Nuclear reaction studies with particle-gamma coincidences using the *Saci-Perere* spectrometer

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**Abstract.** The *Saci-Perere* spectrometer of the University of São Paulo has been configured to perform particle-gamma coincidence measurements in order to study nuclear reaction mechanisms. The motivation of this type of measurement comes from the recent development of nuclear reaction models based on the São Paulo potential with the inclusion of an imaginary part with no adjustable parameters. New preliminary data on the $^{18}$O+$^{110}$Pd transitional system are presented, and apparent similarities to weakly bound cases (e.g. $^7$Li+$^{120}$Sn) are briefly discussed.

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1. Introduction

The *Saci-Perere* (acronym for *Sistema Ancilar de Cintiladores - Pequeno Espectrômetro de Radiação Eletromagnética com Rejeição de Espalhamento*) is a gamma-spectrometer located at the Pelletron 8MV Tandem of the University of São Paulo. It consists of four HPGe detectors equipped with BGO Compton suppressors, with a total photopeak efficiency close to 0.5% (at $E_\gamma = 1.3$ MeV), and an ancillary system of 11 $\Delta E - E$ plastic phoswich scintillators, with a total solid angle coverage of 76% of $4\pi$ [1]. It was designed and used for nuclear structures studies (e.g. [2]) in fusion-evaporation reactions where $p$ and $\alpha$ charged particles are detected, mainly. For nuclear reaction studies, however, the beam-like particles should be detected, and the solid angle range of each detector should be limited, to reduce both the count-rate and the scattering angle integration range [3]. This has been accomplished with a set of collimators placed on the face of each scintillator. With this setup, the $^{18}$O+$^{110}$Pd reaction has been measured at various beam energies (between 46 and 60 MeV) in two separate experiments. The preliminary results show that there is an enhancement of the cross sections in comparison to a “standard” calculation with the potential proposed in [4], similar to the results encountered in weakly bound systems such as $^7$Li+$^{120}$Sn [5, 6]. This had already been observed in the $^{18}$O+$^{110}$Pd transitional system in inelastic excitation functions at a very backward angle with an annular...
2. The $^{18}$O+$^{110}$Pd experiments

The $^{18}$O+$^{110}$Pd was investigated with the Saci-Perere spectrometer in two separate experiments. In the first one, only two HPGe and 7 phoswich detectors were in operation, while on the second one, the full system was used (one of the phoswich detectors, however, presented low gain in the spectra and its analysis has been postponed). The target consisted of a 0.84 mg/cm$^2$ $^{110}$Pd foil with a gold (Au) evaporated layer of 1.49 mg/cm$^2$ thickness. The beam entered by the Pd layer in the first experiment and the Au layer in the second one, in order to explore the vacuum de-orientation effect as a function of the recoil velocity.

The collimator system consisted of 0.3 mm-thick Al plates, with 0.5-3.0 mm diameter holes (increasing with angle), with 11 average (nominal) angles (with relation to the beam direction) varying from $30^\circ$ to $140^\circ$ in $10^\circ$ steps (skipping $90^\circ$). Including the 3 mm diameter beam spot, the scattering angle range of each detector varies between $6^\circ$ and $12^\circ$.

Figures 1 and 2 present sample spectra at a beam energy of 55.8 and 54.1 MeV, respectively (average laboratory energies, considering the energy loss of about 2 MeV through the target), obtained in these experiments. The $^{124}$Xe line comes from total fusion followed by evaporation of neutrons, and is present only at the higher energies and in the singles spectra. The gamma-decay transition from the $4^+$ of $^{110}$Pd is contaminated with an Au line. The 2n transfer related lines ($^{112}$Pd) are observed only at large scattering angles.
Figure 2. Sample spectra of the $^{18}$O+$^{110}$Pd experiment obtained with the Saci-Perere spectrometer. a) Typical plastic scintillator $\Delta E - E$ bi-parametric spectrum, at $\theta_{\text{lab}} = 50^\circ$ - the dashed contour indicates the cut corresponding to the particles which stop within the $\Delta E$ detector thickness (0.1 mm), such as beam-like particles; b) $\Delta E$-projection spectra selected from inside the cut and gated on the $2^+ \rightarrow 0^+$ transition (374 keV) of $^{110}$Pd, or on the $5^+ \rightarrow 3^+$ transition (279 keV) of $^{197}$Au, as indicated in the figure (the Compton and random coincidences related background has been subtracted). c) Singles gamma spectrum at $\theta_{\text{lab}} = 110^\circ$. d) Gamma spectrum of the same detector as in c), in coincidence with particles inside the cut indicated in a), i.e., beam-like particles, essentially.

