Spin determination of particle unstable levels with particle correlations

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Particle correlation functions from central $^{129}$Xe+$^{197}$Au collisions at 50A MeV have been measured with a large area silicon-strip/ CsI detector array. A new technique of spin determination from particle correlation functions is proposed. Two examples of correlation functions are studied. The spin of the first excited level of $^8$B at 0.774 MeV is determined as $J=1$.

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Experiments with rare isotope and with stable beams offer important opportunities to explore the structure of nuclei near and beyond the proton and neutron drip lines. This structure information includes the energies, spins, and parities of nuclear levels near the drip line as well as the probabilities for their formation and decay; such information guides theoretical modeling of the interactions and dynamics within neutron-rich or neutron-deficient drip-line nuclei. Examinations of compilations of nuclear levels reveal that spins of nuclear levels in nuclei near the drip lines are often unknown [1], reflecting the inability of extracting such information via transfer or knockout reactions with unpolarized beams or targets.

In this paper, we propose a new method for nuclear spin determination. We note that central nucleus-nucleus collisions populate much of the many-body phase space collisions broadly, and limited phase space regions far from the entrance channel may be populated uniformly. In central $^{129}$Xe+$^{197}$Au collisions, for example, this implies that the probability of exciting a given nuclear “fragment” such as $^8$B to its first excited level with spin $J$ will be proportional to the $m$-level degeneracy $2J+1$ of that level, providing sensitivity to the spin $J$. In this paper, we show how this spin can be quantitatively determined by comparisons to equilibrium correlation functions and extract the spin of the first excited level of $^8$B.

We report measurements of correlations between charged particles emitted in $^{129}$Xe+$^{197}$Au collisions at $E/A = 50$ MeV that were conducted at the National Superconducting Cyclotron Laboratory of Michigan State University. The data were measured with a large area silicon-strip/ CsI detector array (LASSA), which provided very good energy, angular and isotope resolution for charged particles [2,3]. The LASSA was centered at a polar angle of 30° with respect to the beam axis, covering polar angles of 12° $\equiv \theta \equiv 62°$. Impact parameters were selected by the multiplicity of charged particles, measured with LASSA and the Miniball/Minivall array [4]; the combined apparatus covered 80% of the total solid angle. Reduced impact parameters of $b/b_{\text{max}} < 0.3$ were selected for central collisions.

Correlation functions have been used to measure distant astronomical objects [5] and source sizes [6–12] and freeze-out conditions [13–16] for nucleus-nucleus collisions. Experimentally the two particle correlation function may be defined as follows:

$$\sum Y_{12}(\vec{p}_1, \vec{p}_2) = C [1 + R(E_{\text{rel}})] \sum [Y_1(\vec{p}_1) Y_2(\vec{p}_2)].$$

where $Y_{12}$ is the two particle coincidence yield of a given pair of particles with their individual momenta $\vec{p}_1$ and $\vec{p}_2$, respectively, and the $Y_i(\vec{p}_i)$ are the single particle yields for the two particles measured under the same impact parameter selection but not in the same event. The summations on both sides of the equation run over pairs of momenta $\vec{p}_1$ and $\vec{p}_2$ corresponding to the same bin in relative energy $E_{\text{rel}}$. The correlation function describes how the correlation between interacting particles measured in the same event differs from the underlying two particle phase space. This phase space can be modeled by mixing the single particle distributions of particles from two different events. The correlation constant $C$ is typically chosen so that $R(E_{\text{rel}})=0$ at large relative energies where the correlations due to final state interactions and quantum statistics can be neglected. If the yields are normalized to the appropriate differential multiplicities, $C$ will be of order unity.

Theoretical techniques have been developed to calculate correlation functions for dynamical [10,12] or statistical [17–19] emission and to invert correlation functions to extract the sources of particle emission [11,12]. For correlations that sample phase space far from the entrance channel, the equilibrium limit [19] of the correlation function becomes especially relevant. For this one needs to consider the modifications of the two particle phase space by the long range Coulomb and short range nuclear interactions. Within a simplified geometry wherein the center of mass of a pair of spinless particles with charges $Z_1$ and $Z_2$ is at the center of a
where $Z_1$ and $Z_2$ are the two charges and $V$ is the volume of the source. The integral in Eq. (2) over the distribution of relative separations for the two decay products within the source displays a minimum at small relative energy, whose width depends on the source size. The detailed distribution over the source volume may depend on particle type. If these distributions are not at the focus of interest, it is more straightforward to parameterize this background contribution by an empirical expression [13,21]

$$1 + R_{\text{Coal}} = 1 - \exp[-(E_{\text{rel}}/E_c)^\alpha],$$

which vanishes at zero relative energy and reaches unity at large relative energy. We use this expression in the following analysis.

