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LETTER TO THE EDITOR

STUDY OF RARE RADIATIVE ϕ DECAYS AT JEFFERSON LAB

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The RadPhi Collaboration has proposed the use of the intense tagged photon beam in Hall B at TJNAF to produce ϕ mesons and measure the branching ratios of ϕ's decaying into the $a_0(980)\gamma$ and $f_0(980)\gamma$ all-neutral final states. The comparison of branching ratios for these two decay modes should provide crucial information on the quark substructure of $a_0(980)$ and $f_0(980)$ scalar mesons. Three engineering runs conducted so far measured the photon beam profile, instantaneous rates, pileups and dead times in the detector components, as well as energy and timing resolutions of RadPhi detectors. The measurements demonstrated that the proposed experiment is capable of detecting rare radiative ϕ decays with branching ratios greater than 10^{-5}.

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The RadPhi – a study of rare radiative decays of the ϕ meson – is an experiment in Hall B at Thomas Jefferson National Accelerator Facility (TJNAF), originally approved in 1995 [1].

The experiment was proposed to measure for the first time the branching ratios (BR) of two rare radiative decays of the ϕ meson, $\phi \to a_0(980)\gamma$ and $\phi \to f_0(980)\gamma$. The current edition of the biennial *Review of Particle Physics* [2] lists the upper BR limits of these decays as 5×10^{-3} and 1×10^{-4}, respectively. Recently though, the PHI-97 collaboration has reported the observation of $\phi \to \pi^0\pi^0\gamma$ and $\phi \to \eta\pi^0\gamma$ signals with the SND detector at the VEPP-2M electron-positron collider in Novosibirsk [3]. The reported branching ratios were $BR(\phi \to a_0\gamma) = (0.83 \pm 0.23) \cdot 10^{-4}$ and $BR(\phi \to f_0\gamma) = (3.42 \pm 0.30 \pm 0.36) \cdot 10^{-4}$, respectively.

The physical interest in these measurements stems from their implications for light quark spectroscopy: they offer an unique insight into the quark substructure of the a_0 and f_0 scalar mesons [4]. Several quark structure models of these mesons discussed in the literature are summarized in Table 1. Alternative models predict different electric dipole moments (EDP) of final states in turn determining the value of the ratio

$$\frac{BR(\phi \to a_0\gamma)}{BR(\phi \to f_0\gamma)}. \tag{1}$$

We note that the decay probabilities published by the PHI-97 collaboration suggest that both scalar mesons contain significant 4-quark components without excluding contributions from other quark configurations.

TABLE 1. Quark model predictions for radiative ϕ decay couplings (Ref. [4]).

Scalar meson constitution	$\frac{BR(\phi \to a_0\gamma)}{BR(\phi \to f_0\gamma)}$	Absolute ϕ branching ratios
naive $K\bar{K}$ molecule	1	$f_0 \simeq a_0 \simeq 4 \times 10^{-5}$
$q^2\bar{q}^2$: $K\bar{K}$-like "bag"	1	$< 10^{-6}$
$q^2\bar{q}^2$: $D\bar{D}$-like "bag"	9	$< 10^{-6}$
$q^2\bar{q}^2$: $(q\bar{q})(s\bar{s})$-like "bag"	–	$< 10^{-6}$
$(q\bar{q})^3P_0$: $f_0=1/\sqrt{2}(u\bar{u}+d\bar{d})$	–	$\leq 10^{-6}$
$(q\bar{q})^3P_0$: $f_0=s\bar{s}$	$\simeq 0$	$\simeq 1 \times 10^{-5}$
f_0 glueball, a_0 quarkonium	–	$\leq 10^{-6}$

In the TJNAF experiment, the ϕ mesons are produced by the bremsstrahlung photon beam of 1.6 GeV or higher in Hall B, using the reaction

$$\gamma p \to \phi p. \tag{2}$$

The minimum required primary electron beam energy is 4 GeV, but 6 GeV is preferred. The experiment requires an on-target photon flux of 5×10^7/s. Due to the photoproduction kinematics, ϕ's are strongly boosted in the forward direction so that a radiated photon in the subsequent $\phi \to X\gamma$ channel is an order of magnitude more energetic than when ϕ's are produced in a symmetric e^+e^- collision. The forward boost also increases the acceptances of all-neutral ϕ decay channels to about 50% and 35% for 3γ and 5γ states, respectively.

