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Research Article

A Search for Correlated Quantum States in Nuclear Reactions: First Exciting Results From an Experimental Test

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Abstract

The first experimental test of the Correlated-Coherent quantum States (CCS) model is described in this paper, showing its potentialities in the explanation of anomalous effects in nuclear physics and astrophysics. Some very interesting events, which cannot be ascribed to background, have been observed. The occurrence of nuclear reactions at very low energy is a clear indication of a strong enhancement of Coulomb barrier transmissivity. Some technical issues, which are related to this difficult experiment are discussed, and possible suggestions for the next activity on this topic are also presented.

Keywords: Correlated quantum states, effective Planck constant, proton-lithium reaction at sub-keV energy, monocrystal target, vapor target

1. Introduction

The well-established theoretical concept of Correlated-Coherent quantum States (CCS) [1], [2], which was envisaged from the early years of quantum mechanics, may provide a clue to several open questions in nuclear astrophysics, such as the primordial lithium problem [3] and the enhancement of the cross section and other anomalous effects which have been observed in some nuclear reactions [4] in metallic environments [5]. It may also offer a new perspective in energy-production-related nuclear physics, which would open in turn an entirely new technological field of applications.

The mechanism of formation of CCS in lithium, either in crystalline form lattice or in gaseous phase containing both single *Li* atoms and free Li_2 nanoclusters, when bombarded by a proton beam, was described in a previous paper [6]. On these premises a preliminary test was proposed [7], by focusing on the well-known $^6Li(p,\alpha)^3He$ and $^7Li(p,\alpha)^4He$ reactions which, however, have to be investigated at very low proton beam energy (E < 0.7 keV) in a special, unprecedented, experimental environment.

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Figure 1. The experimental setup.

In this paper, the first encouraging results from the test are reported, which are suggestive of the occurrence of nuclear reactions in an energy region corresponding to a CCS based model predictions.

2. Experimental Setup

It must be stressed that all the equipment required by this test was put at disposal of our research team by an external laboratory (external with respect to our home institutions), and it has not been possible for the authors of this paper to get careful control of the different phases of test preparation. It has also not been possible for lack of time.

A picture of the experimental setup is shown in Fig. 1. A solid target made of lithium polycrystalline foil (area of approximately 1 cm^2, thickness 0.6 mm, purity 99.99%) is irradiated by a proton beam from an ECR ion source. The foil was delivered by the manufacturer in an unspecified gas atmosphere and manipulated in air for insertion in the loadlock chamber. Preliminary surface cleaning was made by using an abrasive pen.

The ion source is a TPIS Plasma Source [9], which is also used to irradiate the target with an Ar ion beam for cleaning purposes. Typical irradiation time is about 20 mins for Ar sputtering.

The Li target is mounted on an Aluminum support (sample holder, SH), isolated from the UHV chamber, with electrical contacts to measure the total impinging ion current I_{SH} and apply a biasing voltage.

The UHV chamber is equipped with a Silicon PIPS (Passivated Implanted Planar Silicon) detector [11], which is offline calibrated for detection of alpha particles in the energy range of interest for the experiment by means of a ^{241}Am source. The detector is located about 15 mm from the SH. No online calibration was foreseen.

No calibration data were provided by the laboratory staff, unfortunately, but we have received assurance about the correctness of the operation.

