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Strong resonances in elastic scattering of radioactive ^{21}Na on protons

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In a first experiment with accelerated beams at TRIUMF-ISAC, the scattering of radioactive ^{21}Na ($T_{1/2}=22.49$ s) on protons has been investigated. ^{21}Na beams of typically 5×10^{7} particles/s were employed while center-of-mass energies from 0.45 to 1.4 MeV were scanned and spectra with high statistics were collected. The experiment was carried out using large area silicon detectors at the TUDA facility. Three strong resonances corresponding to states in ^{22}Mg have been identified at energies of 830 keV, 1115 keV, and 1311 keV, respectively. Using these data, aspects of the $T=1$, $A=22$ mirror system and the s-wave component of the astrophysically important ^{21}Na$(p,\gamma)^{22}$Mg reaction are discussed.

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With the advent of radioactive beams facilities extensive investigations of reactions between radioactive and stable nuclei have become possible. At TRIUMF, the charged particle scattering facility TUDA has been installed at ISAC to study a range of such reactions with radioactive beams. Here, we report results of the first experiment on the elastic scattering reaction ^{21}Na$(p,p)^{21}$Na. This reaction is of particular interest, because it is related to one of great astrophysical importance, i.e., the ^{21}Na$(p,\gamma)^{22}$Mg reaction in the rp process [1]. An elastic scattering experiment employing the same nuclei as in radiative capture allows a better understanding of mirror nuclei and their respective Thomas-Ehrmann [2] shifts as well as providing an efficient way to survey possible high energy resonances of low orbital angular momentum in radiative capture.

The states of ^{22}Mg above the proton threshold ($Q=5.502$ MeV) have been extensively explored in transfer reactions [1,3], and conclusions about the stellar ^{21}Na$(p,\gamma)^{22}$Mg reaction rate have been drawn from these measurements. Some assignments within the $A=22$, $T=1$ mirror system have been proposed [1,3] based on previous identification of ^{22}Ne states [4]. However, such identifications were not always possible, as not all previous measurements agree in the number and energies of states in the region of interest. In particular, there is no clear identification of states in the ^{21}Na$+p$ system available above an energy of more than 0.8 MeV.[1] In the experiment reported here, ^{21}Na scattering from protons has been investigated from 0.45 to 1.4 MeV. Some states of the $T=1$, $A=22$ system have been identified and mirror possibilities are discussed.

[1]Energies, if not otherwise specified, are in the center-of-mass system of ^{21}Na$+p$.

In Ref. [1], the nonresonant direct capture process in the ^{21}Na$(p,\gamma)^{22}$Mg reaction has been roughly estimated based on shell model calculations. Here we also consider the possibility that broad s-wave resonances might significantly extend the effects of radiative capture to low energies. In this Rapid Communication, we report the likely identification of such s-wave resonances in ^{21}Na$+p$ scattering.

With a ground state spin of $J^{\pi}=3/2^{+}$ for ^{21}Na the channel spin of the ^{21}Na$+p$ system is $s=1$, 2 and consequently, states of $J^{\pi}=1^{+}$ or 2^{+} can be populated by a proton of orbital angular momentum 0. In the analog energy region of ^{22}Ne corresponding to energies of about 1.4 MeV in the ^{21}Na$+p$ scattering system, there are indeed two states of this spin/parity combination known ($E_x=6819$, 6854 keV, respectively), while a lower state ($E_x=6636$ keV) has a $J^{\pi}=(2,3)^{+}$ assignment [4]. All known 2^{+} and 1^{+} states probably have large reduced proton widths in analogy to the single particle neutron transfer reaction ^{21}Ne$(d,p)^{22}$Ne [5] and known ^{22}Na, $T=1$ states. Note that unnatural parity states of $J^{\pi}=1^{+}$ are not likely to be observed in the transfer reactions of Refs. [1,3]. In addition, there are five other candidate states observed in ^{22}Ne in the analog proton scattering region from 0.7 to 1.4 MeV. Figure 1 shows the level scheme and some analog assignments suggested here for the $A=22$, $T=1$ system. In addition for the center-of-mass energy region from 0.45 to 0.7 MeV four states with known J^{π} combinations are known [1], but it is probable that they all have small widths.

