Production and spectroscopy of the neutron-rich nucleus ^{166}Dy

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Yrast states up to spin 16$\hbar$ in ^{166}Dy were observed, for the first time, using a quasielastic neutron-transfer reaction in the bombardment of ^{118}Sn with ^{164}Dy at $E_{\mathrm{lab}}=790$ MeV. The ratio of the ^{166}Dy production cross section relative to the inelastic cross section, integrated over the c.m. scattering angle range 110° to 140°, is ≈ 0.0027. This experiment demonstrates that the improved sensitivity, provided by the new generation of highly segmented 4π γ-ray arrays coupled to a 4π heavy-ion detector array, makes subbarrier heavy-ion-induced nucleon-transfer reactions a powerful probe of the structure of neutron-rich nuclei at moderately high spin. A comparison with the production of ^{164}Dy in the reaction between ^{118}Sn and ^{162}Dy is made. [S0556-2813(98)03506-7]

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Weakly bounded neutrons in neutron-rich nuclei may have interesting implications for nuclear structure, such as possible modifications of shell structure and new modes of excitation. Unfortunately, very little is known about the nuclear spectroscopy of neutron-rich nuclei due to the paucity of reactions populating such nuclei. There are several avenues for producing neutron-rich nuclei, such as nucleus fragmentation at intermediate or high energy [1], fission fragmentation by either spontaneous or induced fission [2–5], and deep-inelastic reactions [6,7]. Heavy-ion induced multinucleon transfer reactions have been mentioned as an alternative for producing neutron-rich nuclei, especially for nuclei with masses heavier than 160 [8–10]. However, the combination of stable projectiles and stable targets has unfavorable kinematic matching conditions for transfer reactions leading to heavy neutron-rich nuclei. The resultant small cross sections have limited its use for populating neutron-rich nuclei. The new generation of highly segmented $\sim 4\pi$ γ-ray detector arrays, such as Gammasphere and Euroball, provide a significant improvement in sensitivity and selectivity for detecting high-fold γ-ray events, making it possible to study reaction channels with very small production cross sections. This opens the possibility of accessing and searching for new structure phenomena in neutron-rich nuclei. This paper reports that the sensitivity achieved using such detectors provides a powerful new probe of neutron-rich nuclei. In particular, the quasielastic two-neutron transfer reaction, at near-barrier energies, has been used to study the yrast spectroscopy of the neutron-rich nucleus ^{166}Dy.

Experiments were carried out at the 88-Inch Cyclotron facility of Lawrence Berkeley National Laboratory by bombarding ^{118}Sn with ^{162}Dy at $E_{\mathrm{lab}}=780$ MeV and ^{164}Dy at $E_{\mathrm{lab}}=790$ MeV. The primary experiment ran ~ 66 h of ^{162}Dy beam on target with intensity ~ 1 particle nA while the secondary experiment, performed as a systematic comparison, ran only ~ 4 h of ^{164}Dy with intensity ~ 0.6 particle nA. The target was made by evaporating ^{118}Sn onto a carbon foil of 20 μg/cm^2 plus an overcoating of 6 μg/cm^2 aluminum. The target thickness is ~ 250 μg/cm^2 with an enrichment 99.975% of ^{118}Sn and less than 10^{-4} contamination level for neighboring tin isotopes. Both the scattered Dy-like and the recoiling Sn-like particles were detected by an array of position-sensitive avalanche counters, CHICO [11], in coincidence with the detection of γ rays by Gammasphere consisting of 100 Ge detectors. The highly segmented CHICO, covering a solid angle of $\sim 68\%$ of 4π, obtains a position resolution better than 1° in θ and 9° in ϕ relative to the beam axis and a time resolution of about 500 ps. A total of 700 M events were collected for the experiment using a ^{162}Dy projectile and 23 M events were collected for the experiment with ^{164}Dy. About 4% of the total events have a γ-ray fold of 3 or more.

For a binary reaction, the simultaneous measurement of the scattering angles of both reaction products, plus time-of-flight difference, allows reconstruction of the kinematics and the deduction of the reaction product masses, velocity vectors, and Q value. A mass resolution of about 8 u was obtained for the position and time resolution mentioned earlier. The Q value, calculated assuming the final masses equal the initial masses, is shown in Fig. 1 for both inelastic and the two-neutron transfer (^{166}Dy) channels for the reaction between ^{118}Sn and ^{164}Dy. The Q-value resolution is about 19 MeV for the inelastic channel integrated over the c.m. angles from 110° to 140°.

