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Yield measurements for resonances above the multi-α threshold in ^{20}Ne

Tz. Kokalova,* M. Freer, N. Curtis, N.I. Ashwood, M. Barr, J.D. Malcolm, C. Wheldon, and V.A. Ziman
School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK.

S. Almaraz-Calderon, A. Aprahamian, B. Bucher, M. Couder, X. Fang, F. Jung, W. Lu, A. Roberts, and W.P. Tan
Institute for Structure and Nuclear Astrophysics, Department of Physics,
University of Notre Dame, Notre Dame, Indiana 46556, USA

P. Copp and S.R. Lesher
Department of Physics, University of Wisconsin-La Crosse, La Crosse, Wisconsin 54601, USA
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The reaction ^{16}O(α,^{20}Ne), has been studied with beam energies from 23.0-29.0 MeV in 100 keV steps. Resonant states in ^{20}Ne have been populated which are above the multi-α decay threshold and that decay via ^{8}Be + ^{8}Be + α and ^{8}Be + ^{12}C(0_2^+). An array of four Si-strip detectors was used for the detection of 4 of the 5 emitted α particles enabling the full reconstruction of the kinematics. The normalized yields have been obtained, with indications of significant strength above 24.5 MeV arising from several possible resonances.

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27.30.+t (20≤A≤38)

The possibility that clustered nuclear states built on α-particle cores exist across a wide range of α-conjugate light nuclei [1] is intriguing. The most renowned example being the Hoyle state in ^{12}C [2]. The Hoyle state is of paramount importance to the rate of nucleosynthesis as it provides the gateway for the formation of carbon through the triple α-process. Analogous states in heavier α-conjugate nuclei are predicted close to the multi-α-particle decay thresholds. Whilst a candidate state has been identified in ^{16}O at 15.1 MeV [3–5], 0.7 MeV above the 4α threshold, no corresponding states are known in ^{20}Ne ($S_{5\alpha}$=19.167 MeV). Furthermore, since the Hoyle state is considered (theoretically) as the best candidate for a nuclear condensate [6], interest in analog states in heavier systems has increased rapidly in recent years. The latter are of great importance for testing the existence of this predicted new type of nuclear matter. If nuclear condensation exists, these states will most likely disintegrate into substructures of the same type, *i.e* ^{12}C*(0_2^+) and ^{8}Be. The present study is aimed at probing the energy regime in ^{20}Ne between 20 MeV and 30 MeV. Specifically, the normalized yields for the observed resonances have been measured.

An α-particle beam with an incident energy in the range from 29.0 to 23.0 MeV was provided by the 10 MV FN-tandem accelerator at the University of Notre Dame, USA. The initial beam energy of 29 MeV was chosen on the basis of stability of the beam and cross-section. Starting with 29 MeV, where the ^{20}Ne peak in the Q-value spectra was clearly visible, the beam energy was changed in steps of 100 keV in order to obtain a precise determination of the variation of the cross-section in this energy range. At a beam energy of 23 MeV the statistics were already very low making it difficult to extract any reliable information. The beam was incident on a 2.5 μm mylar foil ($C_{10}H_8O_4$) target. The α-particle ejectiles and break-up products from the recoiling ^{20}Ne* nuclei were recorded using the Birmingham position-sensitive silicon-strip detector array. This large angular-acceptance array consists of four silicon-strip detectors. Each detector has an active area of 50×50 mm^2 comprised of 16 vertical (front) and 16 horizontal (back) strips. The detectors were arranged in such a configuration, that two of the detectors were on the lefthand side of the beam axis: θ_x =−17.0° to −68.0° and θ_y =−14.0° to 14.0° and two on the righthand side of the beam covering θ_x = 11.0° to 65.0° and θ_y =−14.0° to 14.0°, where θ_x and θ_y correspond to the in-plane and out-of-plane angles respectively.

The master trigger condition required at least three events to be registered in the silicon array within a 0.5 μs window. A beam integrator at zero degrees recorded the beam-on-target intensity. Note that the energy resolution of the detectors is ≈100 keV.

Before the break-up events were reconstructed several corrections and calibrations to the silicon-strip detector data were applied. Energy calibrations and gain-matching were carried out using ^{148}Gd (E_α=3.183 MeV) and ^{241}Am (E_α=5.479 MeV) α-particle sources and elastic scattering of 17.0 MeV ^{4}He ions on a 500 μg cm^{-2} Pb target.

