SPECTROSCOPY OF DEEP INELASTIC REACTION PRODUCTS: SCAVENGING PAYS*

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In the past fifteen years, concentrated efforts with a strong Krakovian flavor have focused on developing thick-target $\gamma\gamma$ coincidence methods for exploring the spectroscopy of neutron-rich heavy ion reaction products that cannot be reached by fusion–evaporation reactions. For a typical system, scores of product nuclei are formed with millibarn cross sections or less, the data analysis tends to be complicated, and isotopic assignments can sometimes be problematic. However, by taking advantage of the analyzing power of modern multidetector arrays, it has been possible to extract important new information about a wide range of poorly studied nuclei on the neutron-rich side of maximum stability. An eclectic sampling of results is presented.

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1. Introduction

Recent investigations [1,2] have shown that thick target γ-ray coincidence measurements can be used to explore the yrast spectroscopy of neutron-rich products of heavy-ion collisions that are not accessible by fusion–evaporation processes. In such reactions, many multinucleon transfer products of deep inelastic processes are formed with fairly small cross sections, the population patterns being largely governed by a strong tendency towards N/Z equilibration [3] for both target-like and projectile-like species. Consequently, the γ-ray data analysis is generally complicated, but it can take advantage of the high analyzing power of multidetector Ge arrays to extract useful spectroscopic information about states of moderately high spin in poorly studied nuclei, mostly on the neutron-rich side of stability.

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An important feature of this method of study is that mutual excitation of the binary reaction products can be directly observed through cross-coincidences of γ-rays from both reaction partners. Isotopic assignments for previously unknown γ-ray cascades can thus be established from cross coincidence patterns between the γ-rays from light and heavy reaction product partners. Since, however, the primary products of the deep inelastic collisions often are sufficiently excited to allow subsequent nucleon evaporation, the cross coincidence results need to be interpreted methodically, as discussed for example in Ref. [4]. Fruitful applications of these methods to several reaction system of interest are described in the following sections. They illustrate the use of the word "scavenging" in the title, meaning "extracting something of value from discarded material".

2. ^{92}Mo + ^{60}Ni reaction

Some years ago, Broda *et al.* [1] used the Argonne–Notre Dame BGO facility to study γ-rays from the reaction ^{92}Mo + 255 MeV ^{60}Ni, about 10% above the Coulomb barrier. This experiment had as its main objective the elucidation of high-spin level structures in the fusion–evaporation products ^{149}Ho and ^{150}Er, the 3- and 4-proton $N = 82$ isotones above ^{146}Gd. However, the excellent $\gamma\gamma$ coincidence data acquired were found to include many events arising from inelastic and transfer reaction products. A thorough analysis of these $\gamma\gamma$ data identified the product pairs from twelve binary transfer processes, ranging from $1n$ to 2α transfer. Typically, cross coincidences between the γ-rays from both products were observed.

These results illustrated the potential of thick-target $\gamma\gamma$ coincidence techniques for examining at high resolution some aspects of inelastic/transfer processes, such as correlated energy and angular momentum transfers into both product nuclei. More important, it was obvious that specific applications could include the spectroscopy of neutron-excessive nuclei not reachable by fusion–evaporation reactions.

