Next generation hypernuclear γ-ray spectrometer: Hyperball-J

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Abstract. The next generation hypernuclear γ-ray spectrometer, Hyperball-J, is described. Three of the key aspects in the array construction, namely geometrical configurations, cooling mechanism of Ge detectors, and Compton suppressors, are discussed. Results of simulation for planar and spherical arrangements are compared. Progresses in the development of pulse tube cooling system and PWO background suppression counters are reported.

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1 Introduction

A high precision Ge γ-ray spectrometer dedicated to hypernuclear experiments [1,2] at the J-PARC facility is in its developing and designing stage. The new Ge spectrometer, Hyperball-J, is the third generation array after its predecessors Hyperball [3] and Hyperball2 [2,4]. The array will have a large total photopeak efficiency of ∼6%. Combined with the intense beam provided by J-PARC, it would open new possibilities of studying hypernucleus via γ-γ coincidence technique and of probing Ξ^- atoms by detecting their X rays [5]. The current design, however, is more specifically motivated by the experimental conditions of the Day-1 hypernuclear γ-ray spectroscopy (E13) at J-PARC where mainly p-shell hypernuclei have been proposed for studies to investigate unsolved problems revealed by a series of Hyperball experiments thus far [1].

Hyperball-J is planned to consist of around thirty Ge detectors (70% relative efficiency [6]) surrounded by background suppressors. One of the important design criteria is a highly configurable detector array geometry such as to be optimized for varying beam intensities and limited space/geometry required by different experimental setups, while achieving a large total photo peak efficiency (5 ∼ 7%). Two different array configurations that are planar (wall) and spheroidal (ball) geometries are considered. Flexibility in the Ge detector arrangement can be realized with cooling of Ge crystals by a compact mechanical refrigerator under development in lieu of the present liquid nitrogen dewar. Moreover, mechanical cooling system that can attain lower Ge crystal temperature than that by liquid nitrogen cooling is important. Radiation damages on Ge detectors due to fast neutrons are expected to increase in the experiments at J-PARC, which deteriorate energy resolution. The effects of these damages have shown to be contained below certain Ge crystal temperature, to which the liquid nitrogen cooling fails to reach. Another key requirement in the Hyperball-J array is faster background suppression. PWO scintillators with their fast decay time are promising in place of BGO counters that cannot be used under high counting rates. However, the much smaller light yield of PWO material for a few hundred keV γ rays compared to BGO poses a challenge if used as Compton background suppressors.

2 Array geometry: planar vs. spherical

Both the wall and ball configuration, as shown in Fig. 1, are examined as possibilities for the Hyperball-J array. The wall configuration is made of parallel stacks of coaxial Ge detectors (see Fig. 1 (a)). A total of four rings that are perpendicular to the beam axis can be made so that Ge crystals do not shadow γ rays from a target position with

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Table 1. Array comparisons for three configurations together with two predecessors, Hyperball and Hyperball2. The simulated total photo peak efficiency is obtained for a point γ ray source.

	Hyperball	Hyperball2	Wall	Ball(30)	Ball(27)
Number of detectors	14	20	32	30	27
Number of Rings	3	3	4	3	3
Number of dets. per ring	4,6,4	6,8,6	6,10,10,6	10,10,10	9,9,9
Dist. to center (cm)	10/15	15	13<, <21	18, 19.5	16, 19
Solid angle (% of 4π)			35.4	26.8	27.0
Total photo peak efficiency for 1-MeV γ ray	2.3 (15 cm)	∼4	6.5	4.8	4.9
Peak to Total ratio with suppression (without)			0.39(0.20)	0.53(0.24)	0.54(0.23)
Detector angle			90±(20, 21, 29, 50, 62)	90±(0,23)	90±(0,35)

(a)

(b)

