Resonant elastic and inelastic scattering. Astrophysical applications. New paradigm beyond drip-lines?

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RESONANT ELASTIC AND INELASTIC SCATTERING ASTROPHYSICAL APPLICATIONS NEW PARADIGM BEYOND DRIP-LINES?

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Two experimental techniques have been developed at GANIL using resonant elastic and inelastic scattering reactions in inverse kinematics. These techniques were used to study the structure of unstable nuclei. A brief description of the methods is presented through two examples of application in astrophysics. Moreover, new ideas and simple questions are put forward: what happens in the low energy tail of unbound nuclei ground state resonances?

1. Introduction

With the onset of post-accelerated radioactive beams, our group has developed two experimental techniques well adapted to low beam intensities: inelastic scattering reaction associated with particle-particle correlations technique[1] and the resonant elastic scattering technique[2,3].

2. Inelastic scattering with particle-particle correlations

2.1. *Novae and γ-ray emission*

Novae are nuclear explosions caused by the accretion of hydrogen onto the surface of a white dwarf star. The most powerful γ-ray emission coming from novae is predicted to be at energies of 511 keV and below, originating from positron annihilations. It was shown that the amount of radiation emitted scales with the ^{18}F content of the nova ejecta, which in turn depends strongly on its production and destruction rates. The $^{18}F(p,\alpha)^{15}O$ reaction is believed to be the most important destructive reaction[5]. The reaction rate can be determined indirectly by using the properties of the resonances measured in the compound nucleus $^{19}Ne^*$.

*This study was conducted as part of collaborations E442S and PH221. See references herein for the full list of collaborators.

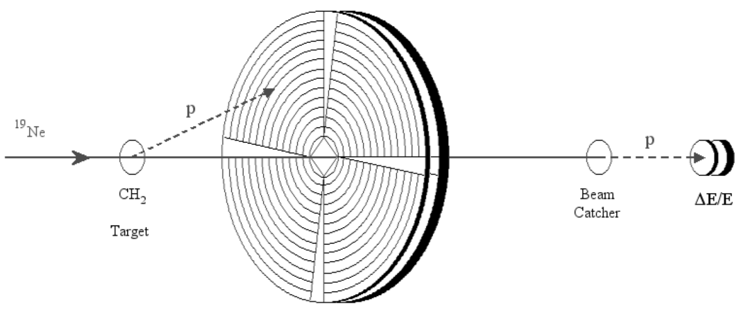

Fig. 1. A schematic view of the experiment setup used to measure the inelastic scattering reaction $H(^{19}Ne,p)^{19}Ne^*(p)^{18}F$

2.2. *Inelastic scattering reaction to measure $^{19}Ne^*$ properties*

Our experiment[1] was performed at the Centre de Recherches du Cyclotron at Louvain-la-Neuve (Belgium) using a $^{19}Ne^{6+}$ radioactive beam, produced with a mean intensity of $\approx 8 \times 10^7$ pps and accelerated to 9 AMeV. The beam was incident on a 3.5 μm thick polypropylene target (see Fig 1). Excited states in ^{19}Ne were populated by inelastic scattering reactions $^1H(^{19}Ne,p)^{19}Ne^*$ occurring in the target. Scattered protons were detected at zero degrees by a $\Delta E/E$ telescope of silicon detectors. A 250 μm-thick aluminium foil was placed between the target and the telescope, and was used as a beam catcher. The intense radioactive beam was stopped inside the catcher while the scattered protons passed through it. An annular double sided stripped telescope of silicon detectors (CD-PAD ensemble)[6] was positioned between the target and the beam catcher. The measured differential cross section for the $H(^{19}Ne,p)^{19}Ne^*$ reaction, with the associated proton detected at zero degree, is presented in Fig. 2 as a function of the $^{19}Ne^*$ excitation energy. This figure is conditioned with the detection of another proton in CD-PAD coming from the emission channel $^{19}Ne^*(p)^{18}F$. A minimum of 6 peaks is required to fit the data. Gaussian shape peaks were used to fit the peaks, except the broad peak E where a Breit-Wigner shape using energy dependant proton width was used. Angular distributions of the protons emitted from the $^{19}Ne^*$ excited states were measured in the CD-PAD detector. They are presented in Fig. 3 for the 6 peaks. The angular correlation technique works very well in this experimental configuration and can be used to assign the spin of the emitting states. The principle of the analysis is presented in [7,8]. The angular distribution should be of the form $d\sigma(\theta_{CM})/d\Omega = \sum_{k=even}^{k_{max}} A_k P_k(cos(\theta_{CM}))$ where P_k are Legendre polynomials. The order k of the polynomial should be an even number and its upper term k_{max} is related to the spin of the excited state. The results obtained with this technique are in very good agreement with the previously measured results in ^{19}Ne. This experi-

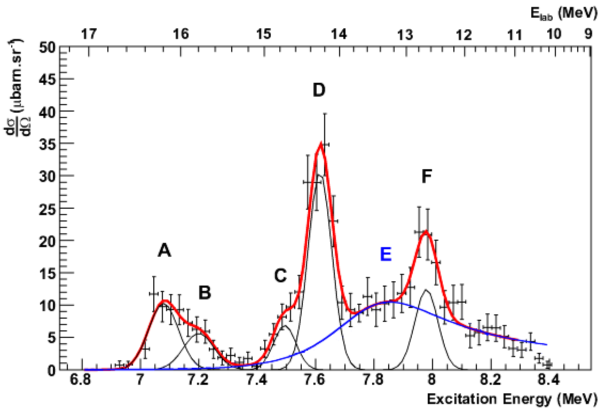

Fig. 2. Measured differential cross section in $\Delta E/E$ detector for the $H(^{19}Ne,p)^{19}Ne^*$ reaction, conditioned with the detection in the CD-PAD detector of another proton emitted from $^{19}Ne^*(p)^{18}F$.

ment gives and confirms for the first time the spin assignment of states B, C, E, F in ^{19}Ne, so far only based on mirror comparisons. We also report the first observation of a broad $J = \frac{1}{2}$ state at $E_x \approx 7.9$ MeV (peak labeled E), whose existence was recently predicted and which is expected to be important to the understanding of γ-ray emission following novae explosions.