With the achieved mass resolution, the projectilelike and targetlike particles were unambiguously identified, and the Doppler-shift corrections were applied accordingly on an event-by-event basis, resulting in a γ-ray resolution of about 1%. This provided unambiguous assignments of observed γ-ray transitions to either of the reaction partners. From the Doppler-shift corrected γ-ray spectrum for both Dy-like and Sn-like nuclei, many nucleon-transfer channels, including up to four-neutron transfer, were identified by threefold or higher γ-ray events and the cross correlations between Sn-like and Dy-like deexcitation transitions. Examples are shown in Fig. 2 where the excitation of ^{166}Dy, populated by the two-neutron transfer channel for the reaction between

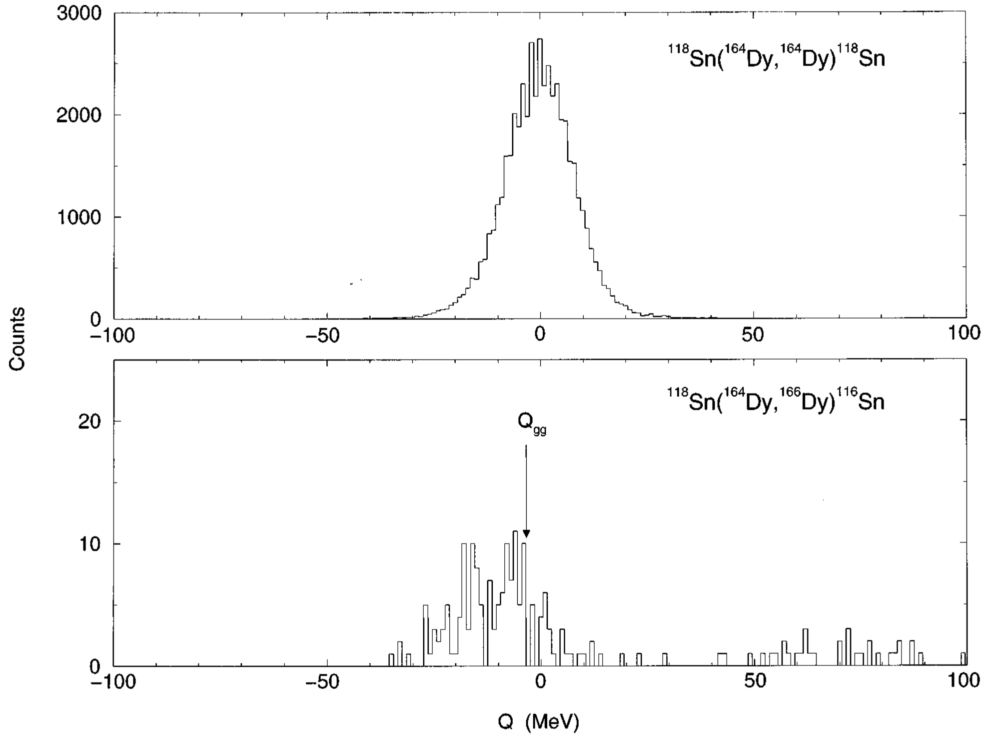

FIG. 1. The measured Q values for the inelastic (upper) and two-neutron transfer (lower) channels for the reaction between ^{118}Sn and ^{164}Dy at the c.m. angle between 110° and 140°.