The interesting signal from the decay of particle unbound states, can be described using a formalism for the second analysis. The interesting signal from the decay of particle unbound states, can be described using a formalism for the second analysis. Given this relationship, we obtain a practical expression for the correlation function as a function of relative energy $E_{\text{rel}}$ [19,21]

$$1 + R(E_{\text{rel}}) = 1 + R_{\text{Coal}}(E_{\text{rel}}) + R_{\text{nuc}}(E_{\text{rel}})$$

where

$$R_{\text{nuc}}(E_{\text{rel}}) = \frac{1}{(2S_1 + 1)(2S_2 + 1)} \frac{h^3}{4 \pi V_{\mu} \sqrt{2 \mu E_{\text{rel}}}} e^{-E_{\text{rel}}/T_{\text{eff}}}$$

$$\times \frac{1}{\pi} \sum_i (2J_i + 1) \frac{\Gamma_i/2}{(E_{\text{rel}} - E_i)^2 + \Gamma_i^2/4} (\text{B.R.}),$$

(6)

where the derivative of the nuclear phase shift is approximated by its Breit-Wigner form, and B.R. is the branching ratio for decay to the measured channel. As the detection efficiency effects influence both the left- and right-hand sides of Eq. (1) in the same manner, efficiency effects are divided out in the correlation function. Thus, Eq. (6) can be folded with the experimental resolution and compared directly to data.

The correlation function depends on the spin of each level [see Eq. (6)]. It also depends on the freezeout volume $V_f$, the effective temperature $T_{\text{eff}}$, and the shape of the Coulomb correlation function. The term involving the effective temperature $T_{\text{eff}}$ does not originate from equilibrium thermodynamics [19]. Instead, it can be understood as an empirical correction [21,23] for collective expansion or rotation of the emitting source [24,25], which influences strongly the background term in the denominator of the correlation function when the two particles (from different events) originate from regions having very different collective velocities [23]. The effects of collective motion are well described for various particle correlations in this experiment by assuming $T_{\text{eff}} = 7$ MeV [21,23]. In our case where we are mainly interested in resonance levels near the threshold, i.e., $E_{\text{rel}} \leq 2$ MeV, the uncertainty of the correlation $R_{\text{nuc}}$ caused by the uncertainty of $T_{\text{eff}}$ (i.e., varying between 5 and 10 MeV) is less than about 10%.

Similarly, by examining the $p^6\text{Li}$ and $p^8\text{Li}$ correlations whose Coulomb correlation functions should be similar to $p^7\text{Li}$, one can extrapolate to the background of the $p^7\text{Li}$ correlation function. This procedure yields parameters $E_c = 0.16$ MeV and $\alpha = 0.5$ and the result shown by the dashed line in the upper panel of Fig. 1 [21]. Best fit values for $V_f$ varied by 30–50% for the proton decays discussed here, reflecting variations in the secondary feeding contributions to both numerator and denominator, which are not included in the simple equilibrium expression. Weisskopf and Hauser-Feshbach calculations predict that, to a good approximation,
the resonant levels are fed in proportion to their spin degeneracies. One constrains the overall magnitude of these corrections, by fitting the correlation function in regions where other levels with known spins and decay branching ratios contribute. The sensitivity to the spin of the resonant levels in this approximation remains as described by Eq. (6).

We now demonstrate how these parameters can be constrained to allow one to determine the spin of a nuclear level for the simple case of $^8$Be. This is an ideal test case because the structural information of $^8$Be is quite complete. The pronounced proton-$^7$Li resonance levels shown in Fig. 1: 17.64 MeV 1$^+$, 18.15 MeV 1$^+$, 18.91 MeV 2$^-$, 19.07 MeV 3$^+$, and 19.24 MeV 3$^+$ [26] are very close to the threshold and easy to analyze. For the proton decay branching ratios of these levels, one has a 100% decay branch to the mirror nucleus $^7$Li. Figure 2 shows two prominent peaks at 19.07 MeV 3$^+$, and 19.24 MeV 3$^+$.

Surprisingly, the spin of this level has not been assigned due to its astrophysical importance to the solar neutrino problem.

Recent calculations in Ref. [28] predict a 1$^+$ level of $^8$Ba at 1.4 MeV, however. In the right panel of Fig. 2, the three resonances including the one at 1.4 MeV are included in the fit. The background (dashed line) is shallower than that of the previous fit to accommodate the additional 1.4 MeV resonance. The present LASSA excitation energy resolution, which broadens the line shape 0.774 MeV level, prevents us from placing stringent constraints on the Coulomb correlation function and, consequently, we cannot confirm or deny the existence of the 1.4 MeV resonance using our data. Even when 1.4 MeV resonance is included in the fit, however, we obtain a spin value $J_1=0.95\pm 0.33$ for the 0.774 MeV level. Thus the spin of the first level at 0.774 MeV is confirmed to be $J_1=1$ whether or not an excited level is present at 1.4 MeV.

We note that the yield of all levels should follow Eq. (6) in the equilibrium limit. Even for other reactions where non-equilibrium effects cannot be neglected, there should be a resonance observed at the location of every level predicted by Eq. (6). We note that the 1.4 MeV level was clearly not observed in the correlation function measurements of Ref. [13] that utilized a higher resolution array. Thus, one can conclude without ambiguity that this proposed state does not exist. We cannot presently rule out higher energy levels above the 2.32 MeV level. Measurements with better statistics using an experimental setup with better resolution should clarify this point.

In summary, the equilibrium approach was used to determine the spins of particle unstable levels. The sensitivity to spin determination of this procedure is illustrated in the $p^{-}\neg{}^7$Li correlation function where three groups of resonances are fitted. By fitting the $p^{-}\neg{}^7$Be correlation function, the spin value of the 0.774 MeV level of $^8$B is determined to be one, regardless of the existence of a proposed $J=1$ state at 1.4 MeV. Applying our techniques to the data Ref. [13] permit the latter level to be ruled out. We believe the
present techniques can provide a powerful new tool to establish the existence of particle unbound levels and determine their spins.

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