The events consisting of four detected α-particles, were reconstructed on an event-by-event basis to determine the energy and angle of the 'missing' fifth α-particle and

*Corresponding author: t.kokalova@bham.ac.uk

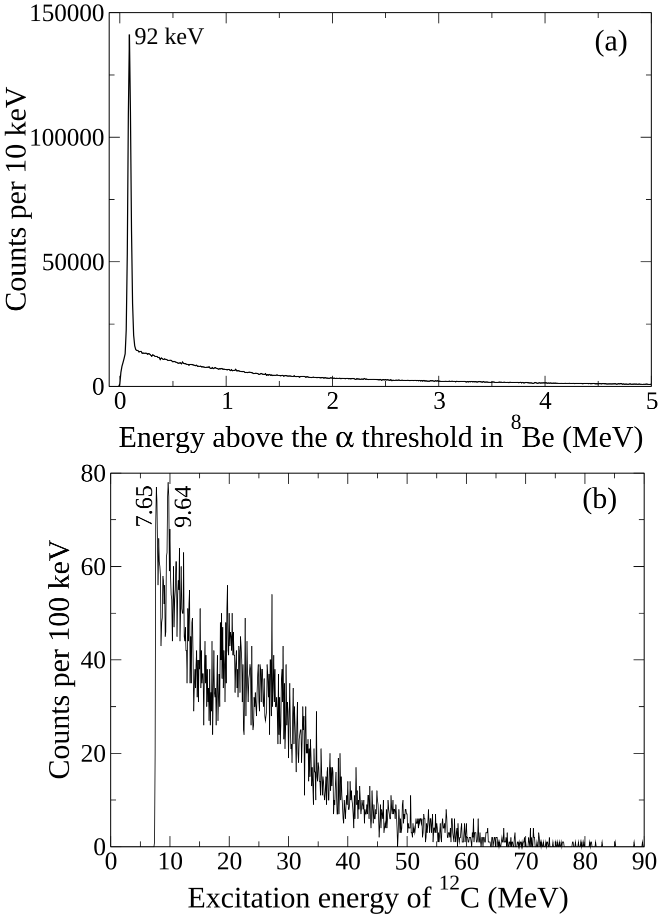

FIG. 1: (a): Reconstructed energy spectra for all two-alpha-particle events for a beam energy of 28.0 MeV. The peak at 92 keV corresponds to the ground state in ^{8}Be and was used for the selection of events for further analysis. (b): Reconstructed energy spectra for all four-alpha events for a beam energy of 28.0 MeV, where two particles are from ^{8}Be in the ground state and the other alpha particle is any of the remaining three alpha particles. The peak at 7.65 MeV corresponds to the Hoyle state, ^{12}C(0_2^+), and was used for the selection of events for further analysis. The 9.64 MeV, 3^-, state in ^{12}C can also be seen.

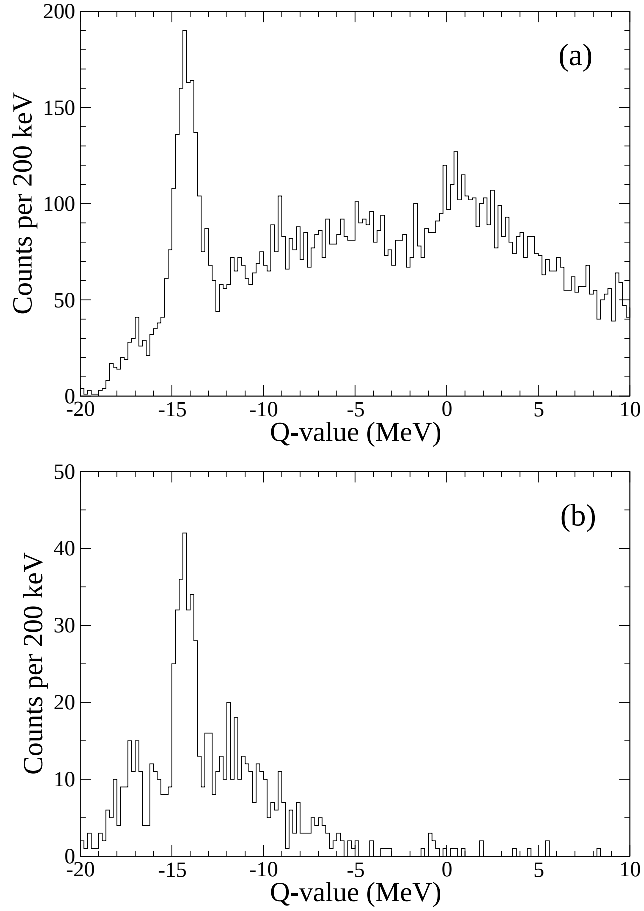

FIG. 2: Q-value spectra assuming the detection of four α particles and reconstructing the undetected fifth α particle. The data shown are for a beam energy of 28.0 MeV. (a) Spectrum gated by the detection of two ^{8}Be nuclei in the ground state. (b) Spectrum gated by the detection of one ^{8}Be nucleus in the ground state and one ^{12}C$^*(0_2^+)$ nucleus with excitation energy, E_x = 7.65 MeV.

