PROCEEDINGS OF SCIENCE

Pair conversion spectroscopy of the Hoyle state

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The triple–alpha reaction leading to the formation of stable carbon in the Universe is one of the most important nuclear astrophysical processes. The radiative width of the so–called Hoyle state, involving the 7.654 MeV E0 and the 3.2148 MeV E2 transitions, is known with a 10–12% accuracy. A novel, more direct approach to determine the radiative width was proposed recently, based on the measurement of the E0 and the E2 internal pair conversion intensities. We report on the development of a new magnetic pair spectrometer with high sensitivity for electron–positron pairs and with excellent energy resolution.

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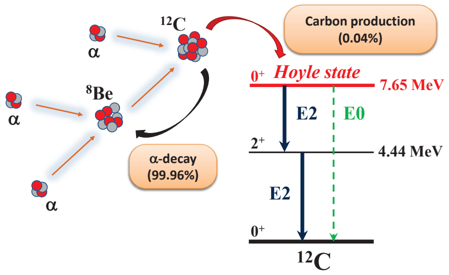

Figure 1: 3α–process and the formation of ^{12}C.

1. Introduction

In this paper we report on the development of a new spectrometer designed to observe the pair conversion of high energy transitions. Test experiments were carried out using radioactive sources as well as the ^{54}Fe$(p,p')^{54}$Fe and ^{12}C$(p,p')^{12}$C reactions. Here, we present the first experimental results obtained with inelastic scattering of protons on a ^{12}C target. Results on the ^{54}Fe(p,p') experiment will be presented elsewhere.

2. Triple–alpha reaction

The triple-alpha reaction, which is responsible for the production of Carbon in the Universe, is often cited as one of the most important nuclear reactions of astrophysical significance. The production and the decay pathways of the 7.6 MeV resonant state, the Hoyle state are illustrated in Fig. 1. During helium burning in the centre of the stars, when both the temperature and the density are sufficiently high, two α particles (^{4}He nuclei) fuse to form the highly unstable nucleus ^{8}Be, which has a halflife of only 6.7×10^{-17} s for decay back into two α particles. Occasionally, a third α particle combines with ^{8}Be before the decay takes place, forming a cluster of three α particles. The Hoyle state is highly alpha–unbound, usually decaying back to ^{8}Be. Only a small fraction of the time, it decays to the ground state of ^{12}C. This pathway, containing the 3.2148 MeV E2 and the 7.654 MeV E0 transitions, is the only source of stable ^{12}C in the Universe. It represents only $\sim$0.4% of the total decay intensity.

The rate, $r_{3\alpha}$, for the triple–alpha reaction [1] can be written as

$$r_{3\alpha} \propto \Gamma_{\rm rad} \exp(-Q_{3\alpha}/kT), \tag{2.1}$$

where $Q_{3\alpha}$ is the energy released in the α decay of the Hoyle state and T is the temperature. The *radiative width* of the Hoyle state, $\Gamma_{\rm rad}$, contains contributions from photon emission, pair conversion and internal conversion. Traditionally, $\Gamma_{\rm rad}$ is determined as the product of three independently measured quantities: $\Gamma_{\rm rad}/\Gamma$, $\Gamma/\Gamma_\pi^{\rm E0}$ and $\Gamma_\pi^{\rm E0}$. A review of the available experimental data [2] indicates that the combined uncertainty on $\Gamma_{\rm rad}$ is about 10–12%.

A new approach was suggested recently [3], based on the direct observation of E0 and E2 transitions de–exciting the Hoyle state. We estimate that the pair conversion intensity of the E0 transition, Γ_π^{E0}, carries about 1.5% of Γ_{rad}, while Γ_π^{E2} is about 0.09%. These intensities suggest

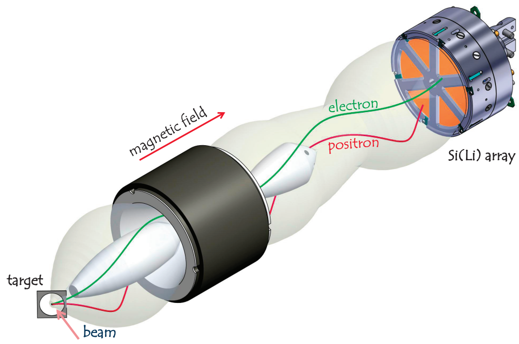

Figure 2: (Color online) Schematic view of the magnetic pair spectrometer. (Courtesy of Caleb Gudu, ANU)

that these two decay channels could be studied. Through the measurements of $\Gamma_{\pi}^{\mathrm{E2}}/\Gamma_{\pi}^{\mathrm{E0}}$, we plan to determine Γ_{rad} from:

$$\Gamma_{rad} = \left[\frac{\Gamma_{\pi}^{\mathrm{E2}}}{\Gamma_{\pi}^{\mathrm{E0}}}\right] \times \left[\left(1+\frac{1}{\alpha_{\pi}^{\mathrm{E2}}}\right)+1\right] \times \left[\Gamma_{\pi}^{\mathrm{E0}}\right], \tag{2.2}$$

where $\alpha_{\pi}^{\mathrm{E2}} = 8.766\times10^{-4}$ is the theoretical pair conversion coefficient, known with an accuracy of ≈ 1 % [4]. Γ_{π}^{E0}, the only known absolute quantity, will be taken from other measurements.