3. Seniority isomers in $Z = 50$ tin nuclei

Our first spectroscopic application of these techniques concerned the yrast level structures of semi-magic tin nuclei. In the $A = 116$–130 tins, the $h_{11/2}$ neutron subshell is being filled, and seniority $v = 2$ and 3 $(\nu h_{11/2})^n$ isomers should occur in all these isotopes. At the start of our investigations $(\nu h_{11/2})^n$ $v = 2$ 10^+ isomers were known in ^{116,118,120}Sn at one end, and in the fission products ^{128,130}Sn at the other, but nothing was known about 10^+ isomers in the ^{122,124,126}Sn isotopes, which are not reachable by fusion–evaporation. We sought these missing isomers among the products of deep-inelastic heavy ion reactions (^{122,124}Sn + ^{76}Ge and ^{122,124}Sn + ^{80}Se), and identified $(\nu h_{11/2})^n$ $v = 2$ 10^+ states in ^{122}Sn and ^{124}Sn with half-lives of 62(3) and 45(5) μs, respectively [5]. The B(E2; $10^+ \rightarrow 8^+$) values in the even-A tins located the point of half-filling of the $\nu h_{11/2}$ subshell (where particles and holes cancel, and the B(E2) becomes zero) very close to $N = 73$. In the $N = 82$ isotones, the πh$_{11/2}$ half-filling occurs just below $Z = 71$, a difference that can be traced to the relative $s_{1/2}$, $d_{3/2}$, and $h_{11/2}$ single particle energies, which are altered by the Coulomb potential [5].

More complete data for the eight semi-magic nuclei from ^{119}Sn to ^{126}Sn were obtained in later measurements using ^{136}Xe and ^{238}U beams on ^{124}Sn targets [6,7]. (Fig. 1 shows how the relative tin yields shifted towards higher masses as N/Z of the composite system was increased.) The results for the

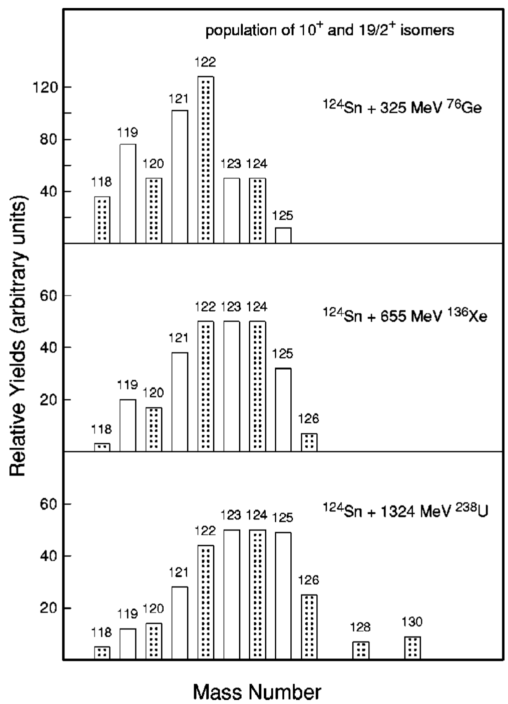

Fig. 1. Relative yields of 10^+ and $19/2^+$ isomers in tin nuclei for three reaction systems. Results for the odd-A and even-A isomers were normalized by assuming equal yields for the ^{123}Sn $19/2^+$ and ^{124}Sn 10^+ isomers.

odd-A nuclei, in which $(\nu$h$_{11/2})^n$ $v = 3$ $27/2^-$ isomers were located, were found to match up excellently with those for the even-A isotopes (Fig. 2), and they reinforced earlier conclusions about the $\nu h_{11/2}$ subshell filling and about the differences between h$_{11/2}$ neutrons and protons. The $(\nu$h$_{11/2})^n$ $v = 3$ configuration assignments for the $23/2^-$ and $27/2^-$ yrast levels in odd-A Sn nuclei could be made with great confidence because the experimental