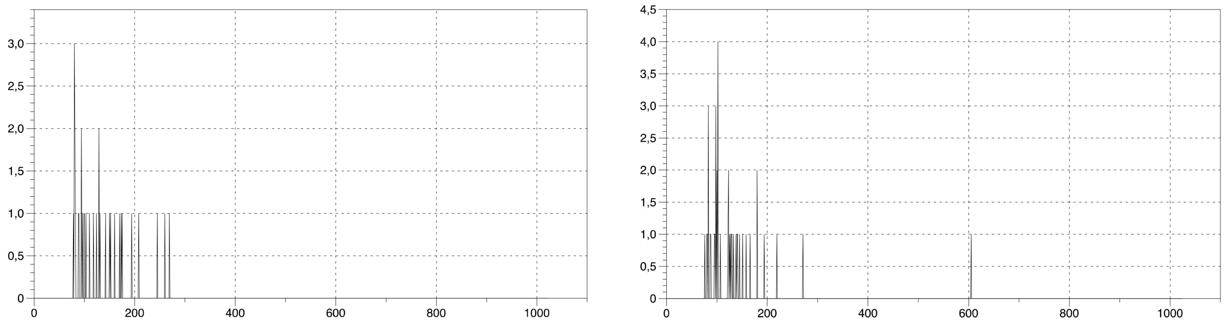

Figure 2. Typical observed spectrum during a 30 mins. Run with ion source off (a) and on (b).

A sample manipulator is used to position and rotate the SH with respect to the ion beam. The beam exit port of the TPIS source is located about 30 mm from the SH. Current flow as measured by a Faraday cup is typically about 150 μA/cm^2 for a current on the SH of 600 μA.

The peak energy definition of the ion beam is dictated by the intrinsic plasma energy, which is around 20 - 25 eV and by a multiple grid assembly, where the bias voltage V_g at the inner "plasma grid" is adjustable by an independent power supply in steps of 1 V in the range 0. – 2000 eV and the extraction grid is usually negatively biased at a fixed potential, $V_b = -200$ V. It must be emphasized that the beam peak energy is not influenced by the latter parameter, but only the energy spread and beam intensity (see Fig. 5 in Ref. [9]).

A better energy definition seems impossible with the present setup: it would require a higher energy beam, with a magnetic analyzer for momentum measurement and precise ion species separation, or the use of time-of-flight or Wien filter techniques, and a decelerating unit (electrostatic lens assembly) to decrease the energy down to the desired value, while providing adequate beam collimation.

Source absolute energy, energy spread, and energy stability are in general crucial issues for cross-section measurements in nuclear astrophysics experiments, and known narrow resonances (or threshold energies for neutron emission) are used as standards to calibrate other instruments, but at the very low energies of our test no such reference exists, to our knowledge.

At the maximum energy of the ion source (< 2 keV) background is mainly due to proton backscattering from target and SH. The entrance window of the PIPS detector is covered by an Au foil thick enough to stop the intense flux of elastically scattered protons.

No nuclear reaction is known at these low energies that may simulate the expected signals.

Nuclear reactions such as (p, nγ), (p, $\alpha\gamma$) which may give rise to spurious signals due to contaminants in the target are also excluded, so the only possible source of background are higher energy cosmic rays. A full characterization of background, and calibration monitoring of the PIPS detector as well, would only be possible by installing a radioactive source with a proper mechanical support inside the vacuum chamber, but this measure unfortunately was not considered from the beginning by the technical staff of the host laboratory.

A typical example of background yield during a 1 hour running time is reported in Fig. 2 with the ion source off (a), and with ion source on (b) with $V_g = 210$ V, $V_b = -200$ V, showing that the occurrence of counting in the higher part of the spectrum is of the order of 1 event/hour, and this is what has been observed in all runs, with one exception, as described below.

The noise generated by ECR source is difficult to estimate since the discriminator threshold was adjusted to cut off on the left-hand side of the pedestal and it was not possible to change it.

3. Experimental Procedure

The model [6] describing a method for the formation of CCS in a crystal lattice of pure lithium when traversed by slow protons is used to determine the experimental procedure. This analysis is based on the fact that the longitudinal motion of a proton in an interplanar crystal channel with potential barriers periodically located on the channel walls is equivalent to its localization in a nonstationary harmonic oscillator.

According to this method [2], [6], the maximum correlation coefficient $r(z)$, hence the maximum yield of reaction products should be reached at a proton longitudinal velocity $v \approx 2a_z \langle\omega\rangle$. This condition corresponds to the parametric resonance frequency $\omega_{res} = 2\langle\omega\rangle$. Here a_z is the crystal period along the particle motion and $\langle\omega\rangle$ is the average frequency which modulates particle oscillations in the transverse potential, corresponding to the characteristic channeling frequency.