3. Data normalization

In order to extract the inelastic and transfer to excited states scattering cross sections from particle-gamma measurements, one has to consider, besides the corrections from upper level feeding, the gamma-ray angular distribution in correlation with the beam like particle scattering angle. These effects can be calculated from the population of magnetic sub-states in a nuclear reaction code. The gamma-ray angular anisotropy is attenuated due to the finite angular coverage of the detectors and to the hyperfine interaction when the recoiling nuclei decays in vacuum (vacuum de-alignment). For energies sufficiently below the barrier, these corrections have been successfully applied for many years in Coulomb excitation codes such as GOSIA [9]. Also, for near $180^\circ$ scattering angle (as in [7]), the gamma-ray angular distribution is independent of the reaction mechanism.

For energies close to the barrier, the Coulomb excitation gamma-ray angular distribution $W(\theta_\gamma)$ can be used as a first order approximation, and, in addition, it turns out that it is weakly dependent on energy. Under this assumption, the experimental yields $Y$ can be related to the cross section using a low energy reference ($E^{\text{ref}}$) measurement (below or at least very near the barrier) to normalize data at each angle, and a low scattering angle ($\theta^{\text{ref}}$) reference (where the theoretical Coulomb cross section can be considered reliable at all energies):

$$Y(E, \theta_p, \theta_\gamma) \approx I(E)N \frac{d^2\sigma}{d\Omega_p d\Omega_\gamma} \Delta\Omega_p(\theta_p) \Delta\Omega_\gamma(\theta_\gamma),$$

where $I(E)$ is the beam intensity of the measurement performed at energy $E$, and $N$ the number of target nuclei. Under the assumption
Figure 3. Angular distributions of the inelastic excitation of the $2^+$ states of $^{110}$Pd ($^{18}$O + $^{110}$Pd reaction). **Left:** Comparison of results among gamma-detectors at different angles ($\theta, \varphi$): 1-(101°, 0°); 2-(37°, 180°); 3-(101°, 36°); 4-(37°, 144°). The $^{18}$O scattering angle is indicated at the top right of each graph. The average is indicated as a dashed line. **Right:** average cross section obtained at three different energies, compared to the SPP/CC (see next section) calculation with potential $U_1$ (solid lines) and to Coulomb excitation (dashed lines).

that $\frac{d^2\sigma}{d\Omega_p d\Omega_\gamma} \approx \frac{d\sigma}{d\Omega_p (E, \theta_p)} W(\theta_p, \theta_\gamma)$, and defining $R_Y(E, \theta_\gamma) = \frac{Y(E, \theta_\gamma)}{Y(E^{ref}, \theta_p)}$ and $R_\sigma = \frac{\frac{d\sigma}{d\Omega_p (E, \theta_\gamma)}}{\frac{d\sigma}{d\Omega_p (E^{ref}, \theta_p)}}$, one obtains: $\frac{d\sigma}{d\Omega_p (E, \theta_p)} = R_y R_\sigma$, independently of $W(\theta_\gamma)$.