The first excited state of ^{21}Na is of $J^{\pi}=5/2^{+}$ and of only 0.332 MeV in excitation energy. Therefore the inelastic ^{21}Na$(p,p'\gamma(0.33))^{21}$Na reaction is also likely to take place for resonant states of higher energies. The thermal population of the $E_x=0.33$ MeV state and subsequent radiative capture can play a role at stellar temperatures exceeding 1 GK. The

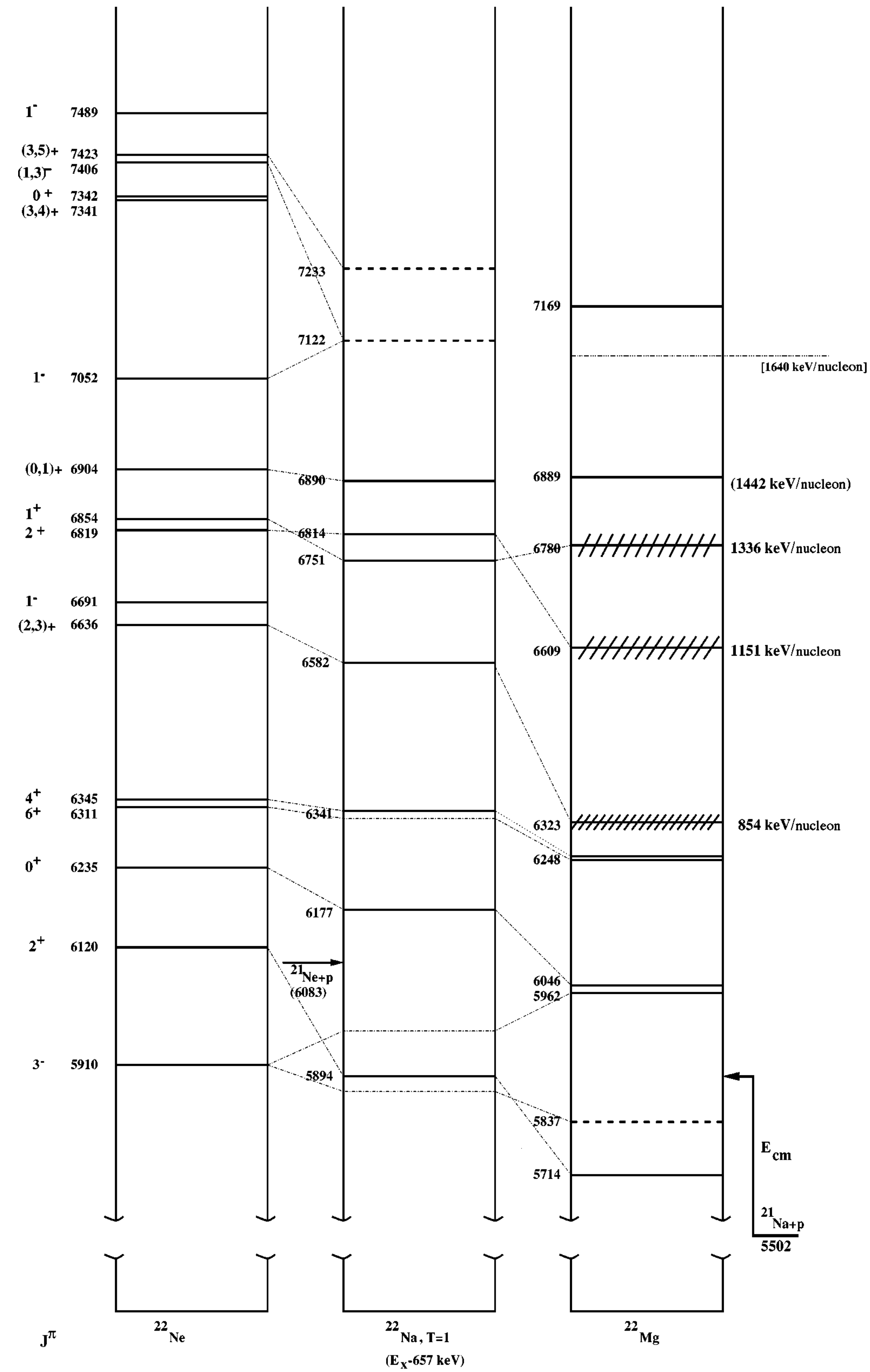

FIG. 1. Analog states in the $A=22$, $T=1$ system and suggested analog assignments in ^{22}Mg. Given are excitation energies E_x in keV in the respective nuclei, except for ^{22}Na, where state energies are lowered by 657 keV, corresponding to the lowest $T=1$ state. Also drawn in are the energies in the laboratory frame of resonances in ^{21}Na$+p$ as suggested in Refs. [1,3]. 1.64 MeV/nucleon is the maximum heavy ion energy achievable at ISAC.

