

JAGIELLONIAN UNIVERSITY in Kraków

Dalitz's Distribution Analysis for $\boldsymbol{o}-\mathrm{Ps} \rightarrow 3 \gamma$ towards c- symmetry violation using the J-PET detector

## Jyoti Chhokar

On Behalf of the J-PET Collaboration Jagiellonian University, Krakow,

## Poland

Investigating the Universe with exotic atomic and nuclear matter

## OVERVIEW

- Dalitz's Plot in general
- Positronium atom
- Approach for obtating Dalitz's plot using JPET tomograph
- Experimental details and pre-selection of data
- Results -- Simulation results of o-Ps and p-Ps and Experimental result for o-Ps
- Discrete Symmetries in physics
- Motivation ---
- Precision test in C-symmetry and their experimental method
- J-PET approach to measure C-symmetry violation


$\square$


HAPPY EASTER

## Dalitz's Plot construction

- Dalitz plots were originally used to investigate a three-body final state , for instance $X \rightarrow A B C$
- Different value of $p_{A}, p_{B}, p_{C}$ possible depending on decay configuration

- 3-body state can be described with 2 D.O.F -> implies 2 variable (there are many choices of what variables to use).

You might suspect

3-body decay will depend upon
the angular momentum between the 3-daughter particles
-- and you'd be right!


Three body decay

visual representation of the phase space of a 3-body decay


$$
S_{i j}^{2}=m_{i j}^{2}
$$

$$
m_{i j}^{2}=\left(E_{i}+E_{j}\right)^{2}-\left(\vec{p}_{i}+\vec{p}_{j}\right)^{2}
$$

$$
x=m_{a b}^{2}=s_{a b}=\left(p_{a}^{\mu}+p_{b}^{\mu}\right)^{2}
$$

$$
y=m_{a c}^{2}=s_{a c}=\left(p_{a}^{\mu}+p_{c}^{\mu}\right)^{2}
$$

- Quantum mechanical Probability gives the interaction potential of the system.


## To Summarize

- Dalitz plots are a powerful tool for studying three body systems
- The Dalitz plot was an important contributor to the tau-theta puzzle of the 1950's, which was eventually solved by the discovery of parity violation
- Dalitz plots give information about particle masses, lifetimes, spins, and interference.



## Positronium (Ps)-- lightest Leptonic object

Due to Charge Conjugation


## 3 Decay System 0-Ps $\boldsymbol{\rightarrow} \mathbf{3 \gamma}$



- Assuming o-Ps decays at rest corresponding cross-section is expressed as

$$
d \sigma_{3 \gamma}\left(k_{1}+k_{2}+k_{3}\right) \delta\left(\omega_{1}+\omega_{2}+\omega_{3}-2 m\right)=\frac{(2 \pi)^{4}\left|M_{f i}\right|^{2}}{4 m^{2} v} \delta \frac{d^{3} k_{1} d^{3} k_{2} d^{3} k_{3}}{(2 \pi)^{9} 2 \omega_{1} 2 \omega_{2} 2 \omega_{3}}
$$

where $M_{f i}$ is Lorentz invariant amplitude for $|o-P s| \rightarrow \mid 3 \gamma>$ transition, m is electron mass, v is electron-positron relative velocity and $k_{i}, w_{i}$ are the wave vectors and frequencies of the formed photons, respectively.

- delta functions express the laws of conservation of energy and momentum

$$
\frac{1}{4} \sum\left|M_{f i}\right|^{2}=(4 \pi)^{3} e^{6} .16\left[\left(\frac{m-\omega_{1}}{\omega_{2} \omega_{3}}\right)^{2}+\left(\frac{m-\omega_{2}}{\omega_{1} \omega_{3}}\right)^{2}+\left(\frac{m-\omega_{1}}{\omega_{1} \omega_{2}}\right)^{2}\right]
$$