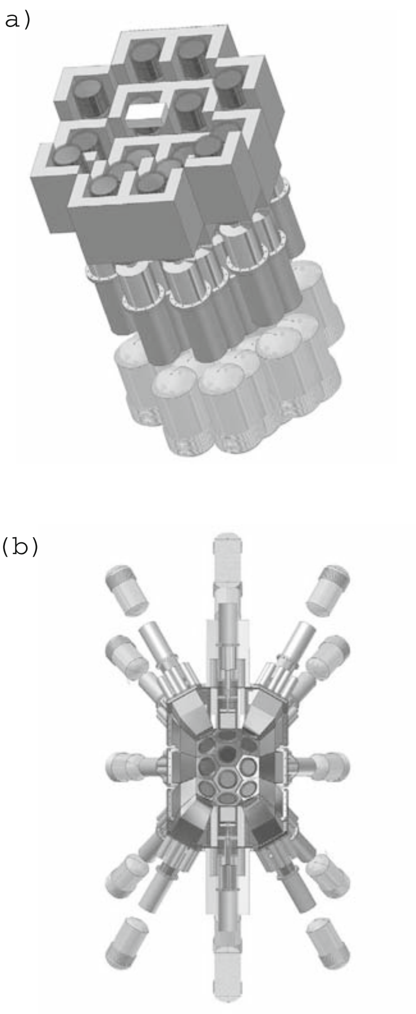

Fig. 1. Two configurations for the Hyperball-J array. Beam axis goes through the center from left to right. (a) Wall type. Half apparatus (lower part) is shown together with a target at the enter. (b) Ball type with 30 detectors (Ball(30) in Table 1).

respect to each other. On the other hand, the ball configuration (see Fig. 1 (b)) is comprised of three rings each having the same number of detectors whose cylindrical axis subtends to a center of sphere. The former configuration is relatively flexible allowing for various geometries that are optimal to specific experimental setups and conditions such as beam intensity, while the latter, though more conventional, cannot be easily altered once designed. Hence, two configurations of the ball type, which differ in distance from the detector end cap to the sphere center have also been considered. Comparison of the three configurations is listed in Table 1.

The quoted total photo peak efficiencies are the simulated values multiplied by a factor which allows to reproduce the measured efficiency for 1.33-MeV γ ray from ^{60}Co source placed 25 cm away from the end cap of Ge detector having 68% relative efficiency. In the wall configuration, eight pairs of detectors, whose end cap touch face to face when the two walls meet, are special. If γ rays incident on one of the paired detectors are Compton scattered and absorbed by the partner detector, photo peaks can be recovered by adding the partially deposited energies on each of the pairing detectors event by event. According to the simulation, these so called add-back events account for 2.4% of total events and adds 0.35% to the total photopeak efficiency for 1-MeV γ ray. This contribution is included in the value reported in Table 1. The advantage of the wall configuration is a large efficiency due to its close packed arrangement of a great number of Ge detectors. The number of Ge detectors in the ball configuration, on the other hand, is mainly determined by the sphere radius and the size of the suppressor. A gain in efficiency/solid angle of the array obtained by increasing the number of detectors is offset by a larger distance between the center and the detector surface as well as a larger area covered by the suppressors.

The difference between the two Ge detector arrangements is also reflected in background suppressor designs.

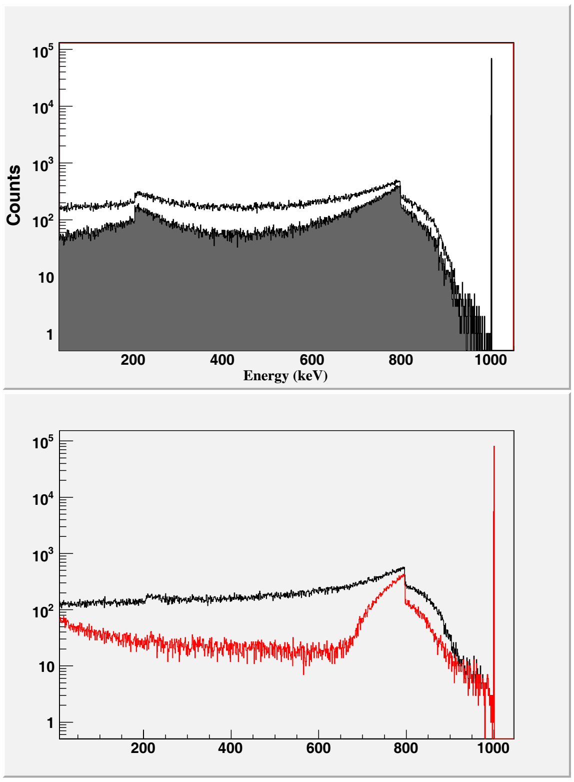

Fig. 2. Simulated Compton suppression spectra of 1 MeV γ ray for the two configurations for the Hyperball-J array. The wall (top) and the ball type with 30 detectors (bottom) are presented. PWO crystals with a thickness of 20 mm are considered. Spectra with and without suppression are shown as filled and un-filled, respectively.