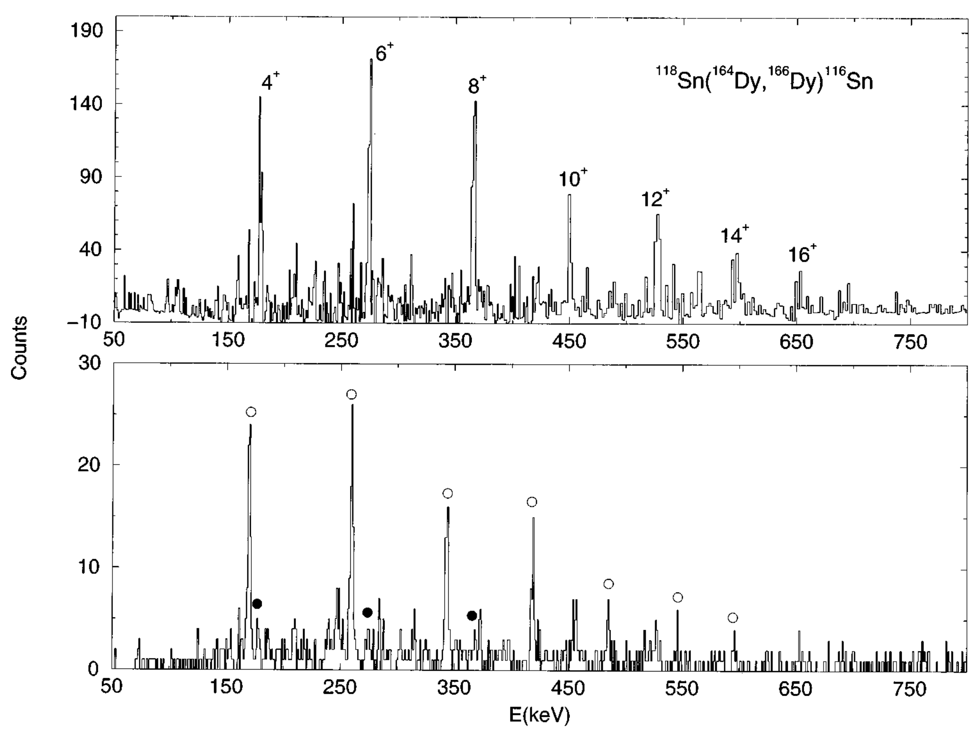

FIG. 2. Yrast transitions of ^{166}Dy from the reaction between ^{118}Sn and ^{164}Dy. Triple or higher coincidence data are shown in the upper figure and the labeled numbers are spins for the $I \rightarrow I-2$ transitions. The lower figure is resulting from the cross correlation in double or higher coincidence data by gating on the $2^+ \rightarrow 0^+$ transition of ^{116}Sn without a background subtraction. The filled circles indicate the transitions of ^{166}Dy while the open circles are for ^{164}Dy.

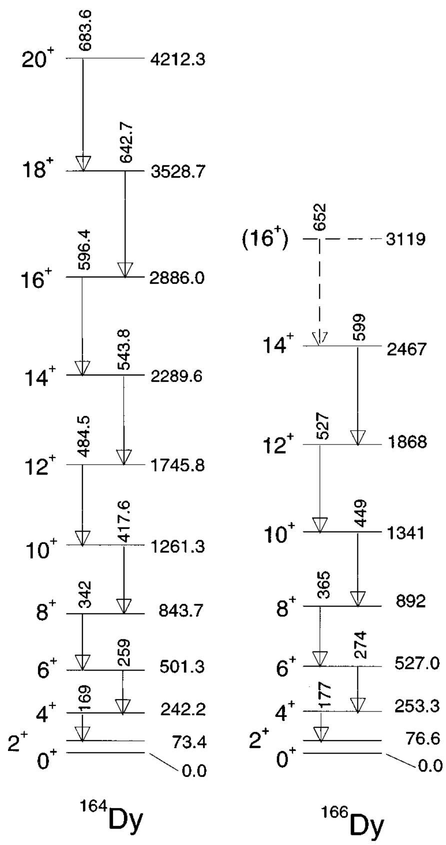

FIG. 3. Partial level schemes for ^{164,166}Dy.

^{118}Sn and ^{164}Dy, is identified through double gating on ^{166}Dy γ rays (upper) and single gating on the $2^+\rightarrow 0^+$ transition of ^{116}Sn (lower). The yrast transitions of ^{166}Dy, which were observed up to spin $6\hbar$ previously via the ^{165}Dy(n,γ) reaction [12], have been extended to spin $16\hbar$ with the limited statistics obtained from this brief experiment. The derived partial level scheme is shown in Fig. 3. In our high statistics study of the ^{118}Sn(^{162}Dy,^{164}Dy)^{116}Sn two-neutron transfer reaction, the yrast states for ^{164}Dy were extended from the previous known $14\hbar$ [13] to spin $20\hbar$. The deduced level scheme is shown in Fig. 3 while the γ-ray spectra are shown in Fig. 4.