properties of this state, i.e., reduced width amplitudes for the decay into this state, are also important in the understanding of Thomas-Ehrmann shifts.

At TRIUMF-ISAC [6] an elastic scattering experiment of radioactive ^{21}Na ($T_{1/2}$=22.49 s) ions on a hydrogen [$(CH_2)_n$] target has been performed for center-of-mass energies of 0.45–1.4 MeV using the TUDA facility. The ^{21}Na was produced from SiC at the ISAC production target with proton beams of typically 3 μA. While the total ^{21}Na current achievable at the proton target was as high as 5×10^8 ^{21}Na s^{-1} for proton currents of 15 μA, it actually had to be reduced by about an order of magnitude to avoid high dead times in the data acquisition system as well as to prevent rapid target degradation. The singly charged ^{21}Na beam was injected into the ISAC RFQ-DTL accelerator [7] and stripped to the 5^+ charge state; a transmission of the beam of typically 80% was achieved for a collimator of 2 mm diameter at the target position. $(CH_2)_n$ targets of 50 and 250 μg/cm^2 were used. With the thick targets a complete coverage of the excitation function was obtained, while thin targets were used to investigate selected energy regions in more detail, typically those of known or expected resonances.

The TUDA facility [8] was configured using two LEDA arrays [9] employing all together 192 channels, and covering angles from 4.5° to 12° and 14° to 33° in the laboratory, respectively. This corresponds to an angular coverage in the center-of-mass system (^{21}Na+p) of 171° to 157° and 152° to 114°. One detector (four sectors), was positioned 20 cm downstream of the target, while the other detector (eight sectors) was positioned 62.8 cm downstream. Eleven sectors were protected by Mylar foil against scattered ^{12}C and ^{21}Na particles while one of the close sectors was left unprotected to normalize against scattering of ^{21}Na on C. For each energy, a short run with a C/Au foil was performed for normalization purposes assuming that ^{21}Na scattering on gold has a pure Coulomb cross section. For gain matching purposes α-source calibration runs were performed with the mylar foils removed. The data acquisition system used spectroscopic amplifiers and peak sensing ADCs for optimum energy resolution. The data were recorded by a VME-CAMAC based system event by event. From the timing clock of the linear accelerator system a signal of 86 ns interval is received and used in the stop of TDC channels. This frequency corresponds to the ^{21}Na beam bunch separation received from the DTL [7]. Typically bunch widths were less than 1 ns (FWHM), the time resolution achieved in the silicon detectors. For all data resulting from beam scattered at the target, a clear correlation between timing and energy is observed, while signals from the β decay of deposited beam particles ("β tail") are uncorrelated.

