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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 $12° \leqslant \theta \leqslant 62°$. Impact parameters were selected by the multiplicity of charged particles, measured with LASSA and the Miniball/Miniwall array [4]; the combined apparatus covered 80% of the total solid angle. Reduced impact parameters of $b/b_{\max}<0.3$ were selected for central collisions.

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

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

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_{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 volume V, an expression for the Coulomb correlation function $1+R_{\mathrm{Coul}}$ may be obtained from semiclassical theory as follows [20,21]:

$$1 + R_{\mathrm{Coul}}(q) = \frac{1}{V}\int_V d^3r \sqrt{1 - \frac{Z_1 Z_2 e^2}{r E_{\mathrm{rel}}}}, \tag{2}$$

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]

$$1 + R_{\mathrm{Coul}} = 1 - \exp[-(E_{\mathrm{rel}}/E_c)^{\alpha}], \tag{3}$$

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 virial coefficient [22]. Taking the spin of the particles and resonances into account, the two particle phase space of relative motion becomes [19]

$$\frac{dn_{12}}{d^3\vec{q}} = \frac{(2S_1+1)(2S_2+1)V_f}{h^3}(1 + R_{\mathrm{Coul}}) + \frac{1}{4\pi^2 q^2}\sum_{J,\ell}(2\ell+1)\frac{d\delta'_{J\ell}}{dq}, \tag{4}$$

where V_f is the free (unoccupied) volume of the system.

Given this relationship, we obtain a practical expression for the correlation function as a function of relative energy E_{rel} [19,21]

$$1 + R(E_{\mathrm{rel}}) = 1 + R_{\mathrm{Coul}}(E_{\mathrm{rel}}) + R_{\mathrm{nuc}}(E_{\mathrm{rel}}) \tag{5}$$

where

$$R_{\mathrm{nuc}}(E_{\mathrm{rel}}) = \frac{1}{(2S_1+1)(2S_2+1)}\frac{h^3}{4\pi V_f \mu\sqrt{2\mu E_{\mathrm{rel}}}}e^{-E_{\mathrm{rel}}/T_{\mathrm{eff}}} \times \frac{1}{\pi}\sum_i (2J_i+1)\frac{\Gamma_i/2}{(E_{\mathrm{rel}}-E_i^*)^2+\Gamma_i^2/4}(\mathrm{B.R.}), \tag{6}$$

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_{eff}, and the shape of the Coulomb correlation function. The term involving the effective temperature T_{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 $T_{\mathrm{eff}}=7$ MeV [21,23]. In our case where we are mainly interested in resonance levels near the threshold, i.e., $E_{\mathrm{rel}} \leqslant 2$ MeV, the uncertainty of the correlation R_{nuc} caused by the uncertainty of T_{eff} (i.e., varying between 5 and 10 MeV) is less than about 10%.

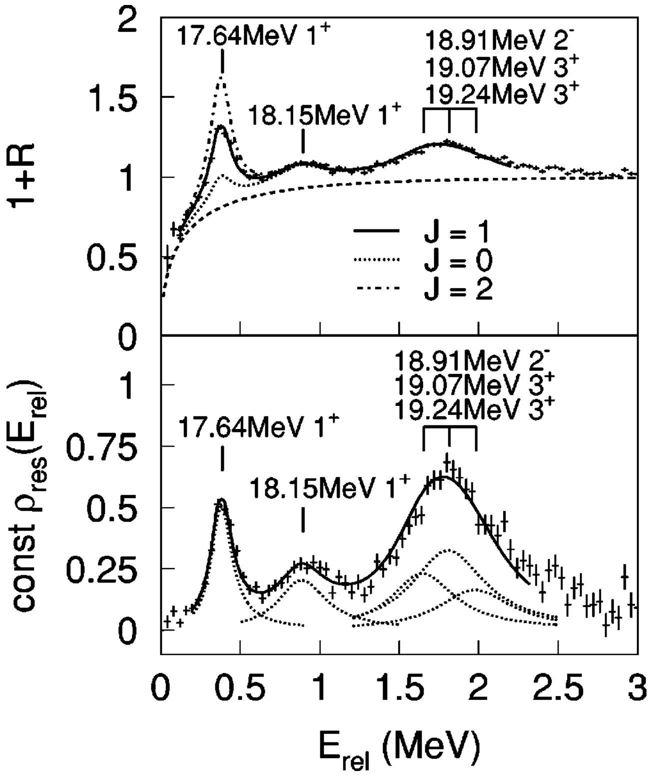

FIG. 1. In the lower panel the density profile of the resonances of ^{8}Be is shown for the p-^{7}Li correlation after subtracting the background shown as the dashed line in the upper panel. The best fit (solid line) is performed by varying the background and the spin value of the 17.64 MeV state. Two calculations are shown as the dotted and dot-dashed lines in the upper panel assuming that the spin of the 17.64 MeV state is 0 and 2, respectively, and keeping the other parameters the same.