This choice should give rise to a very fast increase of the *r(z)* coefficient within the 4^{th} period of Li lattice, up to a maximum theoretical value of $|1 - r(z)| = 10^{-9}$. This value of the correlation coefficient corresponds to very large fluctuations of proton transverse kinetic energy (many tens of keV) [2], [6]. The estimated range of optimal proton longitudinal kinetic energies $mv^2/2$ for such regime is 400–600 eV for a Li lattice.

According to the results of CCS analysis and the parametric oscillator theory [6], another much weaker and much narrower (1 - 2%) maximum is expected at the main unperturbed frequency $\omega_{main} = \omega_{res}/2 = v/\ a_z \approx \langle\omega\rangle$ of the particle's transverse motion.

Several series of energy scanning runs were made therefore in the range 180 - 640 V to fully cover the expectation area for optimum energies.

In some cases the experimental conditions, such as the angle between the beam axis and the normal to the SH, were changed from one run to the next.

A systematic scanning in V_g range 300 - 480 V in steps of 20 V for a duration of 30 mins was made. In the first series 380 - 480 V the extractor grid voltage was set to 0, while in the other it was set to -200 V, according to TPIS manual prescriptions, which suggests that the voltage at the extractor grid should be always lower than -200 V, although, according to user's experience this plays no significant role in the operation of the ion source.

Two further scans, one at higher energy 500 - 640 V and the other at lower energy, 180 - 280 V were also done. In all these measurements the H gas flow was often adjusted to keep chamber pressure at values around $2 \cdot 10^{-2}$ mbar, resulting indeed between 1.4 and $3.2 \cdot 10^{-2}$ mbar.

The SH current, which in principle should be a monitor of the ion current at the target, was also quite unstable during these runs, oscillating between 9 and 30 μA. A visual inspection of SH after the end of the test shows that ion irradiation appears not well focused on the sample, but it is spread out on the whole surface of the SH. This might be avoided by using a concave grid, according to the reference paper [9]. This is important for Ar sputtering, too.

To reproduce as much as possible the experimental conditions under which a very high counting rate of alpha particles was observed by an independent team [8], a bipolar power supply is used to apply negative voltage V_{bias} to the SH. This alleged extraordinary effect in fact was observed at a nominal $E_p = 225$ eV and $V_{\text{bias}} = -222.6$ V, but it is unclear from their unpublished work how the proton energy is determined, and if the given value is comprehensive of the plasma energy.

4. First Results

A total measurement time of more than 30 hours over 7 full days was devoted to the search for significant events. None was detected, with one exception: on the first run of day 19.11.2019 some counts were observed indeed (Fig. 3). Experimental parameters were $V_g = 210$ - 220 V, $V_{\text{bias}} = -200$ V, P$\sim$5.4.0$\cdot 10^{-3}$ mbar, impact angle $= 0°$, run duration 60 minutes. The proton energy on target at the time that energetic ions were observed is estimated to be centered around 440 eV.

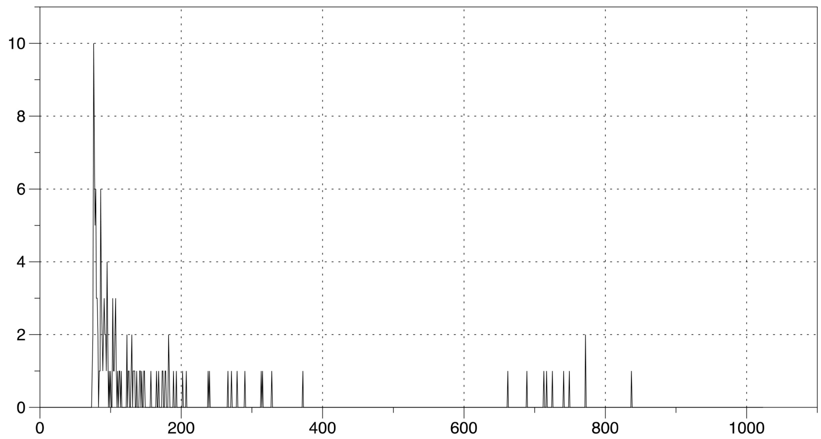

Figure 3. Measured spectrum in the run of 19.11.2019.