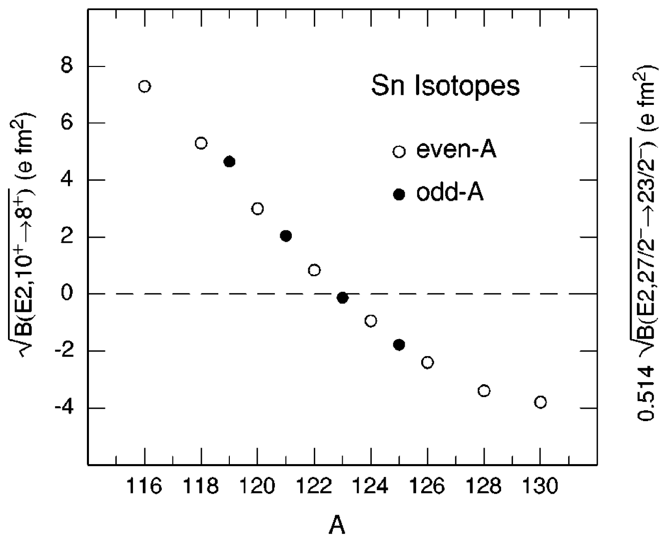

Fig. 2. E2 transition amplitudes for $(\nu h_{11/2})^n$ $10^+ \rightarrow 8^+$ and $27/2^- \rightarrow 23/2^-$ transitions in even-A and odd-A tin isotopes.

excitation energies were correctly predicted within a few keV by fractional parentage calculations which made use of the accurately known ground state masses of tin isotopes. The tiny $B(\mathrm{E2};\ 27/2^- \rightarrow 23/2^-)$ determined for ^{123}Sn — less than 0.002 W.u. — manifested anew the $\nu h_{11/2}$ subshell half-filling at $N = 73$. The thousandfold decrease in this B(E2) value observed between ^{119}Sn and ^{123}Sn exhibited in a particularly vivid way how transition probabilities are influenced by the subshell occupation number n.

4. ^{130}Te + ^{64}Ni experiment at GASP

Thick target $\gamma\gamma$ coincidence measurements for the system ^{130}Te+275 MeV ^{64}Ni were performed using the 40 Ge detector GASP array at Legnaro National Laboratory. Our principal goals were the yrast spectroscopy of neutron-rich Ni nuclei (especially magic ^{68}Ni, with $N = 40$) and of poorly studied $A > 125$ Te nuclei, which were also of some theoretical interest. In the experiments, a 275 MeV ^{64}Ni beam bombarded a 1.2 mg/cm^2 ^{130}Te target backed with 14 mg/cm^2 ^{208}Pb, which stopped all reaction products. The $\gamma\gamma$ coincidences were stored without any multiplicity restriction, and the beam was pulsed with 200 ns repetition time, so that prompt and delayed events could be separated. The nickel nuclei up to and including ^{68}Ni were identified among the lighter deep inelastic reaction products, and the first information about yrast excitations in ^{68}Ni was obtained, as already reported [8]. The high-lying 2^+ state at 2033 keV in ^{68}Ni and the 0.86 ms 5^- isomer decaying by a slow E3 transition were clear manifestations of the shell model kinship betwen ^{68}Ni with $Z = 28$, $N = 40$ and its alter ego ^{90}Zr with $Z = 40$, $N = 50$. On the heavy mass side, much new information was also obtained about yrast excitations for the odd-A and even-A tellurium nuclei in the $A = 125$–131 mass range [4]. For isotopic assignments of previously unknown γ-ray cascades, the prompt $\gamma\gamma$ cross-coincidence observed between Te and Ni partners were of vital importance. The results provided the first information about yrast excitations in the odd-A isotopes ^{127}Te, ^{129}Te, and ^{131}Te, where low-lying β-decaying $11/2^-$ isomers were the highest spin states known before. The energy systematics of the odd- and even-A Te isotopes, as discussed in Ref. [4], are displayed in Fig. 3.