3. Resonant elastic scattering

3.1. *X-ray bursts and a new alternative pathway*

X-ray bursts are very similar to novae explosions, except that the white dwarf star is replaced by a neutron star. In these explosive events, the carbon and nitrogen elements are mainly transformed into ^{14}O and ^{15}O by successive proton captures [9]. Then, the pathway for new proton captures is hindered by the proton-unbound nuclei ^{15}F and ^{16}F. The reaction flux and the energy generation are then limited by the relatively slow β^+-decay of ^{14}O ($t_{1/2}$=71 s) and ^{15}O ($t_{1/2}$=122 s), which creates waiting points. In such explosive environments, ^{16}F is strongly populated in the ground state (g.s.) or in the first excited state, and leads to an equilibrium between formation and decay of this proton-unbound nucleus. We proposed β^+-decay of ^{16}F to ^{16}O as an alternative channel. The calculation of this process requires the measurement of the energies, widths, spins and parities of the low lying states of ^{16}F.

3.2. *Resonant elastic scattering to measure $^{16}F^*$ properties*

A radioactive ^{15}O beam was produced at the SPIRAL-GANIL facility. Mean intensities of 10^7 pps at an energy of 1.2 A.MeV were obtained. The excitation function

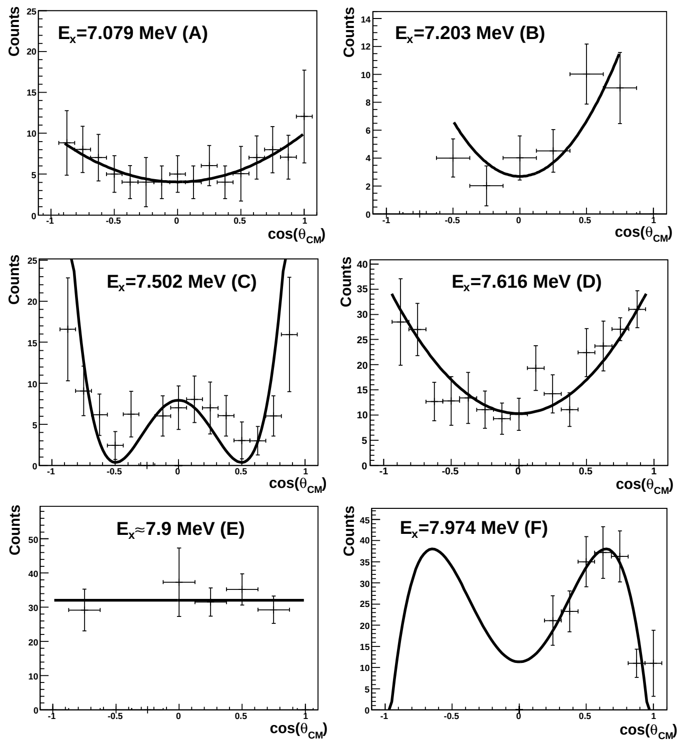

Fig. 3. Angular distributions of the protons emitted from the six measured $^{19}Ne^{*}$ excited states.

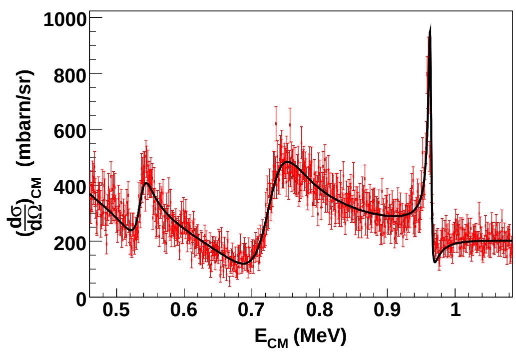

Fig. 4. Measured differential cross section for the $H(^{15}O,p)^{15}O$ reaction.

for the elastic scattering at these low energies can be described by the Rutherford scattering, but shows "anomalies", i.e. various resonances that are related to individual states in the compound nucleus. The principle of the measurement is described in [10] and references therein. A 31(1) μm thick polyethylene $(CH_2)_n$ target was used, thick enough to stop the beam inside. The scattered protons were detected by a silicon detector, placed at forward angles (180° in the center of mass frame) within an angular acceptance of 2°. Protons were identified using their energy and time-of-flight. The energy resolution was 3 keV in the center of mass (c.m.) frame. Fig. 4 shows the excitation function for the $H(^{15}O,p)^{15}O$ reaction. The measured cross section was reproduced by an R-matrix calculation using the code ANARKI [10] which is seen to be in a good agreement with the data. The R-matrix analysis was also used to extract the properties of the first three states in ^{16}F. A significant difference was found between the present and the recommended value of the width for the first excited state.

4. New paradigm?

Ground states of particle-unbound nuclei are seen as resonances. According to the Heisenberg's uncertainty principle, the shorter is the lifetime of the state the broader is the resonance. The Breit-Wigner function describes perfectly the shape of the resonance when energy-dependent partial-widths are used. In the low energy tail of a resonance, close to the particle-emission threshold, the partial-width for the emission of a charged particle through the Coulomb barrier is dramatically reduced. In this region of the resonance, the charged particle could be "trapped" inside the unbound nucleus. This question is a very important issue and could be the door for a new paradigm [11,12].

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