The quasielastic nature for the production of these neutron-rich nuclei is evident from the measured Q value (see lower part of Fig. 1) where an excitation energy of about 7–8 MeV is indicated. The production cross sections were measured from the yields of the $8^+\rightarrow 6^+$ transition of Dy-like nuclei by double gating on both the $4^+\rightarrow 2^+$ and $6^+\rightarrow 4^+$ transitions in threefold or higher γ coincidence data. These cross sections relative to the inelastic cross sections are shown in Table I. The data were integrated over the c.m. angles between 110° and 140° which is near the grazing angle. The spin distribution based on the γ-ray yields is nearly the same for both the transfer channel and inelastic channel. This indicates that the γ-ray multiplicity is similar for both channels and thus the above approach is justified [14]. The production of Dy neutron-rich nuclei for both cases is about 0.002–0.003 of the total cross section and is about 0.25 of that for neutron-deficient nuclei where the kinematic

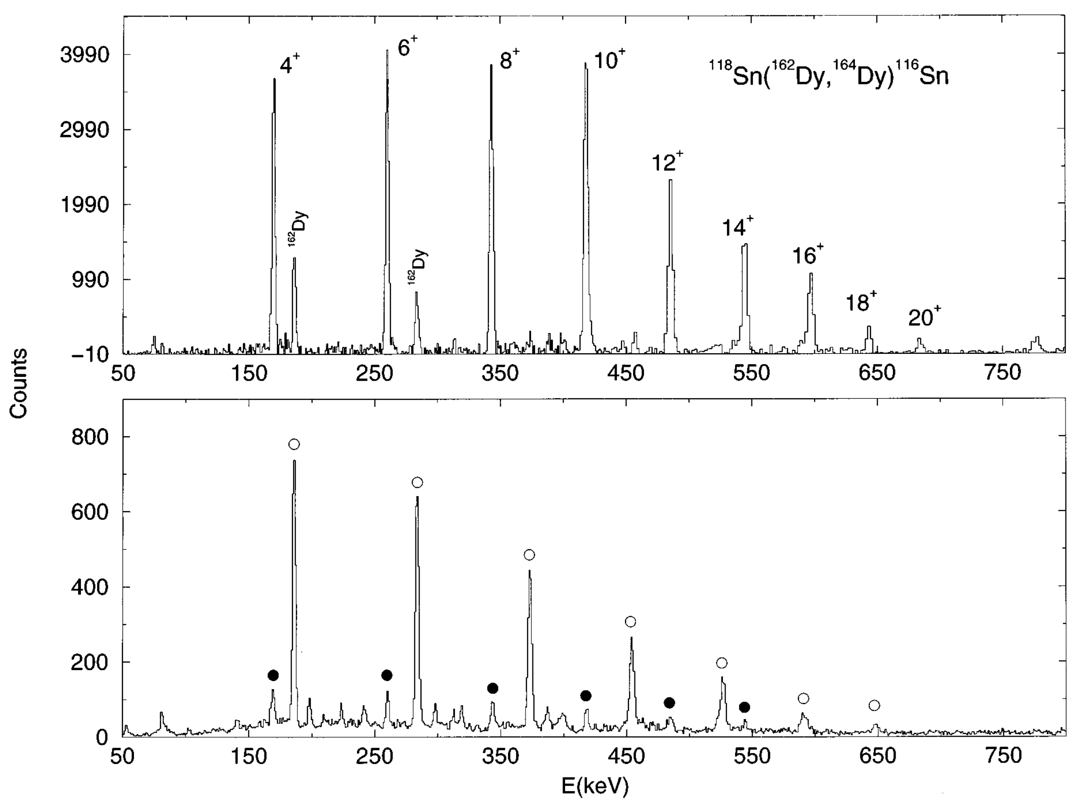

FIG. 4. Yrast transitions of ^{164}Dy from the reaction between ^{118}Sn and ^{162}Dy. Triple or higher coincidence data are shown in the upper figure and the labeled numbers are spins for the $I\rightarrow I-2$ transitions. The lower figure is resulting from the cross correlation in double or higher coincidence data by gating on the $2^+\rightarrow 0^+$ transition of ^{116}Sn without a background subtraction. The filled circles indicate the transitions of ^{164}Dy while the open circles are for ^{162}Dy.