The resulting cross-section for annihilation with formation of photons having specified energies is

$$
d \bar{\sigma}_{3 \gamma}=\frac{8 e^{6}}{6 v m^{2}}\left\{\left(\frac{m-\omega_{1}}{\omega_{2} \omega_{3}}\right)^{2}+\left(\frac{m-\omega_{2}}{\omega_{1} \omega_{3}}\right)^{2}+\left(\frac{m-\omega_{1}}{\omega_{1} \omega_{2}}\right)^{2}\right\}
$$



- 5 combination of Feynman diagram results in the transition element as shown above

In CM frame, energies of three gamma quanta from an Ps annihilation, can be expressed as a functions of angles $\left(\theta_{12}, \theta_{23}, \theta_{13}\right)$ between momentum vectors


## Solution of equation can be presented as:

$$
\begin{gathered}
E_{1}=-2 m_{e} c^{2} \frac{-\cos \theta_{13}+\cos \theta_{12} \cos \theta_{23}}{\left(-1+\cos \theta_{12}\right)\left(1+\cos \theta_{12}-\cos \theta_{13}-\cos \theta_{23}\right)}=\omega_{1} \\
E_{2}=-2 m_{e} c^{2} \frac{\cos \theta_{12} \cos \theta_{13}-\cos \theta_{23}}{\left(-1+\cos \theta_{12}\right)\left(1+\cos \theta_{12}-\cos \theta_{13}-\cos \theta_{23}\right)}=\omega_{2} \\
E_{3}=2 m_{e} c^{2} \frac{1+\cos \theta_{12}}{\left(1+\cos \theta_{12}-\cos \theta_{13}-\cos \theta_{23}\right)}=\omega_{3}
\end{gathered}
$$


$\square \theta_{12}=\cos ^{-1}\left(\frac{p_{3}^{2}-p_{1}^{2}-p_{2}^{2}}{2 p_{1} p_{2}}\right)$
$\square \theta_{23}=\cos ^{-1}\left(\frac{p_{1}^{2}-p_{2}^{2}-p_{3}^{2}}{2 p_{2} p_{3}}\right)$
$\square \theta_{31}=\cos ^{-1}\left(\frac{p_{2}^{2}-p_{1}^{2}-p_{3}^{2}}{2 p_{1} p_{3}}\right)$
Using momentum-energy conservation: relation between Theta's and energy is calculated

- $w_{1}+w_{2}+w_{3}=2 m_{e}$

$$
\begin{aligned}
& m=511 \mathrm{keV} \\
& 0 \leq \theta_{12}, \theta_{23}, \theta_{13} \leq 180^{\circ}
\end{aligned}
$$

## Jagiellonian - Positron Emission Tomograph



Fig. 3. Represents the J-PET detector front view which consists of 192 plastic scintillators. Also represents the azimuthal angle between three photon which are annihilating from the ${ }^{22} \mathrm{Na}$ source placed in center of detector.


Preselection of the Signal: o-Ps-> $3 y$


Signal Event --- $\boldsymbol{Y}_{1}+\boldsymbol{Y}_{2}+\boldsymbol{Y}_{\mathbf{3}}+\boldsymbol{Y}_{\text {dex }}$


PMT
Active scintillator region
Single Module of the J-PET detector single Module of the J-PET det

Active scintillating region $=|23.0| \mathrm{cm}$


Figure 3: Representation of the interaction positions on the Z -axis of the photon interaction in the detector geometry.

## Time Over Threshold as a measure of Energy Deposition



Sum of the TOT from four thresholds from both side of the scintillator


Time_Over_Threshold [ns]

Fig. represents the signal (purple) from the two PMT fixed each side of scintillator, and signal from both of the PMT probed at four threshold. Right spectra shows the TOT distribution in which there is $\mathbf{2}$ Compton edges one for 511 kev and another for 1274 keV photons.

Selection of o-Ps using three Azimuthal Angle of interacting Photons


Fig. 6. Represents the distribution of the sum $\left(\theta_{12}+\theta_{23}\right)$ and difference ( $\theta_{12^{-}} \theta_{23}$ ) of the two smallest azimuthal angles between the $3 y$ of o-Ps decay (left) before cut (right) after cut

Figure 6 : Representation of the distribution of the relative azimuthal angles between the decay of o-Ps into $3 \gamma$. (Above) experimental data in log scale (right) experimental data in linear scale

## 3D Dalitz's Angular Plot for $o-P s \rightarrow 3 \gamma$



Generation of Corrected Experimental result

J. Chhokar, Acta Physica Polonica A, 137 (2), p. 134-136 (2020)

## Symmetry



Noether's theorem: For every symmetry in Physics there is a corresponding conservation law.