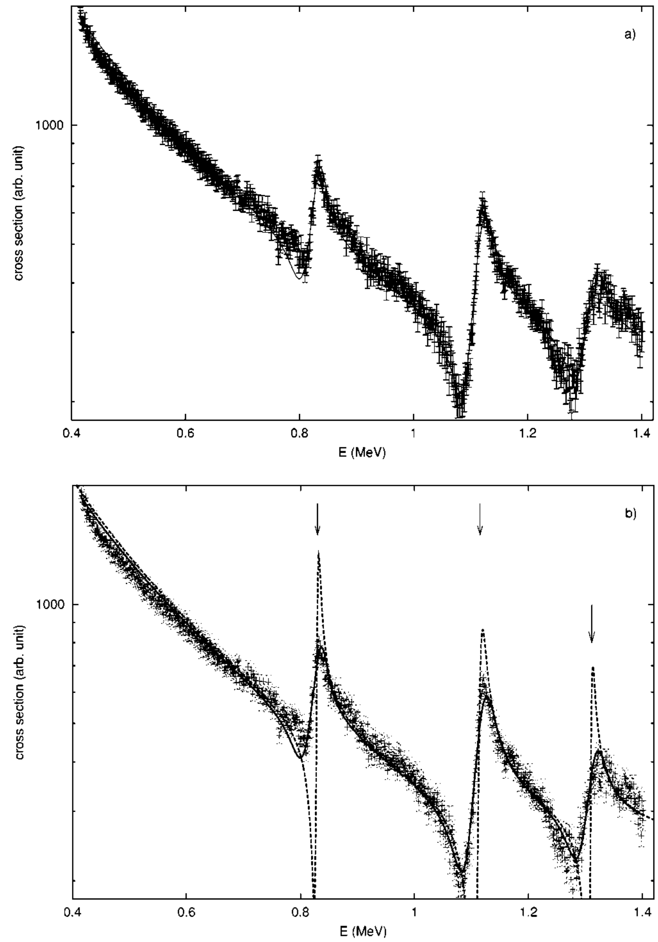

FIG. 2. Excitation function from thick target data derived by summing and concatenating the recoil proton spectra from all detector elements at 4.7° (lab). The cross section is in arbitrary units. (a) shows the data and the convoluted fit (straight line). (b) shows the data, as well as highlighted the convoluted and unconvoluted (dashed line) fits. Positions of states from the fit are marked by arrows in (b), see Table I.

TABLE I. Properties of strong resonances of ^{21}Na+p between E=0.45 and 1.4 MeV from the s-wave R-matrix fit (see text). Energies and widths have been derived by applying boundary shifts [13]. Widths quoted are only for an s-wave fit to the elastic channel. Energy errors in the present data reflect uncertainties in the fit only. A systematic beam energy uncertainty of ±5 keV/nucleon has been added linearly to the energy errors from the fit.

E_{lab} (keV/nucleon)	E_R (keV)	E_x (keV)	E_x (keV) [1]	Γ (keV)	θ_s [a]
863±10	830±10	6332±10	6322.6±6	7^{+4}_{-2}	0.31
1159±10	1115±10	6617±10	6608.5±5.6	14±5	0.21
1363±10	1311±10	6813±10	6780.4±9.6	8±5	0.11

[a] $\theta_s=\sqrt{\frac{2\mu}{3}\frac{a}{\hbar}}\gamma_s$, see Ref. [14].

Recoil protons emanating from the $(CH_2)_n$ target were observed as the primary signal. Their energy distribution in the recoil peak directly reflects the excitation function corresponding to the beam energy loss in the target. Several strips of the LEDA detector at the same angle were added up using gain matching from the α calibration. Runs at different energies overlapping in the excitation function range were then concatenated to yield the composite excitation function. Figure 2 shows the composite excitation function derived from several thick target measurements using eight detector elements at 4.7° (lab). The energy calibration for this excitation function was undertaken by using the position of the high energy side of the proton distributions (front energy) of the respective targets since this proton energy corresponds to the energy of an elastic beam energy event (convoluted only by the detector resolution and beam energy spread). No second order corrections for nonlinearities in beam and proton straggling were employed in this preliminary analysis. The energy calibration of the accelerator was derived from known resonances in $^{15}N(p,\alpha\gamma)^{12}C$ [10]. The combined systematic error in energy is estimated to be ± 5 keV/nucleon. A more sophisticated analysis of the data involving the use of stopping power information, rebinning of the data accordingly, and deriving proper convolutions for theoretical fits is in progress [11].

A preliminary *R*-matrix fit was investigated for these data ($a=5.3$ fm). A simplified single channel approach was employed using only *s*-wave states. Besides apparent states, a background state fixed to 10 MeV [12] was included. The fit to the data is shown in Fig. 2(b), and corresponds to $\chi^2_\nu=2.0$. Some problems arise as the convolution did not take properties of each individual target into account, but rather adopted average parameters for the targets. In particular for the seminarrow peaks at 0.83 and 1.12 MeV, the derived width of the states depends partially on the parameters of the convolution. Also investigated were more involved fits which included *p* and *d* waves as well as a treatment of the inelastic channel. While improving the fit quality considerably, they confirm the basic assumptions of a simple *s*-wave fit. In all fits, some uncertainty arises from the strength of the inelastic channel not being fixed. However, possible uncertainties have been included in the errors of quoted state energies and widths.

