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Measurement of the ^{40}Ca(^{3}He,t)^{40}Sc reaction

V. Y. Hansper, A. E. Champagne, S. E. Hale, C. Iliadis, and D. C. Powell
The University of North Carolina at Chapel Hill, Chapel Hill, North Carolina 27599-3255
and Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708-0308

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Levels in ^{40}Sc below 2.5 MeV excitation energy have been populated in a high-resolution study of the ^{40}Ca(^{3}He,t)^{40}Sc reaction. Three new states have been observed at energies $E_x = 1703$, 1871, and 1925 keV. Correspondence of the observed ^{40}Sc levels with known $T=1$ states in ^{40}K and ^{40}Ca are based on predictions provided by the isobaric multiplet mass equation. Our results confirm recently estimated stellar reaction rates for proton capture on ^{39}Ca.

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In stellar hydrogen burning at temperatures in excess of $T = 0.1$ GK, initially abundant nuclei are gradually transformed to heavier isotopes by proton capture reactions and β^+ decays [1]. It was pointed out previously [2] that at sufficiently high stellar temperatures, the abundance flow will reach the isotope ^{39}Ca. Depending on the magnitude of the ^{39}Ca+p reaction rate as compared to the β-decay rate of ^{39}Ca, the subsequent flow could continue via the reaction sequence ^{39}Ca($\beta^+\nu$)^{39}K(p,γ)^{40}Ca(p,γ)^{41}Sc or by ^{39}Ca(p,γ)^{40}Sc(p,γ)^{41}Ti($\beta^+\nu$)^{41}Sc. The former path is expected to slow down the abundance flow towards heavier isotopes because of the long β-decay half-life of ^{39}Ca ($T_{1/2} = 860$ ms), the slow ^{40}Ca+p reaction, and a possible (p,α) reaction competing with the (p,γ) reaction on ^{39}K. Consequently, a quantitative estimate of the stellar reaction rate for ^{39}Ca(p,γ)^{40}Sc ($Q = 0.54$ MeV) could be important for modeling the nucleosynthesis in the Ca mass region and beyond.

Large-scale reaction network calculations of explosive hydrogen burning nucleosynthesis have been performed recently by Iliadis *et al.* [3]. The results indicate that the ^{39}Ca+p reaction plays a minor role at temperatures typical for nova outbursts ($T \leqslant 0.35$ GK) since the abundance flow does not reach the calcium region. Similarly, network calculations performed for a x-ray burst model that achieved a peak temperature of $T = 1.5$ GK indicate only a small influence of the ^{39}Ca+p reaction rates on the resulting nucleosynthesis. This is because the inverse photodisintegration of ^{40}Sc will compete with the proton capture reaction on ^{39}Ca for such high temperatures. As a result, a large amount of material accumulates at ^{39}Ca and the abundance flow will depend mainly on the reaction Q value rather than on the reaction cross section. However, at intermediate temperatures of $T = 0.4$–1.5 GK that are, for example, typical of stable hydrogen burning on the surface of accreting neutron stars [4], the ^{39}Ca+p reaction rate will most likely have an impact on nucleosynthesis.

A direct measurement of the ^{39}Ca+p reaction requires the use of a radioactive ion beam. However, the low ^{39}Ca beam intensities produced at present-generation radioactive ion beam facilities are not promising for direct cross section measurements. Therefore, indirect experimental techniques have to be applied in order to estimate the reaction rates. The most recent calculation of ^{39}Ca+p reaction rates is presented in Iliadis *et al.* [3]. In that work, contributions of four resonances and the direct capture process have been taken into account. Resonance energies were calculated by using ^{40}Sc excitation energies measured in the ^{40}Ca(^{3}He,t) charge-exchange reaction [5]. Furthermore, proton and γ-ray partial widths have been estimated from measured spectroscopic factors and mean lifetimes of the corresponding states in the mirror nucleus ^{40}K. According to Ref. [3], the resulting statistical uncertainties of ^{39}Ca+p reaction rates amount up to one order of magnitude for stellar temperatures below $T = 2$ GK.

The estimated reaction rate depends sensitively on the values for the excitation energies of the first two levels above the proton threshold and on the analog state assignments of isospin triplet states in $A = 40$ nuclei. Precise ^{40}Sc excitation energies below $E_x = 2.5$ MeV have been reported in only one study [5]. Analog state assignments are complicated by the fact that for several known ^{40}K levels the corresponding states in ^{40}Sc are missing [6]. In the present work, we have reinvestigated the ^{40}Ca(^{3}He,t)^{40}Sc reaction with special emphasis on the measurement of precise excitation energies and on detecting the missing ^{40}Sc levels.