Figure 3 presents the results of the measurements with the above (preliminary) normalization, using $E^{ref} = 46$ MeV and $\theta^{ref} = 40^\circ$. It is shown, at left, that the results are consistently independent of the gamma detector angles relative to the beam and to the particle detector (at 53.6 MeV average beam energy). Similar result is obtained at 55.8 MeV (not shown), however, in this case only two gamma-detectors were used in the experiment (at polar angles 37° and 101°, both in the horizontal plane). At right, the angular distributions obtained from the average of all available gamma detectors are presented at three different energies.

4. The theoretical models
It is well established [10] that the São Paulo Potential (SPP) [11, 12, 13] provides a good description of elastic and quasi-elastic processes near the barrier, when used in a Coupled
Channels (CC) calculation with the inclusion of the main channels. The SPP is theoretically founded on the Pauli non-locality, which arises from quantum exchange effects. The SPP, in the local equivalent version, is given by:

\[ V_{SP}^{LE}(R, E) = V_F(R) e^{-\frac{4\nu^2(R)}{c^2}} \]  

where \( V_F(R) \) is the double folding [14] potential, and the term \( e^{-\frac{4\nu^2(R)}{c^2}} \) is the local velocity \( (\nu(R)) \) dependent correction arising from Pauli non-locality. More recently, a new generation of SPP/CC calculations has been developed [4] with the aim of describing reactions at energies for which dissipative processes, such as deep inelastic collisions (DIC), are important. This has been done with the introduction of an imaginary potential with the same shape of the SPP:

\[ U_1(R) = (1 + 0.6i)V_{SP}^{LE}(R) \]  

which has been applied successfully to a significant number of systems. For the weakly bound cases, however, modifications of this potential are proposed [5]. Sakuragy, Yahirol, and Kamimura [15] have shown, with the method of coupled discretized continuum channels (CDCC), that the dynamic polarization potential due to the \(^6\)Li breakup is strongly repulsive, and effectively reduces the intensity of the real double-folding potential (in a single-channel calculation) by a factor of 0.5-0.6. Indeed, a reasonable description for the \(^7\)Li + \(^{120}\)Sn system [6, 5, 8] is obtained with the following potential:

\[ U_2(R) = (0.6 + 0.6i)V_{SP}^{LE}(R) \]  

It is expected that other weakly bound systems might also be well described with the use of this potential (see also [16]). It has to be noticed, however, that the above approach could not be applied to a collision with a very high-Z target, where the long-range Coulomb-breakup plays an important role. The inclusion of the Coulomb break-up in the calculations is under development.

5. Discussion

As mentioned above, there has been a previous particle-gamma measurement of the \(^{18}\)O+\(^{110}\)Pd system [7]. In that experiment, besides quasi-elastic cross sections obtained from separate particle singles spectra runs, particle-gamma measurements were performed with an annular particle detector in coincidence with two gamma-ray detectors. The excitation functions extracted for the inelastic and transfer to excited states are well described, below and near the barrier, with a coupled channels calculation employing the São Paulo Potential as the bare interaction (Eq. 1). At somewhat higher energies, however, the experimental cross sections are relatively enhanced and a better agreement with the data is again accomplished [6, 5, 8] by the use of the potential \( U_2 \) as in the \(^7\)Li case. This suggests that again a dynamic polarization potential which decreases the effective real potential is in operation. This could be due to an increased level density, at somewhat high excitation energies, of the transitional nucleus of \(^{110}\)Pd.

The present angular distribution measurements confirm the tendency of enhancement of experimental cross sections relative to the theoretical results with potential \( U_1 \). These results are preliminary. The data are still under analysis. The calculations with the potential \( U_2 \) have not been performed yet. Detailed calculations of the particle-gamma angular correlation, considering the nuclear potential, are necessary for a more precise and reliable comparison.

6. Conclusions

Particle-gamma angular distributions can be measured with the Sasci-Perere spectrometer system. Preliminary angular distributions have been obtained for the \(^{18}\)O+\(^{110}\)Pd reaction. The
results confirm the tendency observed in [7] of an enhancement of the cross sections at large scattering angles which could be related to the increase in the density of states in transitional regions.

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