The properties of the three dominant states found between $E=0.45$ and 1.4 MeV are listed in Table I. The argument for these states having a leading angular momentum of $l=0$ in proton capture is their shape in the excitation function [11], as well as the large magnitude of the widths which excludes high angular momenta. The two lower energy states have been observed in the transfer reaction of Ref. [1], however, the lowest one has not been observed in Ref. [3]. The reaction meachanism of Ref. [3] is sensitive exclusively to natural parity states suggesting a choice of $J^\pi=2^+$ for the upper state, and $J^\pi=1^+$ or 3^+ for the lower one, if the reaction mechanism of Ref. [1] allows for a weak population of unnatural parity states. It should be noted, however, that the population of the $E_x=6.322$ MeV state is apparently not supressed in Ref. [1]. A *d*-wave state (3^+), as suggested from the shell model calculations in [1] is not possible from elastic width considerations; however, the shell model calculation of Ref. [1] truncates at this state. The broad state at 1.31 MeV may correspond to a state in Refs. [1,3]. It has been fitted here by an *s* wave, because with a *p* wave the low energy minimum in the excitation function cannot be reproduced. Because all states have considerable reduced width amplitudes, a large Thomas-Ehrmann shift for these states is expected. The observation of an inelastic channel decay of these resonances would shed some more light on the spin assignment. Such data are under evaluation.

At present, the γ strengths, the spin/parities J^π, the individual decay schemes of these states, and their respective interference signs for identical spin/parity are unknown. Employing γ strengths of $\Gamma_\gamma=0.3$ eV for all resonances[2] in the fit and assuming dominant ground state decay, leads to an order of magnitude estimate for the likely influence of these resonances on the $^{21}Na(p,\gamma)^{22}Mg$ reaction at astrophysically relevant energies. The result is that the low energy tails of these resonances are of comparable strengths to nonresonant direct capture as estimated in Ref. [1], Eq. (7). A more comprehensive calculation of the $^{21}Na(p,\gamma)^{22}Mg$ reaction rate of these resonances in the low temperature region would have to include also knowledge of exterior contributions to the resonance wave functions [14]. Besides their low temperature contributions, it is probable that the strong resonances found here are the main contributors to the stellar reaction rate of $^{21}Na(p,\gamma)^{22}Mg$ for temperatures of 1 GK and higher, both starting from the ground as well as the first excited state of ^{21}Na. Some of the resonance γ-decay properties can and will be determined at the DRAGON facility at TRIUMF.

Three prominent states of ^{22}Mg have been identified in the elastic scattering of radioactive ^{21}Na ions on protons. These are likely to be of an *s*-wave nature corresponding to known analog states in ^{22}Ne and ^{22}Na, where there are strong $l=0$, $T=1$ proton resonances in $^{21}Ne+p$ at $E_p=524$ keV (2^+), 702 keV (1^+), and 768 keV (2^+), respectively [4]. However, particularly the position and presence of the unnatural parity 1^+ state, which has both a large single particle as well as γ-decay strength, has yet to be confirmed by additional experiments. These states will dominate high temperature burning of ^{21}Na via $^{21}Na(p,\gamma)^{22}Mg$ as well as probably influencing the low temperature stellar rate of this reaction. However, to determine the γ strengths and other properties of these states, additional radiative capture measurements are needed. Further analysis [11] of the elastic data set will likely reveal more narrow states of ^{22}Mg in the energy range covered and will pose some spin/parity restrictions for all states discovered.

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[2]Note that the γ strength of the 1^+, $E_x=6854$ keV state in ^{22}Ne is known to be $\Gamma_\gamma=1.7$ eV [4].

merous tunes and energy changes of the ISAC RFQ-DTL accelerator. We would also like to express our thanks to Pierre Leleux and Paul Demaret (UCL, Louvain la Neuve, Belgium) for supplying the $(CH_2)_n$ targets used in this measurement. We wish to thank Peter Jackson (TRIUMF) for fruitful discussions and comments on this manuscript. This work was supported by the EPSRC (U.K.) and NSERC (Canada).

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