The ^{40}Ca(^{3}He,t)^{40}Sc reaction was studied using ^{3}He beams provided by the TUNL FN tandem Van de Graaff accelerator. The target was composed of 47 μg/cm^2 of $^{\mathrm{nat}}$Ca evaporated onto a 22 μg/cm^2 carbon backing. Outgoing reaction products were detected using a position-sensitive avalanche counter [7], located in the focal plane of an Enge splitpole magnetic spectrometer. Data were taken at $\theta_{\mathrm{lab}} = 10°$ and 15° so that states arising from target contamination or from deuterons misidentified as tritons could be distinguished from the states of interest. A second run at $\theta_{\mathrm{lab}} = 10°$ was carried out in order to check the results from the first run. The beam energies for the two runs were 26.064(2) MeV and 26.076(2) MeV. These values were derived from an intercomparison of states populated by the ^{27}Al(^{3}He,d)^{29}Si and ^{27}Al(^{3}He,t)^{29}Si reactions at $\theta_{\mathrm{lab}} = 5°$, 10°, and 15° and the quoted uncertainty includes the differences in energy lost by the deuterons and tritons within the ^{27}Al target.

Spectra of states observed in ^{40}Sc are displayed in Figs. 1 and 2. The observed energy resolution was approximately 15 keV. The energy dispersion of the focal plane was determined using well-known states populated in the ^{12}C(^{3}He,p)^{14}N, ^{27}Al(^{3}He,p)^{29}Si, and ^{28}Si(^{3}He,p)^{30}P reac-

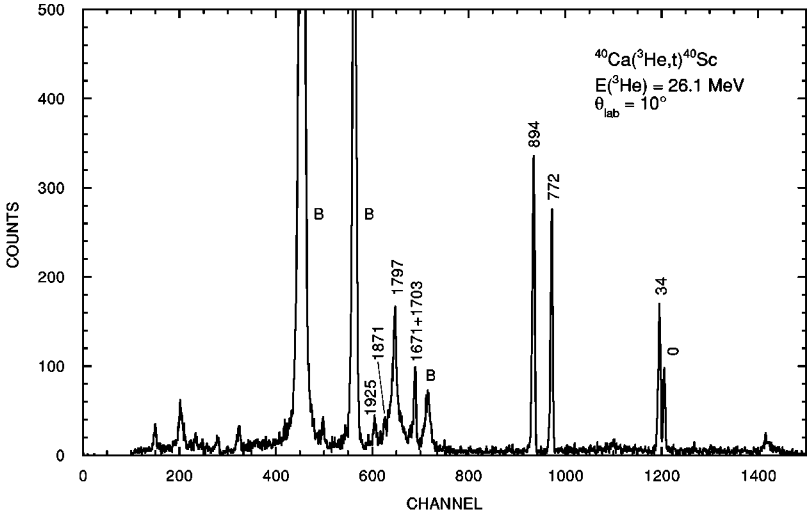

FIG. 1. Triton spectrum measured with the ^{40}Ca(^{3}He,t)^{40}Sc reaction at $\theta_{\rm lab}=10°$. Backgrounds from oxygen are labeled as B. At this angle, the 2370-keV state is obscured by one of these lines.

tions, measured at the same magnetic field and detector position as for the ^{40}Ca(^{3}He,t)^{40}Sc reaction. This information was then used to calculate the difference in triton energies between the excited states in ^{40}Sc and the ground state. Excitation energies were determined from these energy differences. Because of a nonlinearity in an ADC module, this procedure had to be slightly modified for the data from the second run at $\theta_{\rm lab}=10°$. In this case, the excitations energies above $E_x=1.6$ MeV were determined relative to our value for the 895-keV state, derived from the previous run.

Excitation energies of ^{40}Sc measured in the present work at detection angles $\theta_{\rm lab}=10°$ and 15° are listed in the first column of Table I and the weighted average is given in column 3. Altogether we have observed three new ^{40}Sc states at energies $E_x=1703$, 1871, and 1925 keV. The tabulated uncertainties include contributions from the beam energy, peak centroids and the dispersion calculation. Systematic errors associated with drifts in the magnetic field or motion of the beam on target have a negligible influence on the energy difference and therefore have been ignored. Similarly, the energy difference is insensitive to uncertainties associated with energy losses in the targets. Previously compiled results [6,8], which have been adopted from measurements of Refs. [5,9], are listed in column 4 for comparison. It can be seen that the agreement between the present results and those of Ref. [6] is excellent. The last column of Table I lists the weighted average of the two data sets.