Discrete symmetries:

1) Parity transformation:

$$
\mathrm{P}(x)=-x
$$


2) Charge conjugation :

$$
\text { particle } \leftrightarrow \text { antiparticle }
$$

3) Time reversal:

$$
t \rightarrow-t
$$

## Precision test in C - forbidden decay

Millls and Berko -- 1967 -- First experiment to test C-symmetry

Using Bose Statistics assumption: Seperated the Cforbidden $3 \boldsymbol{\gamma}$ decay of p-Ps from the allowed $3 \boldsymbol{\gamma}$ decay of o-Ps state by studying angular distribution of 3 photons.

Branching Ratio (R) ~ 2.8 * $\mathbf{1 0}^{-6}$ (68\% C.L)
For calculation of $R$ used only three combination of angles:

$\rightarrow$ Six Nal- scintillators

1. Symmetric configuration $\left(120^{\circ}, 120^{\circ}, 120^{\circ}\right)$
2. Other set of angle $\left(60^{\circ}, 150^{\circ}, 150^{\circ}\right)$
$\rightarrow$ Suppressed allowed $3 \mathbf{Y}$ using NO as quenching
3. $\left(90^{\circ}, 120^{\circ}, 150^{\circ}\right)$
A. P. Mills and S. Berko, Phys. Rev. Lett. 18, 420 (1967)

## Angular distribution of 3 photons for o-Ps and p-Ps



Fig. 1. Represents the relative azimuth angle between the 3 annihilation photons. (left) Represents the angular distribution of these 3 photons (above) as decaying from o-Ps and (below ) decaying from p-Ps

## Jagiellonian - Positron Emission Tomograph



Fig. 3. Represents the J-PET detector front view which consists of 192 plastic scintillators. Also represents the azimuthal angle between three photon which are


## Positronium Lifetime :



Positron lifetime distribution in the XAD4, obtained from measurement with the J-PET detector. Measurement was conducted by placing a 22Na source covered in XAD4 polymer in the center of the geometry. The lifetime spectra was obtained by identifying the prompt photon and the three annihilated photons


Lifetime of Positronium [ns] from the decay of o-Ps.

[^0]
## 3D Dalitz's Angular Plot for p-Ps -> 3g -Simulated Data




Lifetime of Positronium [ns]

## Conclusions

$\checkmark$ First Experimental Angular Distribution spectra (Dalitz's Plot) for the o-Ps-> 3 र using J-PET detector.
$\checkmark$ Angular Distribution spectra for the p-Ps->3 $\gamma$ obtained using Monte Carlo Simulation.
$\checkmark$ And p-Ps and o-Ps will be separated using lifetime spectra.

Backup Slides

$$
\begin{gathered}
x=m_{a b}^{2}=s_{a b}=\left(p_{a}^{\mu}+p_{b}^{\mu}\right)^{2} \\
y=m_{a c}^{2}=s_{a c}=\left(p_{a}^{\mu}+p_{c}^{\mu}\right)^{2} \\
1 \mathrm{~s}_{23}(\min ) \\
2 \mathrm{~s}_{23}(\max ) \\
3 \mathrm{~s}_{12}(\min ) \\
4 \mathrm{~s}_{12}(\max ) \\
5 \mathrm{~s}_{13}(\min ) \\
6 \mathrm{~s}_{13}(\max )
\end{gathered}
$$

## Dalitz's Plot




Figure Left: Energy spectrum of photons originating from three-photon annihilation of an electron and a positron. Right: Dalitz plot of o-Ps $\rightarrow 3 \gamma$ decay. Its boundaries are determined by kinematic constrains of the decay.


[^0]:    K. Dulski, et al., Hyperfine Interact, 239:40 (2018)