ultimately obtain the Q-value for the ^{16}O(α, 5α) reaction. Note that there is no particle identification form the silicon array and the kinematic reconstruction is done assuming all of the events in the detectors are α particles. In reality, there are protons, deuterons and tritons, as well. For those events the kinematic reconstruction doesn't work correctly resulting in bumps which can be seen in Fig. 1. The x, y and z components of the momentum were calculated for the fifth particle from the components of the four detected particles ($p_{i\alpha}$, where $i = x, y, z$) and the beam. The square of each component was then summed to yield the square of the total momentum, $p^2_{\alpha 5}(tot.)$, and the energy, $E_{\alpha 5}$,

$$
\begin{aligned}
p^2_{\alpha 5}(tot.) &= \sum_{i=x,y,z} \left(p_{i\,beam} - \sum_{n=1}^{4} (p_{i\alpha n}) \right)^2 \quad \text{and} \\
E_{\alpha 5} &= \frac{p^2_{\alpha 5}(tot.)}{2m_\alpha}.
\end{aligned} \tag{1}
$$

In order to reduce the background a condition was set on the energy of the reconstructed fifth alpha particle. This result is subsequently used to calculate the Q-value, given by the difference between the beam energy and the sum of all five α-particle energies:

$$
Q = \left(\sum_{n=1}^{5} E_{\alpha n} \right) - E_{beam}. \tag{2}
$$

This approach led to the highest signal-to-noise ratio for the ^{20}Ne events. Once the Q-value spectrum was obtained the events were separated into those decaying via ^{8}Be+^{8}Be+α and (a further subset of these data) those de-exciting through the ^{8}Be+^{12}C$^*(0_2^+)$ channel. The ^{8}Be+^{8}Be+α channel is identified by searching for four α-particles, two pairs of which have been reconstructed to yield the ^{8}Be ground-state at an energy of 92 keV above the α-particle threshold (see Fig. 1(top)). A further condition on these pre-selected events tested whether the remaining unpaired α-particle could be combined with either of the ^{8}Be nuclei to form the ^{12}C$^*(0_2^+)$ state (see Fig. 1(bottom)). The example Q-value spectra shown in Fig. 2 are for events obtained with a beam energy of 28 MeV and the Q-value peak, is present in both panels: at -14.1 and -14.2 MeV for the ^{8}Be+^{8}Be+α and ^{8}Be+^{12}C$^*(0_2^+)$ channels respectively, in very good agreement with the calculated Q-value of -14.4 MeV for the reaction ^{4}He + ^{16}O $\rightarrow$ ^{20}Ne* $\rightarrow 5\alpha$.

After reconstructing the Q-value spectrum the efficiency of the detector set-up was calculated using the "Resolution8" Monte-Carlo simulation software. This code was tailored to the detector configuration and included energy-loss and energy- and angular-straggling through the target, yielding the absolute geometrical efficiency of the silicon array. Further details of the "Resolution8" Monte-Carlo simulation code can be found in Refs. [7, 8]. The efficiency curves can be seen in Fig. 3 as red dashed lines.

Due to the poor statistics and the fact that the absolute thickness of the mylar target is unknown it has not been possible to calculate absolute cross-sections. Nevertheless, excitation spectra for ^{20}Ne for the different decay channels have been constructed (Fig. 3) representing normalized yield and the presence of some structure is clearly visible. The efficiency of the detector array was also calculated (as mentioned above), assuming the same conditions as during the experiment, which if taken into account together with the yield curves gives a better presentation of the strengths of the peaks in both decay channels ^{20}Ne$^*\rightarrow^8$Be+^{8}Be+α and ^{20}Ne$^*\rightarrow^8$Be+^{12}C$^*(0_2^+)$, respectively.

Firstly, it is worth noting that the observed spectra between excitation energies of 23.1 and 24.0 MeV in ^{20}Ne show no significant structure with the first yield increases occurring for excitation energies above 24.5 MeV, corresponding to incident α-particle bombarding energies in excess of 24.7 MeV. Also of note is that despite the lower threshold for the ^{12}C* channel ($S_{8\mathrm{Be}8\mathrm{Be}\alpha}$=19.35 MeV and $S_{8\mathrm{Be}12\mathrm{C}^*}$=16.42 MeV) this mode is significantly suppressed compared to the ^{8}Be+^{8}Be+α route by a factor of $\sim$2.