In Table II we list isospin triplet states ($T=1$) in $A=40$ nuclei. The information for ^{40}K and ^{40}Ca, including analog state assignments, is adopted from Ref. [6]. The assignments of ^{40}Sc levels is not straightforward since the J^π values for most states are unknown. Analog state correspondences based on experimental excitation energies alone are unreliable because of the possibility of considerable Coulomb displacement energies. In this work we have used a method described in Ref. [3] to which the reader is referred for details. In brief, measured excitation energies of ^{40}K and ^{40}Ca levels, for which the spins and parities are well known, are used together with the isobaric multiplet mass equation (IMME) [10] in order to calculate excitation energies of ^{40}Sc analog states via

$$E_x(^{40}\mathrm{Sc})=2E_x(^{40}\mathrm{Ca})-E_x(^{40}\mathrm{K})+2[c-c(\mathrm{g.s.})]. \quad (1)$$

The coefficient c is a measure for the isotensor Coulomb energy of a specific isobaric triplet. It was shown in Ref. [3] that for $T=1$ states in $A=28$, 32, 36, and 40 nuclei the last term in Eq. (1) can be neglected in a first-order approximation. Using this procedure, excitation energies in proton-rich nuclei have been predicted *on average* within 50 keV [3] of their actual values. Possible analog assignments of ^{40}Sc levels are then found (i) by minimizing the difference between measured ^{40}Sc excitation energies and E_x values calculated with Eq. (1) and (ii) by matching experimentally determined spin-parity restrictions with well-known quantum numbers of the isobaric triplet.

Measured ^{40}Sc excitation energies and E_x values estimated with the IMME are listed in columns 5 and 7, respectively, of Table II. The analog assignments for the first three excited ^{40}Sc levels at $E_x=34$ (3_1^-), 772 (2_1^-), and 894 keV (5_1^-) are unambiguous, with the latter two states corresponding to the lowest-lying resonances in the ^{39}Ca$+p$ reaction. The state at $E_x=2283$ keV has been observed in β-delayed proton decay studies [11,12] and selection rules

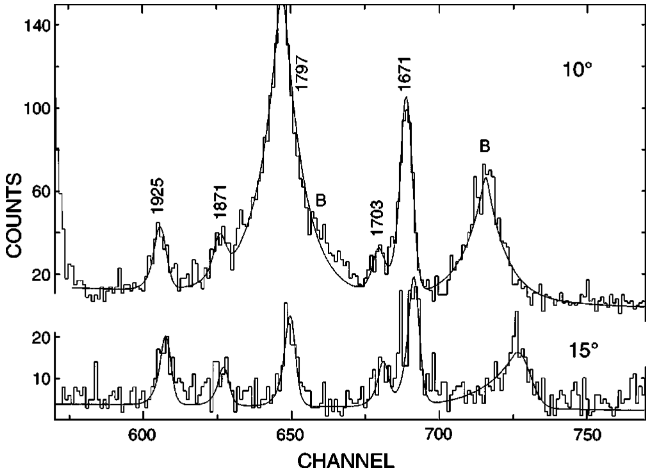

FIG. 2. Triton spectra at $\theta_{\rm lab}=10°$ and 15° showing states the energy range $E_x=1500$–2000 keV. The solid lines are fits to the data.

TABLE I. Energy levels of ^{40}Sc below $E_x = 2.5$ MeV.

	Present work		Endt [a]	Adopted [b]
10°	15°	Average [c]		
35.4 *28*	34.3 *32*	35.1 *16*	33.6 *15*	34.3 *11*
772.5 *28*	772.0 *32*	772.2 *16*	772 *2*	772.1 *12*
896.0 *28*	894.0 *32*	895.1 *20*	892 *2*	893.5 *14*
1672.0 *33*	1671.0 *36*	1671.6 *19*	1667 *4*	1670.7 *17*
1703.5 *40*	1704.0 *50*	1703.2 *22*		1703.2 *22*
1793.0 *32*	1800.0 *36*	1796.1 *24*	1799 *4* [d]	1797.0 *20*
1875.0 *40*	1868.0 *36*	1871.1 *27*		1871.1 *27*
1936.0 *40*	1930.0 *36*	1932.7 *27*		1932.7 *27*
			2430 *120* [e]	2283 *6* [f]
	2376.0 *50*	2376.0 *50*	2366 *4*	2370.0 *30*

[a] Reference [6].

[b] Weighted average of columns 3 and 4; all levels, except $E_x = 34$ keV, are unbound ($Q_{p\gamma} = 539.10$ *4.46* keV [14]) and correspond to resonances in ^{39}Ca$+p$.

[c] Weighted average of columns 1 and 2.

[d] The value 1779 keV given in Ref. [6] is a typographical error; the correct value is 1799 keV (see Refs. [5,8]).

