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Published in:
Nuclear Physics A

DOI:
10.1016/S0375-9474(03)00899-6

Publication date:
2003

ELSEVIER

Nuclear Physics A718 (2003) 605c–607c

NUCLEAR PHYSICS A

www.elsevier.com/locate/npe

Alpha-decay branching ratios of near-threshold states in ^{19}Ne and the astrophysical rate of $^{15}O(\alpha,\gamma)^{19}Ne$

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The $^{15}O(\alpha,\gamma)^{19}Ne$ reaction is one of two routes for breakout from the hot CNO cycles into the *rp* process in accreting neutron stars. Its astrophysical rate depends critically on the decay properties of excited states in ^{19}Ne lying just above the $^{15}O + \alpha$ threshold. We have measured the α-decay branching ratios for these states using the $p(^{21}Ne,t)^{19}Ne$ reaction at 43 MeV/u.

1. Introduction

Novae are thermonuclear runaways initiated by the accretion of hydrogen- and helium-rich material from stellar companions onto the surfaces of white dwarfs in binary systems. Energy production and nucleosynthesis in the hottest novae are determined principally by the CNO, NeNa, and MgAl cycles [1]. Under high temperature and density conditions, e.g. in accreting neutron stars, breakout from the hot CNO cycles into the *rp* process occurs [2], dramatically increasing the luminosity of outbursts and synthesizing nuclei up to masses of 100 u [3]. Several reactions have been suggested as pathways for this breakout [4], but only two are currently thought to be possibilities: $^{15}O(\alpha,\gamma)^{19}Ne$ and $^{18}Ne(\alpha,p)^{21}Na$. In astrophysical environments the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction proceeds predominantly through resonances lying just above the $^{15}O + \alpha$ threshold at 3.529 MeV in ^{19}Ne, as the direct capture component is very small by comparison [5]. The reaction rate in novae is determined by the α-width Γ_α of the 4.033 MeV $3/2^+$ state, owing both to its close proximity to the $^{15}O + \alpha$ threshold and its low centrifugal barrier to α-capture.

A previous attempt to determine Γ_α for this state was based upon measurements of α-transfer reactions to the analog state in the mirror nucleus ^{19}F [6]. Such determinations, however, are subject to large uncertainties. Direct measurements of the low energy cross section, which require high-intensity radioactive ^{15}O beams, are planned. At ^{19}Ne excitation energies relevant to novae and accreting neutron stars, only the α- and γ-decay channels are open, as the proton and neutron separation energies are 6.4 and 11.6 MeV respectively. Hence, by populating these states and observing the subsequent α- and γ-decays, one can deduce the branching ratio $B_\alpha \equiv \Gamma_\alpha/\Gamma$. If Γ_γ is also known, one

0375-9474/03/$ – see front matter
doi:10.1016/S0375-9474(03)00899-6

can then calculate Γ_α and thereby the contribution of each state to the resonant rate of $^{15}O(\alpha,\gamma)^{19}Ne$. A pioneering effort of this kind was made by detecting α particles from the decay of ^{19}Ne states populated via the $^{19}F(^3He,t)^{19}Ne$ reaction [7], but the sensitivity of the experiment was insufficient to measure B_α for the critical 4.033 MeV state, which was expected to be of order 10^{-4}. Despite vigorous efforts worldwide, up to now no experiment has reached this level.

In an experiment at the Kernfysisch Versneller Instituut, we have obtained branching ratio data of high sensitivity by applying a novel method introduced at Argonne National Laboratory using a different reaction [8]. Populating the important states via the $^{21}Ne(p,t)^{19}Ne$ reaction in inverse kinematics with a ^{21}Ne beam energy of 43 MeV/u, we detected either ^{19}Ne recoils or their ^{15}O α-decay products in coincidence with tritons in the Big-Bite Spectrometer (BBS). The large momentum acceptance of the BBS ($\Delta p/p = 19\%$) allowed detection of either ^{19}Ne recoils or ^{15}O decay products along with tritons emitted backward in the center of mass system. Positioning the BBS at 0° maximized the yield to the 4.033 MeV $3/2^+$ state in ^{19}Ne. This state, whose dominant shell-model configuration is $(sd)^5(1p)^{-2}$, was selectively populated by an $\ell = 0$, two-neutron transfer from the $3/2^+$ ground state of ^{21}Ne. Position measurements in two vertical drift chambers (VDCs) allowed reconstruction of the triton trajectories. Excitation energies of the ^{19}Ne residues were determined from the kinetic energies and scattering angles of the triton ejectiles. The γ-decays of states in ^{19}Ne were observed as ^{19}Ne-triton coincidences in the BBS, whereas α-decays were identified from ^{15}O-triton coincidences.

