum. **37**, 1605 (1966).

[6] S. Triambak, A. García, E. G. Adelberger, G. J. P. Hodges, D. Melconian, H. E. Swanson, S. A. Hoedl, S. K. L. Sjue, A. L. Sallaska, and H. Iwamoto, Phys. Rev. C **73**, 054313 (2006).

[7] M. C. Pyle, A. García, E. Tatar, J. Cox, B. K. Nayak, S. Triambak, B. Laughman, A. Komives, L. O. Lamm, J. E. Rolon, T. Finnessy, L. D. Knutson, and P. A. Voytas, Phys. Rev. Lett. **88**, 122501 (2002).

[8] K. T. Knöpfle *et al.*, Phys. Rev. C **4**, 818 (1971).

[9] U. Abbondanno, R. Giacomich, L. Granata, M. Lagonegro, G. Poiani, P. Blasi, and R. A. Ricci, Nuovo Cimento **70A**, 391 (1970).

[10] K. Blaum *et al.*, Phys. Rev. Lett. **91**, 260801 (2003).

[11] J. Britz, A. Pape, and M. Antony, At. Data Nucl. Data Tables **69**, 125 (1998).

[12] G. Audi, A. H. Wapstra, and C. Thibault, Nucl. Phys. **A729**, 337 (2003).

[13] P. M. Endt, Nucl. Phys. **A521**, 1 (1990).

[14] J. Sempau *et al.*, Nucl. Instrum. Methods Phys. Res. B **132**, 377 (1997).