The experimental apparatus is placed in the Hall B alcove, 39 meters downstream from the bremsstrahlung radiator. The sensitive detectors are shielded from the background originating upstream by a compact 1 m $\times$ 1 m lead brick wall. The charged particle background is further suppressed by the upstream particle veto (UPV) and the charged-particle veto array (CPV). The UPV and CPV hodoscopes consist of differently sized scintillator paddles to equalize instantaneous background rates. The essential part of the level-1 trigger is the recoil proton detector (RPD), a polar array of ΔE–E plastic counters covering the forward angular range of 40°-60°. This detector is placed downstream of a 1.0 cm diam. $\times$ 2.5 cm cylindrical solid beryllium target.

The heart of the RadPhi detector is a 624-element lead glass calorimeter (Fig. 1). The design, construction and the performance of two smaller but similar prototype calorimeters are described in Ref. 5. The calorimeter energy resolution, as measured in commissioning runs, is 14 MeV at the nominal π^0 mass, Fig. 2. More detailed

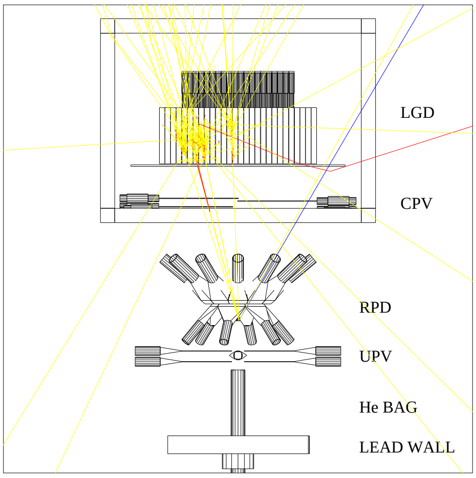

Fig. 1. The cross section of the GEANT *visualization of the RadPhi Detector. The lead brick shielding wall with the collimator and the background-reducing helium bag reaches the upstream charged particle veto. The scintillators of the recoil proton hodoscope surround the beryllium target. The segmented lead glass calorimeter, downstream charged particle veto and the monitoring system are enclosed in a light-tight box. The simulated $\phi \to \eta\gamma$ radiative decay trajectories are superimposed on the drawing.*

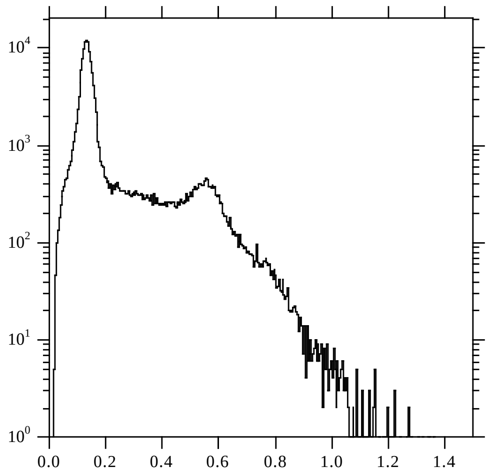

Fig. 2. Effective mass spectrum for two-cluster neutral events reveals π^0 and η peaks. Calibration of the modular lead-glass calorimeter requires that the π^0 peak be centered at the nominal π^0 mass. The resulting width of the π^0 peak is 14 MeV.

description of the detector components and the analysis of the test run data are given at the experiment URL site [6]. The level-1 trigger is defined by the coincidence of recoil proton signal and the tagger hit in the upper 20% energy range, in addition to the absence of charge particle veto signal:

$$\text{LEVEL-1 TRIGGER} = \text{RPD} \times \overline{\text{CPV}} \times \text{TAGGER}, \tag{3}$$

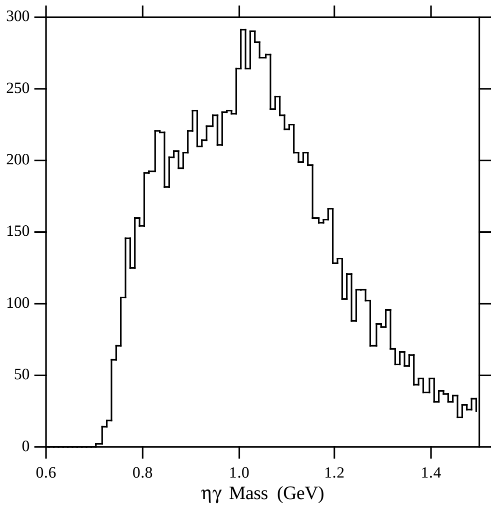

Fig. 3. The $\eta\gamma$ effective mass distribution: there is clear evidence for the $\phi \to \eta\gamma$ decay. The relative yield normalized to the observed number of the $\omega \to \pi^0\gamma$ decays is consistent with the known branching ratios and production cross sections.