3. Design of the new pair spectrometer

The Hoyle state will be populated in the laboratory using the $^{12}\mathrm{C}(p,p')^{12}\mathrm{C}$ reaction at 10.5 MeV, a resonant bombarding energy [5]. Electron–positron pairs will be recorded using the ANU Super-e electron spectrometer [6], augmented with an array of six Si(Li) detectors, as shown in Fig. 2. The 2.1 Tesla superconductive solenoid is mounted perpendicular to the beam of the 14UD Heavy Ion accelerator at the Australian National University. The target is tilted at 45 degrees to the beam direction, allowing the beam to pass through the target and ensuring that electrons and/or positrons (referred here as *“particles"*) are transported from the rear of the target. For a given magnetic field, the two axial baffles and the diaphragm (Fig. 2) define an energy range of particles that can reach the detectors. A key element of the new pair spectrometer is a Si(Li) array, consisting of six detectors, located 35 cm from the target. Most of the particles will complete two and a half loops before impinging on the detector. A valid pair event is defined as one in which any pair of the six detectors has fired and the summed energy of the two particles (E_+ and E_-) satisfies the relation: $E_{tr} = E_+ + E_- + 2\times m_{\circ}c^2$, where E_{tr} is the transition energy. The highest pair efficiency can be achieved when $E_+ \approx E_-$. For each event, the time difference between detector pairs is also recorded to select true coincidences.

The original lens system [6] has been significantly modified in order to improve the efficiency for electron–positron pairs as well as enhance the suppression of events produced by high energy photons. Details of the design of the pair spectrometer can be found in our recent publication [2] and a full report is being prepared.

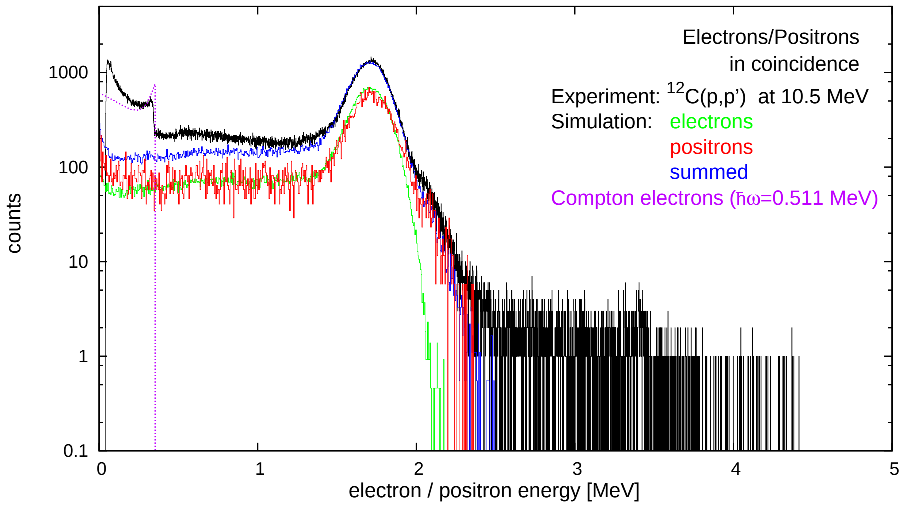

Figure 3: (Color online) Electrons and positrons of the 4.439 MeV E2 transition. Calculated spectra for electrons (green), positrons (red) as well as summed (electron+positron, blue) are compared with experiment (black). The theoretical distribution of Compton electrons for a 0.511 MeV incident photon energy is also show (purple).

4. Pair conversion measurement from ^{12}C + proton bombardment

Test experiments have been carried out with the *"Honey"* detector array consisting six triangular 4.2 mm thick Si(Li) detectors together with the modified absorber system. *"Honey"* was originally developed for $e-e$ coincidence spectroscopy of conversion electrons (see, for example, [7]). A typical energy spectrum of coincidence events is shown in Fig. 3. It was recorded with a 10.5 MeV proton beam incident on a 2 mg/cm^2 ^{12}C target. The magnet current of the solenoid was set to 4.803 A. At this setting, electrons and positrons with kinetic energies between 1.4 MeV and 2.0 MeV are transported from the target to the detector. This energy range is centered around 1.708 MeV, which is optimal for the observation of the 4.439 MeV E2 electron–positron pairs in ^{12}C. The experimental spectra in the figure were produced by adding together gain–matched coincidence data from the six detectors. The shape of the spectrum in the 1.4–2.0 MeV energy range samples the distribution of the emitted pairs, as well as the energy dependence of the detection efficiency for a fixed magnetic field. Pair events of other electromagnetic transitions from ^{12}C (3.2148 MeV E2, 7.654 MeV E0) as well as from ^{16}O (6.05 MeV E0, 6.130 MeV E3, 6.916 MeV E2 and 7.115 MeV E1 from the oxygen absorbed in the target) can also produce events in the detector. Other types of radiation, including scattered beam particles and high energy photons, are expected to be largely suppressed by the absorber system. For example, photons, emitted from the target and heading straight to one of the Si(Li) detectors, have to pass through 8.2 cm of HeavyMet. Compared to our initial experiments with the original lens system [8], the count rate above 2 MeV in energy, which was previously dominated by high energy photons, has been reduced by two orders of magnitude.