There are four (L, W, U, ∞) and two (regular hexagon and irregular pentagon) shapes in background suppressors for the wall and the ball configuration, respectively. All suppressor types in the wall configuration consist of crystal pieces having an uniform dimension. In order to achieve the large solid angle, the middle piece is shared in the W and ∞ type suppressors which accommodate two detectors as shown in Fig. 1 (a). When there is a hit in the middle crystal and two sharing detectors are fired in coincidence, such an event is discarded. Then if one of the two Ge detectors is hit by one γ ray with a full energy absorption and the middle crystal is hit by a Compton escaped γ ray from the other detector, this event contributes to an accidental suppression. A simulated Compton suppressed spectrum for 1-MeV γ ray is shown in Fig. 2 (top). It can be noted that suppression at low energy is more effective in accord with L, W and U type suppressors that mostly see forward Compton scatted γ rays. For the ball configuration, all suppressor crystals must be tapered to tile a sphere of a given radius by a maximum number of Ge detectors. Due to irregular pentagonal shape of the suppressors, the total number of basic unit shapes of the crystals cannot be less than 5 for the ball array as opposed to 1 in the wall configuration. Putting these technicalities aside, as clearly demonstrated in Fig. 2 and by the simulated peak to total ratio for 1-MeV γ ray in Table 1, the ball configuration has a superior Compton background suppression factor over a wider energy range than the wall type.

3 Mechanical cooling of Ge detectors

Radiation damage of Ge crystals, which deteriorates detector performances, is one of the critical issues to be considered for a stable operation of the array throughout the duration of an experiment. Based on the experience with a kaon beam, a conservative estimate of a neutron flux is of the order of a few $10^8/\mathrm{cm}^2/1$ month run at J-PARC, which is a significant enough dose for Ge detectors to see the effect. Interaction of a fast neutron with a germanium atom results in dislocation of many other crystal atoms from the lattice and then in the creation of hole traps. This effect manifests as low energy tailing of γ-ray peaks in a spectrum due to incomplete charge collection of the holes produced by the absorbed γ ray. It has been shown in Ref. [7] that the effect of neutron damage on Ge detectors is very sensitive to Ge crystal temperature and that the effect could be minimised if the crystal is kept cold below 85 K. A conventional cooling of Ge crystal is done by liquid nitrogen (LN_2), normally stored in a dewar as a detector component. However, the lowest operating temperature of Ge detector that this cooling can reach is $\sim$ 90 K. Therefore, it is essential to develop an alternative to the LN_2 cooling for the Hyperball-J array.

Since April 2006, there has been an active development of mechanical cooling of Ge detectors under the Tohoku, KEK and Fuji Electric Systems Co. Ltd. collaboration. A pulse tube refrigerator manufactured by Fuji has been coupled to an ORTEC PopTop Ge detector (P type, resistive feedback, 30% relative efficiency) for a feasibility test. In general, mechanical cooling of Ge detectors with its moving components introduces microphonics noises, to which Ge detectors are notoriously sensitive, resulting in poor resolution. In this regard, the pulse tube has the biggest advantage because motions of solid pistons for expansion and contraction of He gas are replaced by virtual ones. In addition, this particular refrigerator, originally designed for use in space applications, is compact in size and requires no maintenance for 50,000 hours of operation (a warranted value). For the wall configuration, the quoted photo peak efficiency in Table 1 assumes the distance between the adjacent detectors be 130 mm. Hence, stacking of the detectors as shown in Fig. 1 can be realized only with a dewar/refrigerator diameter less than this length. Failure in satisfying such a requirement means a reduction in solid angle, i.e., in efficiency of the array.

During the first cooling of the detector, crystal temperature was successfully brought to 77 K, although the measured resolution in this condition was too poor to be used in experiments. In a further series of tests, the resolution degrading components have been identified and evaluated through combined measurements of γ rays from ^{60}Co source and pulser signals fed to the test input of a Ge detector to measure external noises. Then microphonics and electrical noise from the refrigerator system have been minimized with several modifications and improvements in the current cooling set up. As of this writing, a comparable energy resolution of 1.9 keV to that obtained by LN_2 cooling of 1.8 keV has been achieved, but at much higher temperature. Though this temperature is significantly higher than our goal of 85 K, the test results are encouraging. A further development is vigorously pursued at the present.