Recoils and decay products were detected and stopped just in front of the VDCs by fast-plastic/slow-plastic phoswich detectors that provided energy loss and total energy information. A separate array of phoswich detectors was used to identify tritons after they passed through the VDCs. Timing relative to the cyclotron radio frequency signal was also employed for unambiguous particle identification. An Al plate prevented many of the heavy ions copiously produced by projectile fragmentation reactions of the ^{21}Ne beam in the $(CH_2)_n$ target from reaching the VDCs. The spatial extent of the heavy-ion phoswich array was sufficient to guarantee 100% geometric efficiency for detection of ^{19}Ne recoils and ^{15}O decay products for ^{19}Ne excitation energies ≤ 5.5 MeV. This resulted largely from the forward focusing of the ^{19}Ne recoils, which emerged at angles $\leq 0.36°$ for tritons with scattering angles $\leq 4°$. The low decay energies of the states studied limited the angular and energy spreads of the ^{15}O decay products. High geometric efficiency, combined with the excellent background rejection afforded by detecting ^{15}O nuclei instead of α particles, provided sensitivity to very small α-decay branches.

2. Results

The ^{19}Ne excitation energy spectrum obtained from ^{19}Ne-triton coincidences, representing γ-decays of states in ^{19}Ne, is shown in Fig. 1 (a). Its most prominent peak is due to the 4.033 MeV $3/2^+$ state. The 4.379 MeV $7/2^+$ state is the second most strongly populated. Contributions from other known states are indicated. The experimental resolution of 90 keV FWHM is insufficient to resolve the 4.140 and 4.197 MeV states from one another; the 4.549 and 4.600 MeV states are also unresolved. However, the astrophysically important 4.033 and 4.379 MeV states are well separated from the others. The curve shown in

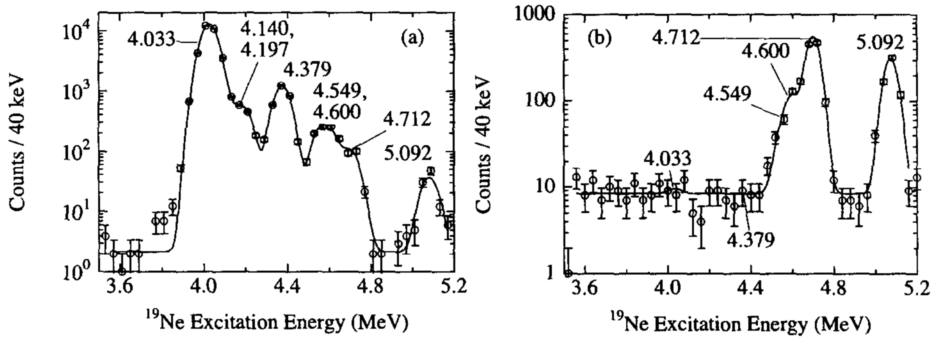

Figure 1. a) ^{19}Ne-triton coincidences (γ-decays of states in ^{19}Ne). The curve is the sum of a constant background and 8 Gaussians centered at the energies of known states in ^{19}Ne, the widths of which were determined by the experimental resolution of 90 keV FWHM. b) ^{15}O-triton coincidences (α-decays of states in ^{19}Ne). The curve is the sum of a constant background and 6 Gaussians corresponding to known states in ^{19}Ne, the widths of which were fixed by the experimental resolution. The ^{15}O + α threshold lies at 3.529 MeV.

Fig. 1 (a) is the sum of a constant background and 8 Gaussians centered at the known energies of the states, with standard deviations fixed by the experimental resolution of 90 keV FWHM.

Fig. 1 (b) shows the ^{19}Ne excitation energy spectrum obtained from ^{15}O-triton coincidences, corresponding to α-decays of states in ^{19}Ne. The observed states are labeled by their energies; the 4.549 and 4.600 MeV states cannot be resolved. A fit consisting of Gaussians plus a constant background is shown as well. The states below 4.549 MeV decay overwhelmingly by γ-emission, while the higher-lying states observed here decay preferentially by α-emission, simply because the larger available decay energy enhances the barrier penetrability. The background represents a larger fraction of the total events in the ^{15}O-triton coincidence spectrum than in the ^{19}Ne-triton coincidence spectrum, though it is still very small. This background is well reproduced by a constant, the value of which is determined to a precision of 7% (1σ).

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