The energy attributable to such events is in the region around $\sim$ Q/2, according to the detector's calibration, where α-particles from $^{7}Li(p,\alpha)^{4}He$ (Q = 17.35 MeV) are expected.

A significant counting at lower energy, separated from higher energy counting, was detected as well. These events occurred in a very short time interval, of the order of a few seconds. No precise time recording is possible with the present setup, unfortunately. No similar effects have been observed during any other run. Attempts to reproduce the results of this run by changing the nominal impact angle and repeatedly Ar cleaning of the target surface failed.

5. Target Characterization

Lithium target characterization is the crucial issue in this experiment. Metallic Li is highly reactive with nitrogen, carbon, oxygen and water vapour from the atmospheric air. This reactivity has to be taken into account for the production process as well as for the quality of the target when exposed to ambient air. A further complication in our case consists of the requirement of a pure monocrystalline Li target, unlike all other experiments on the same reactions, which have used LiF or metallic lithium alloys so far. A regular crystalline structure without defects is needed, although this might be necessary only for the very first layers, since the correlation coefficient is shown to grow rapidly for impinging protons at the optimum velocity. Another basic requirement is crystal orientation: optimum conditions are found for protons moving along the system of crystal planes in analogy with the physics of "classical" channeling of positively charged particles. On the other hand, unlike what occurs in the channeling model, the onset of CCS is not due to an average atomic potential along the crystal axis, but because of the presence of a periodic structure of the crystal potential along the direction of motion. The difference between these modes lies in the value of the energy of the longitudinal motion: the channeling condition and the potential averaging are fulfilled only at a relatively high energy $E > 30\text{-}50$ keV, and the formation of the CCS in periodic crystal potential at a much lower optimal energy $E < 1$ keV.

Fabrication of pure Li monocrystals with the Czochralski system is a rather complex procedure, thereby resulting in a very expensive product, if careful surface polishing is also taken into account [10]. Furthermore, absolute crystal orientation cannot be specified by the manufacturer, as it is defined as "random", although its accuracy is quite good (typically $< 0.1°$). This difficulty can be overcome nevertheless, e.g., by single crystal orientation measurement with the well-known method of X-ray diffraction goniometry.

Otherwise, a polycrystalline, rather cheap, Li foil can be used but quite clearly the condition for the onset of CCS would occur only if the proton beam could impinge on a crystal grain of the specimen that has the proper crystallographic orientation. The observation of CCS-related particle reactions thus would be a matter of chance entirely, as in the present test and in the previous experiment [8], unless a comprehensive and more sophisticated tool to spatially characterize grain geometry and orientation such as the Electron Backscatter Diffraction (EBSD) method is employed [11].

Owing to the mentioned issues in handling solid Li targets, it is important to foresee in future tests the study of CCS formation also in Li vapour targets, as theoretically described in a previous work [6], and experimentally observed, with a much higher alleged intensity than in a Li solid target [8].

6. Conclusions

What can be learnt from this very preliminary but also very encouraging test of the CCS model?

- Proton beam quality has to improve substantially: an ion irradiation facility with accurate energy definition, high current and beam spot size control down to energy of the order of 100 eV is required. An electrostatic decelerator would probably be necessary to fulfill the latter requirement.
- The target is perhaps the crucial issue in this context: the future experiment must be flexible enough to host both solid and gas Li targets, if a complete and accurate investigation of the CCS model as applied to the p-Li reaction is desired. Clearly, the use of a very thin oriented target made of lithium single crystal is the best solution.
- Much more time must be allowed for test preparation and run, because this is a search for rare events. The present test was carried out over a period of two-and-a-half weeks, which is clearly too short, especially if compared with the previous experiment which took 25 series of long duration tests performed at 4 different facilities and spanning over seven years [8].

Fortunately, such a facility might be soon available in Europe, after some upgrade.

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