[e] From β-delayed proton decay study of Ref. [9].

[f] Weighted average of β-delayed decay studies of Refs. [11,12].

for Gamow-Teller transitions imply an assignment of 1^+_1. The IMME predicts the energy of this level to within 160 keV. Below we discuss the analog assignments of other ^{40}Sc levels. These are based on weak arguments and, therefore, have been placed in parenthesis in Table II. According to Ref. [13], the measured ^{40}Ca(^{3}He,t)^{40}Sc angular distributions for $E_x = 1797$ and 2370 keV suggests J^π values of either 3^- or 4^-. These two levels have been assigned previously [13] to 3^-_2 and 4^-_2, respectively. However, note that the former assignment is in poor agreement with the excitation energy predicted by the IMME (Table II). Consequently, we have assigned 3^-_3 and 4^-_2, respectively, to $E_x = 1797$ and 2370 keV. It was also suggested by Ref. [13] that both the measured (^{3}He,t) angular distribution and the cross section strength for the previously unresolved doublet at $E_x = 1.67$ MeV are consistent with J^π values of $1^- + 2^-$. In the present work, the doublet has been resolved, resulting in measured values of $E_x = 1671$ and 1703 keV (Table I). We have assigned 1^-_1 and 2^-_2 to these two levels, in reasonable agreement with the IMME results. The remaining two levels at $E_x = 1871$ and 1925 keV (Table I) have not been observed previously, and are associated with 0^+_1, 2^+_1, or 3^+_1. Note that the IMME predicts another ^{40}Sc level at ≈ 1.45 MeV (Table II). A weak indication for this state might be visible in Fig. 1, but insufficient statistics precludes an unambiguous identification.

TABLE II. Isospin triplet states ($T = 1$) in $A = 40$ nuclei (E_x in keV).

^{40}K [a]		^{40}Ca [a]		^{40}Sc [b]		IMME [c]
E_x	J^π	E_x	$J^\pi;T$	E_x	J^π	E_x
0	4^-	[7658]	$4^-;1$	0	4^-	0
30	3^-	36	$3^-;1$	34		42
800	2^-	767	$2^-;1$	772		734
891	5^-	893	$5^-;1$	894		895
1644	0^+	1748	$0^+;1$	(1871,1933)		1852
1959	2^+	1906	$2^+;(1)$	(1871,1933)		1853
2047	2^-	1747/1983 [d]	$2^-;1$	(1671,1703)	$(1^-,2^-)$	1683
2070	3^-	1761	$3^-;1$			1452
2104	1^-	1774/1947 [d]	$1^-;1$	(1671,1703)	$(1^-,2^-)$	1617
2260	3^+	2120	3;1	(1871,1933)		1980
2290	1^+	2207	1;1	2283	1^+	2124
2291	3^-	1945/2011 [d]	$3^-;1$	(1797)	$(3^-,4^-)$	1665
2397	4^-	2391	$4^-;1$	(2370)	$(3^-,4^-)$	2385
2419	2^-	2382	$(2,3)^-;1$			2345

[a] From Ref. [6]; the ^{40}Ca excitation energies are given relative to the energy of the first $T = 1$ state at $E_x = 7658$ keV.

[b] Proposed analog state assignments of the present work (Sec. III).

[c] Estimated ^{40}Sc excitation energies by using the IMME (see Sec. III).

[d] Configuration-mixed doublets.

In the present work, we have measured excitation energies of low-lying ^{40}Sc levels. The energies of the first two states above the proton threshold have been measured to a precision of $\leqslant 2.0$ keV, and are in agreement with previously reported values [5]. These two states correspond to low-energy resonances at $E_R^{cm} = 233$ and 354 keV and dominate the ^{39}Ca$+p$ reaction rates below $T = 1.0$ GK [3]. For this temperature region, the present results thus confirm the ^{39}Ca$+p$ reaction rates recommended recently [3].

The previously reported [5] doublet at $E_x \approx 1.67$ MeV has been resolved in the present work, resulting in ^{39}Ca$+p$ resonance energies of $E_R^{cm} = 1132$ and 1164 keV. We have also observed two more, previously undetected ^{40}Sc states, corresponding to resonances at $E_R^{cm} = 1332$ and 1386 keV. Resonances above $E_R^{cm} = 1$ MeV dominate the reaction rates at $T = 1.0$–2.0 GK [3]. The individual reaction rate contributions will depend on assumptions for their J^π values. In the present work we have obtained analog assignments for the corresponding levels by using the IMME. Our results are consistent with previous assumptions [3] and, therefore, support the recommended reaction rates and estimated uncertainties of Ref. [3] at $T = 1.0$–2.0 GK.

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