TABLE I. Ground state Q_{gg}(MeV) values and probabilities (in parenthesis) for various neutron-transfer channels between ^{162,164}Dy and ^{118}Sn.

Projectile	Projectilelike nuclei ^{160}Dy	^{162}Dy	^{164}Dy	^{166}Dy
^{162}Dy	0.9	0.0	-2.3	
	(0.0065)	(1.0)	(0.0019)	
^{164}Dy		1.7	0.0	-3.5
		(0.011)	(1.0)	(0.0027)

matching condition is more favorable. This production cross section ratio is very similar to that obtained for deep-inelastic reactions [7] leading to neutron-rich nuclei. However, it is important to note that, relative to the deep-inelastic reaction, the quasielastic reaction mechanism in the sub-barrier regime brings in much less excitation energy and produces much cleaner γ-ray spectra [8–10]. The sensitivity for this experimental setup can be gauged by the observation of ^{158}Dy, which has a production probability of $\sim 5\times 10^{-5}$. For cases having more optimal kinematic matching conditions, it is possible, with this sensitivity level, to use either neutron or proton transfer reactions to study neutron-rich nuclei up to four neutrons away from the stability line with masses heavier than 160.

The moment of inertia for ^{166}Dy, together with those from ^{160,162,164}Dy, are shown in Fig. 5. This figure also includes the inelastic data where the ground-band transitions up to spin $24\hbar$ and $22\hbar$ were observed for ^{162}Dy and ^{164}Dy, respectively [14]. One notable feature is the flatness of the moment of inertia as a function of rotational frequency for ^{166}Dy relative to that of neighboring nuclei. The same phenomenon was observed for the neutron-rich nucleus ^{178}Yb populated to spin $12\hbar$ via the deep-inelastic reaction [7] and was interpreted as due to a smaller interaction strength, relative to that of the lighter Yb nuclei, between the ground band and the S band. This interaction strength, deduced from the measured decay branching ratios of the state at spin $18\hbar$ of the S band [14], is weak; that is, about 10 keV for ^{162}Dy and also is weak for ^{164}Dy from a systematic study of this region [15]. According to these systematics, an apparent even weaker interaction strength in ^{166}Dy, relative to that of

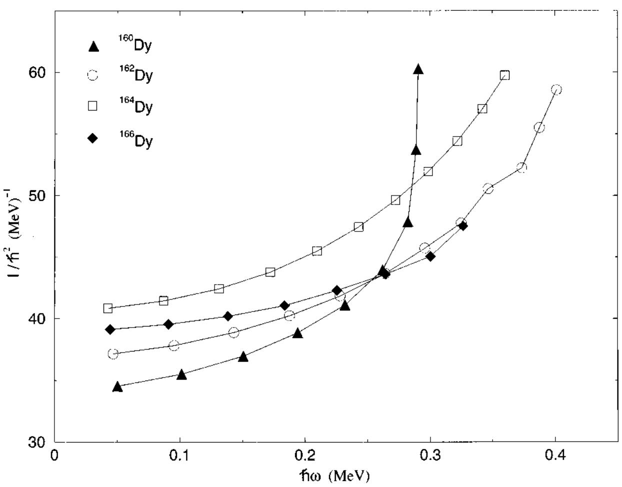

FIG. 5. Moment of inertia for ^{160,162,164,166}Dy.

^{162,164}Dy, is an unlikely explanation for the observed flatness of moment of inertia. Other explanations, such as weaker pairing, cannot be ruled out.

In summary, quasielastic transfer reactions between ^{118}Sn and ^{162,164}Dy at near-barrier energies have been studied by coupling the heavy-ion detector CHICO to Gammasphere. The quasielastic nature of the production of neutron-rich Dy-like nuclei was recognized by the measured Q-value distributions. The implied ''coldness'' of this reaction mechanism has many advantages for studying neutron-rich nuclei: (1) the limited number of open reaction channels results in clean γ-ray spectra, (2) since the neutron evaporation is negligible, the unambiguous assignments of γ rays to either the projectilelike or targetlike nuclei is very helpful for identifying the excitation of unknown nuclear species from the γ-ray cross correlations. The achieved sensitivity from this experimental setup, coupled to quasielastic neutron or proton transfer reactions, provides a powerful new probe of nuclear structure in neutron-rich nuclei that are up to four neutrons away from the stability line.

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