To examine further the composition of the spectrum, detailed simulations have been carried out using the PENELOPE–2008 code [9]. Some of the results are included in Fig. 3. In these

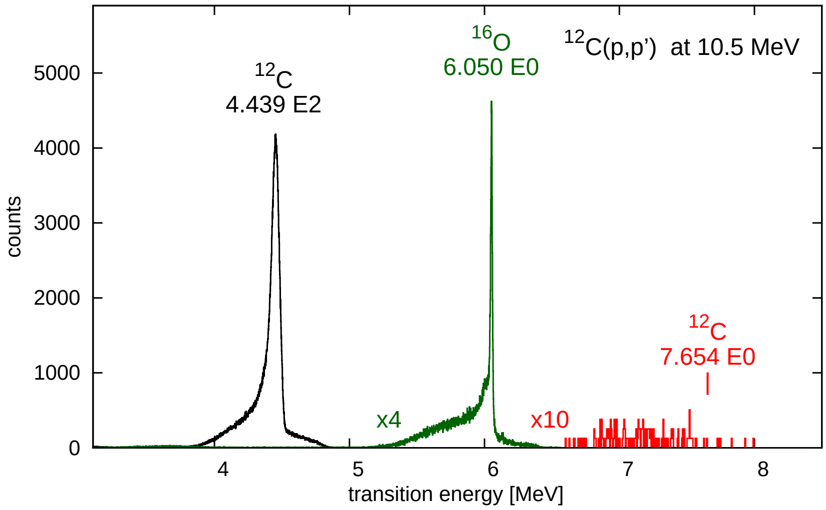

Figure 4: (Color online) Pair spectrum from a 2 mg/cm^2 thick carbon target bombarded with 10.5 MeV protons. Note the scaling factors on the 6.050 MeV E0 and 7.654 MeV E0 spectra. The 7.654 MeV E0 spectrum was compressed by factor 5.

calculations, equal number of electrons and positrons were used to study the detector response. The energy spectra of the incident particles were extracted from trajectory calculations used to design the lens absorber and the Si(Li) array. While most particles will be fully absorbed in the detectors, some of them will deposit only part of their energy. The calculations correctly reproduce most of the events caused by backscattering, or in the case of high energy electrons and positrons, by secondary photons escaping from the detector.

Initially puzzling feature of the experimental spectrum in Fig. 3 was a bump above 2 MeV in energy. While this is not visible in the simulated electron spectrum, the calculations with positrons can correctly reproduce the position and the shape of that part of the spectrum. This lead us to conclude that these events were produced when the positrons and the annihilation photons were recorded in the same Si(Li) detector.

The low energy part of the spectrum in Fig. 3 is dominated by a Compton edge at 0.34 MeV, which would correspond to a primary photon energy of 0.511 MeV. Additional PENELOPE simulations have been carried out with the assumption that the annihilation photons were produced by positrons hitting the detector. However, this could not be verified. An alternative explanation is based on the assumption that the Compton scattering takes place further away from the detector in the absorber system (Fig. 2) and the Compton electrons are transported to the detector by the magnetic field. To fully explain these features, further studies that combine the PENELOPE simulations with detailed trajectory calculations are required.

Finally, representative pair spectra recorded with a 100 nA proton beam over a period of 16 hours are shown in Fig. 4. The figure combines data collected for equal beam charges at three different magnetic field settings, optimised for the 4.439 MeV E2, the 7.654 MeV E0 transitions in ^{12}C and for the 6.050 MeV E0 transition in ^{16}O. The spectra were constructed from summed coincidence events using a ± 6 ns gate on the time differences. The 4.439 MeV E2 transition is the most intense peak containing 95000 counts and its line shape is governed by the Doppler effect, as the half life of the 4.439 MeV state is shorter than the stopping time of the recoils. A similar line shape is expected for the the 7.654 MeV E0 transition; however, this line has not been observed in the current short experiment. On the other hand, the 6.050 MeV excited state in ^{16}O has a much longer lifetime, resulting in a FWHM of 15.4 keV for the 6.050 MeV E0 pair peak. In comparing the pair spectrum shown in Fig. 4 with the results of Alburger [10], it is evident that the energy resolution of our spectrometer is much better.

5. Summary

In summary, we have developed a new magnetic pair spectrometer combined with a Si(Li) array that provides an excellent energy resolution and sensitivity to record electron–positron pairs in proton–induced nuclear reactions. A new, 9 mm thick, more effective Si(Li) detector array and associated electronics is being constructed. Additional studies to improve the calibration of the pair spectrometer and the shielding around the spectrometer to use higher beam intensities are underway.

Acknowledgement

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