The first indication of significant strength in the two break-up channels is at 24.5 MeV. Beyond excitation energies of 25 MeV, further evidence of resonances in the yield data are observed. In general, the structures seen have widths of the order of 100 keV, but, additionally, broader structures are also seen, most notably at $E_x\approx$25.6 MeV and 27.3 MeV in the ^{8}Be+^{8}Be+α channel.

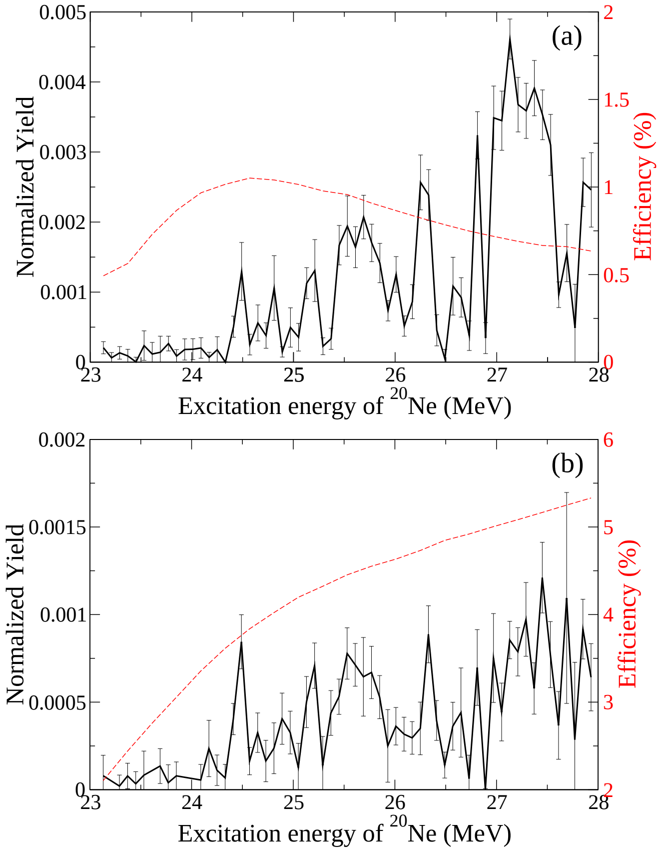

FIG. 3: (color online) Arbitrary scale for the events decaying via (a) the ^{8}Be+^{8}Be+α channel and (b) via the ^{8}Be+^{12}C(0_2^+) channel. Note the different vertical scales. The (red) dashed line shows the detector efficiency simulated using the same conditions as for the experimental data.

It is clear that for the 24 to 26 MeV region there is a direct correspondence between the two competing decay channels with structures at the same energies in each. Beyond 27 MeV the ^{12}C+^{8}Be channel contributes a constant strength (in line with the approximately constant efficiency (dashed line in Fig. 3)), as observed here, despite a significant increase in strength in the ^{8}Be+^{8}Be+α channel.

In Ref. [9], several states in this energy regime are known, the majority associated with high-spins, $I = 8-10\hbar$.

The structures observed in the current work invite further study and represent candidates for a possible Hoyle-state analog resonance. Of particular importance is the establishment of the spins, since to-date the previously reported resonances in this excitation region (Table I) are of high-spin (where known) and can therefore, be ruled out as Hoyle-like $I^\pi = 0^+$ states. In order to improve on these measurements both excitation function measurements with a smaller step size and a high resolution (spectrometer) measurement need to be performed.

In summary, the excitation spectrum of ^{20}Ne has been probed using an α-particle beam at incident energies

TABLE I: Published resonances in ^{20}Ne [9] from 23 to 28 MeV.

$E_x(^{20}\text{Ne})$ (MeV)	I^π	Γ (keV)	Γ_α/Γ (%)
22.80(6)	9^-	500	100
22.87(4)	9^-	225(40)	100
23.4(2)	8^+	500	—
23.70(3)	(9^-)	≤200	100
24.21(3)	8^+	350	100
24.9(5)	—	broad	—
25.10(5)	8^+	≈200	100
25.67(5)	—	≈400	100
27.1(1)	(9^-)	700	100
27.50	10^+	broad	—
28.00	8^+	1600	100

of 23.0 to 29.0 MeV on a mylar-foil target. Tentative resonances have been observed and, using a full kinematic reconstruction of the emitted α particles and tailored Monte-Carlo simulations, the normalized yields have been obtained. Previously there was no information for the ^{8}Be+^{8}Be+α and ^{8}Be+^{12}C$^*(0_2^+)$ yields in this excitation energy region. From the spectra obtained it can be concluded that at excitation energies above 24 MeV there is strong indication of several resonances providing an excellent starting point for dedicated future measurements.

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