4 PWO background suppressors

Background suppressors in hypernuclear γ-ray spectroscopy are another important components of the Hyperball-J array. They function not merely as Compton suppressors, but also as detectors of high energy backgrounds. Electromagnetic showers from π^0, produced in $K^- \rightarrow \pi^- + \pi^0$ and $\Lambda \rightarrow n+\pi^0$, as well as penetrations of high energy charged particles show up as a huge continuous background in γ-ray spectra superimposed on Compton backgrounds from γ transitions of up to a few or several MeV. Because of its large effective atomic number, with a high absorption rate of γ rays, and a sufficient light yield, BGO scintillator has been widely used as a Compton suppression counters. In fact, it was the choice for the Hyperball and Hyperball2 array. It is necessary to set a discriminator threshold below single photoelectron in order to gain high detection efficiency and a good time resolution. However, BGO crystals have a long decay constant of 300 ns (see Table 2) which introduces a few μ second suppression dead time. Any subsequent γ rays detected on the same detector within this time could be accidentally suppressed (∼10% in the past experiments). At J-PARC, the dead time reaches 100% since the beam intensity is expected to be an order of magnitude larger.

Alternatives to BGO crystals are pure CsI and PWO detectors, both of which have decay constants of the order of 10 ns as compared in Table 2. Since the effective atomic number and the density are small for pure CsI, its radiation length is 1.7 times of that of BGO. Then a double thickness of CsI is required in order to achieve a comparable suppression factor of BGO counters. Due to the geometrical constraints of the planar configuration currently under study, the maximum allowable crystal thickness is 35 mm, while in the case of the spherical arrangement the limit is 20 mm. Therefore, pure CsI crystals can be used for the wall, but not for the ball configuration. PWO crystals, on the other hand, has a similar γ-ray absorption rate to that of BGO crystals. Thus they can be used as Compton suppressors, independent of the array configurations, provided that their small light yield could be overcome. To this end, several PWO crystals with various doping conditions have been tested with the aim of enhancing the light yield. Moreover, average number of photoelectrons for these crystals have been measured as a function of crystal temperature (20°C, 0°C, and -25°C). The measurements have shown that the light yield increases by four times when the crystals are cooled at -25°C compared to that at the room temperature. The necessity of cooling PWOs below 0°C adds complications to the practical designing of background suppressors. A few PWO cooling methods have been tried and are currently tested.

Table 2. Properties of scintillators as background suppressors.

Crystal	BGO $Bi_4Ge_3O_{12}$	PWO $PbWO_4$	CsI pure
Effective atomic number	75	76	54
Density (g/cm^2)	7.23	8.28	4.53
Decay constant (ns)	300	∼6	10/1000
Radiation Length (cm)	1.12	0.89	1.86
Light yield (NaI=100)	15	1	4/1

5 Summary

Two Hyperball-J array configurations for hypernuclear γ-ray spectroscopy at J-PARC have been proposed. The planar (wall) configuration is suited for experiments in which a large efficiency is required especially with low beam intensity. Also with its flexible geometry, the array can accommodate auxiliary detectors inside the array if necessary. Situations like these are anticipated for the Day-1 experiments. When a stable full intensity beam becomes available at J-PARC, the spherical (ball) configuration would be ideal with its superb background suppression capability. Thus, the two geometries are complementary. In addition to the novel planar array geometry, new developments have been undertaken. Mechanical cooling of Ge crystals without resolution deterioration paves a way to a stable and longer continuous operation of Ge detectors under sever radiation damaging environment. Furthermore, its compact design is a key to make the wall configuration possible. PWO background suppressors replacing BGO counters with long decay constant have been found functional if the crystals are doped and cooled in order to achieve increased light yield.

References

1. H. Tamura *et. al.*, `http://j-parc.jp/NuclPart/pac_0606/pdf/p13-Tamura.pdf`.
2. H. Tamura *et. al.*, these proceedings.
3. O. Hashimoto, H. Tamura, Prog. Part. Nucl. Phys. **57** (2006) 564-653.
4. Y. Ma *et. al.*, these proceedings.
5. K. Tanida *et. al.*, these proceedings.
6. Knoll, *Radiation detection and measurement* (John Wiley and Sons, New York 1979) p. 457.
7. E. Hull *et. al.*, IUCF Annual Rep. (1992-93) 143.