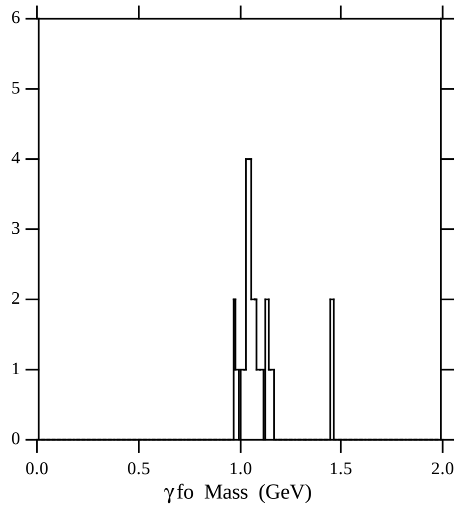

Fig. 4. The $\pi^0\pi^0\gamma$ effective mass spectrum constrained by the requirement that the dipion mass be consistent with the $f_0(980)$ meson ($0.88\ \text{GeV} \leq m_{\pi^0\pi^0} \leq 1.08\ \text{GeV}$).

while the level-2 trigger takes into account the total energy deposited in the LGD using the FASTBUS "Mass and Multiplicity" module [7].

Three engineering runs have been completed so far, with debugging and subsequent improving of the detector performance and with collection of more than 14M physics triggers. The physics results of the data analysis can be summarized as follows:

- bremsstrahlung beam profile extracted from the target scintillator scans matches the theoretical shape given by the zero-emittance electron beam,
- π^0 and η signals are clearly seen in the two-photon data sample,
- LGD calorimeter detector modules are calibrated to place the π^0 peak at its nominal mass,
- post-calibration η mass as well as π^0 and η mass resolutions agree well with the Monte Carlo simulation of the calorimeter response,
- $\omega \to \pi^0\gamma$ and $\phi \to \eta\gamma$ decays (Fig. 3) are seen in three-photon events and extracted relative yields are reasonable,
- $K_s^0 \to \pi^0\pi^0$ is observed in the four-cluster sample with the nominal K^0 mass,
- $\phi \to \pi^0\pi^0\gamma$ and $\phi \to f_0(980)\gamma$ (Fig. 4) are possibly seen in five-cluster events,
- six-cluster neutral events clearly show $\eta \to \pi^0\pi^0\pi^0$ decays where photons with energies down to 150 MeV can be reconstructed,
- $\omega \to \eta\gamma$ decay has not yet been observed.

TABLE 2. Yields of all-neutral ϕ radiative decay modes in a 30 day RadPhi experiment: Monte Carlo prediction of Ref. 10. Assuming a 2.5 cm *long* ^{9}Be *target, a* 5×10^{-35} m^2 *ϕ photoproduction cross section at 4* GeV *and* 5×10^7 *tagged bremsstrahlung photons per second, yields* 2.5×10^6 *ϕ's per day (n = photon multiplicity, ϵ =acceptance).*

Radiative decay	$10^6 \times BR$ (all decays)	$10^6 \times BR$ (neutral decays)	n	ϵ (%)	Yield (events)
$\pi^0\gamma$	1300	1300	3	35	45000
$\eta\gamma$	13000	5000	3	35	175000
$\eta'\gamma$	100	2	3	30	70
$a_0\gamma$	100	40	5	7	300
$f_0\gamma$	100	30	5	10	300

For the next physics run, we plan to upgrade the level-1 trigger to discriminate against the energy deposited in the four-cell lead-glass cluster [8]. The overall detector acceptance will also be increased by replacing the RPD hodoscope with the barrel-veto gamma (BVG) calorimeter [9]. The BVG detector is a medium-resolution spaghetti calorimeter equipped with a segmented scintillator hodoscope.

In the proposed configuration, it will enclose the target region, track charged particles, detect low-energy photons at large and backward polar angles and serve as a trigger for recoiled protons. The 30-day data taking run is planned early in the year 2000 with the full tagged-photon flux and the electron beam energy of 4 GeV or greater. Expected yields of all-neutral ϕ radiative decay processes are shown in Table 2.

Acknowledgements

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PROUČAVANJE RIJETKIH RADIJATIVNIH RASPADA ϕ U JEFFERSONOVOM LAB

Suradnja RadPhi predlaže upotrebu snažnog snopa označenih fotona u dvorani B u TJNAF za proizvodnju ϕ-mezona i mjerenje njihovih omjera grananja za raspade u konačna posve neutralna stanja. Usporedba omjera grananja ta dva načina raspada treba dati ključne podatke u strukturi $a_0(980)$ i $f_0(980)$ skalarnih mesona. Izvedena tri ispitna mjerenja pokazuju da se predloženim eksperimentom mogu opažati rijetki radijativni raspadi ϕ-mezona s omjerom grananja većim od 10^{-5}.