Similarly, by examining the p-^{6}Li and p-^{8}Li correlations whose Coulomb correlation functions should be similar to p-^{7}Li, one can extrapolate to the background of the p-^{7}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 ground state level of ^{7}Li for the 17.64 MeV level, 96% g.s. (ground state) and 4% first excited state (0.478 MeV) decay branches for the 18.15 MeV level, 86% g.s. branch for the 18.91 MeV level, 100% g.s. branch for the 19.07 MeV level and 50% g.s. branch for the 19.24 MeV level [26]. Using this spectroscopic information, the correlation function was fitted by fixing $T_{\text{eff}}=7$ MeV and varying Coulomb background [Eq. (3)], the freezeout volume V_f and the spin value of the 17.64 MeV level as free parameters.

Figure 1 shows the best fit (solid line), which occurs for a background with parameters of $E_c=0.152$ MeV and $\alpha=0.547$, $V_f \approx 10^4$ fm^3 and a spin value of 1.06 ± 0.1. To illustrate the sensitivity of this technique to the spin determination, calculated correlations (dotted and dot-dashed lines) are shown in Fig. 1 assuming that the spin of the 17.64 MeV level is 0 and 2, respectively. The significant separation of $J=0.2$ calculations from the $J=1$ fit shows a strong sensitivity to the spin that the fit provides. The description provided by the fit for the levels themselves is shown more sensitively in the lower the panel of Fig. 1 where the corresponding density of resonances [defined by the second term on the r.h.s. of Eq. (4)] is plotted. The dotted lines represent the individual resonance levels and the solid line is the convoluted fit by applying the known structural information of these resonances. The fit is good everywhere except at the high energy end where the contributions from higher lying levels are not included due to incomplete spectroscopic information.

We now turn our attention to the first excited level of ^{8}B at 0.774 MeV. This nucleus has been studied extensively due to its astrophysical importance to the solar neutrino problem. Surprisingly, the spin of this level has not been assigned due to lack of a suitable experimental technique [26,27]. However, it is often assumed to be the 1^+ analog of the 17.64 MeV level in ^{8}Be [26] and of the first excited level in the mirror nucleus ^{8}Li. Figure 2 shows two prominent peaks in the proton-^{7}Be correlation function corresponding to the first excited level of ^{8}B at 0.774 MeV and the 3^+ level at 2.32 MeV, respectively [26]. If we assume that only two levels (at 0.774 and 2.32 MeV) exist in the region of interest with 100% g.s. proton decay branches, we obtain the solid line in the left panel of Fig. 2 as the best fit, the dashed line as the Coulomb background and a spin value of $J_1=0.98\pm0.29$. The result confirms the suggested spin assignment from the mirror nucleus.

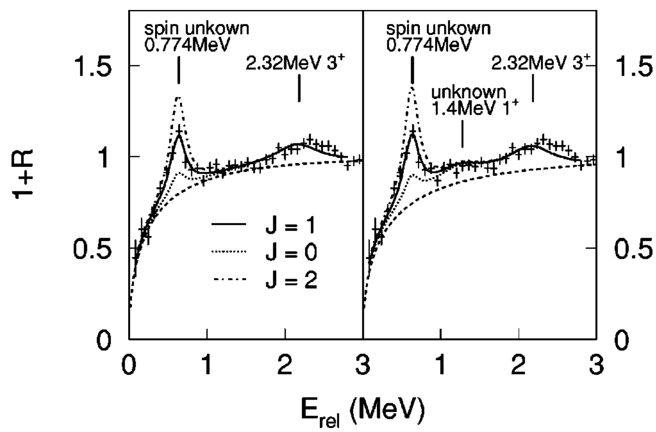

FIG. 2. In the left-hand side panel the p-^{7}Be correlation function is fitted by the solid line assuming there are only two states at 0.774 and 2.32 MeV. The dashed line is the fitted background. The dotted and dot-dashed lines are the calculations assuming that the spin of the 0.774 MeV state is 0 and 2, respectively. In the right-hand side panel similar fits are done assuming the existence of an additional state at 1.4 MeV.

Recent calculations in Ref. [28] predict a 1^+ level of ^{8}B 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 $J_1=0.95\pm0.33$ for the 0.774 MeV level. Thus the spin of the first level at 0.774 MeV is confirmed to be $J=1$ 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 nonequilibrium 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-^{7}Li correlation function where three groups of resonances are fitted. By fitting the p-^{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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