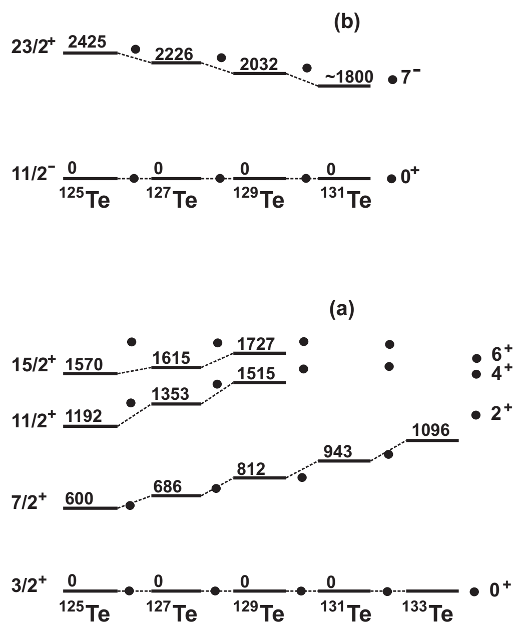

Fig. 3. (a) Energy systematics of lowest-lying positive parity sequences in odd-A and even-A Te nuclei. (b) Energy systematics of $23/2^+$ yrast states in odd-A Te nuclei and known 7^- states in even-A Te nuclei; the $23/2^+$ energies are expressed relative to 0 keV for the low-lying $11/2^-$ isomeric states.

5. Other reaction systems and conclusion

Scavenging seems a particularly fitting description for an investigation, spearheaded by B. Fornal, in which low multiplicity subsets of $\gamma\gamma$ data from reactions of ^{34}S, ^{36}S, and ^{37}Cl beams on thick ^{160}Gd targets were reexamined. These high statistics data were originally acquired by the Khoo–Janssens team at Argonne NL for studies of discrete superdeformed bands in $A \sim 190$ Hg and Tl nuclei formed in fusion–evaporation reactions. The reanalysis of

Fornal *et al.* [9] was successful in extracting useful new information about a number of poorly known *sdf*-shell nuclei, including $N = 19$ ^{33}Si and ^{34}P, and $N = 22$ ^{38}S and ^{39}Cl. This development may be seen as a forerunner of the light nuclei studies that will be discussed later in this session by R.V.F. Janssens and R. Broda.

Of special note is one early $\gamma\gamma$ study [2] of deep inelastic products from the reaction ^{106}Cd + 255 MeV ^{54}Fe that outstripped in scope and detail other studies of this type. In this case, in-beam and off-beam $\gamma\gamma$ coincidence measurements were performed, and production yields for more than 200 nuclei were determined (Fig. 4).

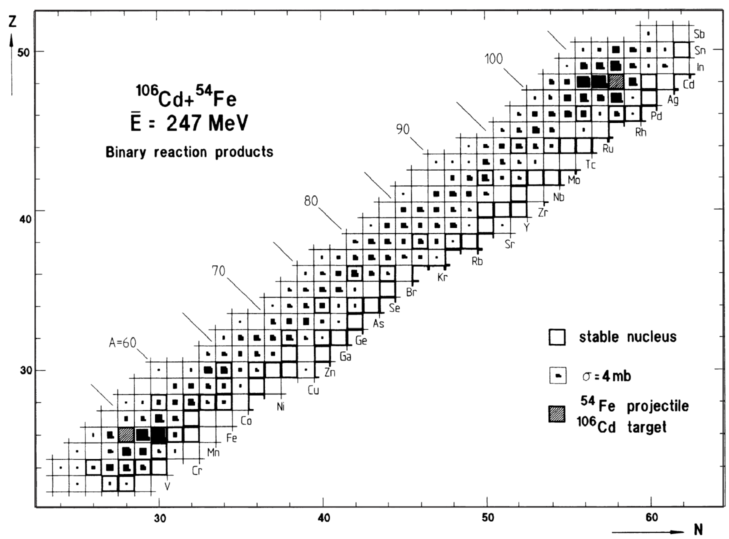

Fig. 4. Production cross sections of binary reaction products for 247 MeV ^{54}Fe ions on ^{106}Cd (from Ref. [2]).

Further analysis led to conclusions about the average number of neutrons and protons emitted by the primary deep inelastic products. A follow-up detailed study [10] for the system ^{208}Pb + 350 MeV ^{64}Ni confirmed and amplified these findings.

In summary, thick target γ-ray measurements for multinucleon transfer products of deep inelastic heavy ion reactions have yielded valuable information about yrast and near-yrast states in neutron-rich nuclei that are otherwise hard to reach.

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