BRIEF REPORTS

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First evidence for excited states in ^{101}In

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The first evidence for excited states in ^{101}In is presented. ^{101}In is the lightest In isotope observed in an in-beam experiment. Two γ-ray transitions at 1309 and 341 keV, respectively, are strong candidates for a cascade to the ground state in this nucleus. In shell-model terms it has one proton hole and two neutron particles outside the double shell closure at ^{100}Sn. New ideas for improving the peak to background ratio in certain γ-ray spectra from fusion evaporation reactions are introduced.

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We are presently, in a series of experiments, trying to supply information on single particle energies and interaction matrix elements in the ^{100}Sn region. Such information will be of great importance for understanding the shell structure of atomic nuclei. During the past few years the experimental data in this region have grown significantly. Excited states are today known in more than ten isotopes that had not been identified in-beam as late as five years ago [1–11]. In the shell model ^{101}In has one proton hole and two neutron particles outside the closed neutron and proton shells of ^{100}Sn. This means it is one of the three closest lying neighbors of ^{100}Sn with known excited states. It can thus be described on a similar footing as ^{97}Ag [12], that has three proton holes, and ^{99}Cd [13], that has two proton holes and one neutron particle outside the double shell closure.

In the present experiment we have used a configuration of the NORDBALL [14,15] array with a selective power of the order of 10^{-5} with respect to the total experimental yield. A beam of ^{58}Ni at 261 MeV provided by the accelerator facility at the Niels Bohr Institute was used to induce fusion evaporation reactions in a target of ^{50}Cr. Two targets were used during the experiment. The first had a thickness of 4.8 mg/cm^2 and a gold backing of 11.0 mg/cm^2. The corresponding numbers for the second target were 3.1 mg/cm^2 and 19.6 mg/cm^2, respectively. The enrichment was 96.8% in ^{50}Cr. The main target contaminant was ^{52}Cr (3.0%).

For identification of the residual nuclei we utilize an experimental technique based on detecting the particles evaporated by the compound nucleus. The target position is surrounded by an assembly of twenty-one thin (170μm) silicon detectors [16] measuring the stopping power of the emitted charged particles. The difference in measured stopping power between differently charged particles is used to discriminate between emitted protons and α particles. The measured efficiency for detecting an α particle was approximately 40% and for a proton 60%. In the forward hemisphere a second layer consisting of eleven liquid scintillators assist in deducing the neutron multiplicity of each event [17]. Technically this is accomplished by deriving the zero-crossing time of the detector signal for use together with the time-of-flight information [18]. Because of the characteristics of the scintillator, different responses are obtained for photons and neutrons. An efficiency of $\sim$ 25% is typically reached for detecting a single neutron from the current reaction. The intrinsic efficiency of the detectors is approximately 50% which means that about half of the emitted neutrons pass through the forward 1π sr covered by these detectors. Timing, γ-ray multiplicity, and sum-energy information are supplied by a set of thirty individual BaF_2 crystals. Energies and times of the coincident γ rays are measured by fifteen escape-supressed Ge detectors. The total Ge detector photo peak efficiency in this configuration is $\sim$ 1%. Complementary information on the experiment may be found in a conference report [19].

Because of the low cross section for neutron deficient residues two separate trigger conditions were combined. The first one was the standard trigger of the array that demands at least two shielded Ge detectors fired in coincidence with a minimum of one of the BaF_2 detectors. The second trigger condition was fulfilled if at least one shielded Ge detector and one BaF_2 detector fired at the same time as one or more neutrons were detected. Totally 1100 million events of the first type and 1400 million events of the second type were registered.

With this combination of beam and target ^{101}In is produced via the $1p1\alpha 2n$ channel. Using typical values for the detection efficiencies one finds that $\sim$1.5% of the registered ^{101}In events are detected with the correct particle multiplicity. On the other hand, exit channels involving less neutrons have much larger cross sections. The probability that such an event instead is detected in the two neutron channel depends mainly on two factors. As mentioned above the liquid scintillators give a response for γ rays as well as for neutrons. If the γ-neutron discrimination is imperfect a leakage from lower to higher neutron multiplicity occurs. This effect is $\sim$0.5% after off line filtering. A much more severe effect is the scattering of neutrons between the detectors in the multidetector system. The measured scattering is of the order of 5%. This means that the γ-ray spectra corresponding to two emitted neutrons are dominated by events where in reality one neutron was emitted. It is therefore of interest to find a way to reduce the background in these spectra.

We are presently pursuing an idea based on a very simple

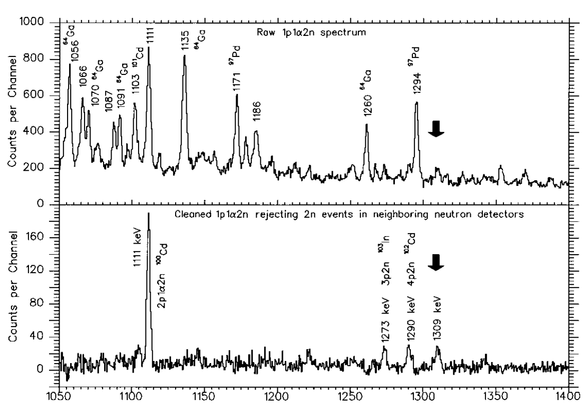

FIG. 1. The upper spectrum is gated by $1p1\alpha 2n$. The lower spectrum is gated by the same particle combination with the additional condition that two neutrons were not detected in neighboring neutron detectors and subtracting 8% of the upper spectrum. The $2n$ channels are enhanced relative to the $1n$ channels. The presence of lines corresponding to $2p1\alpha 2n$, $3p2n$, and $4p2n$ is caused by the limited detection efficiency and the nonperfect α-proton separation of the Si-detector array.

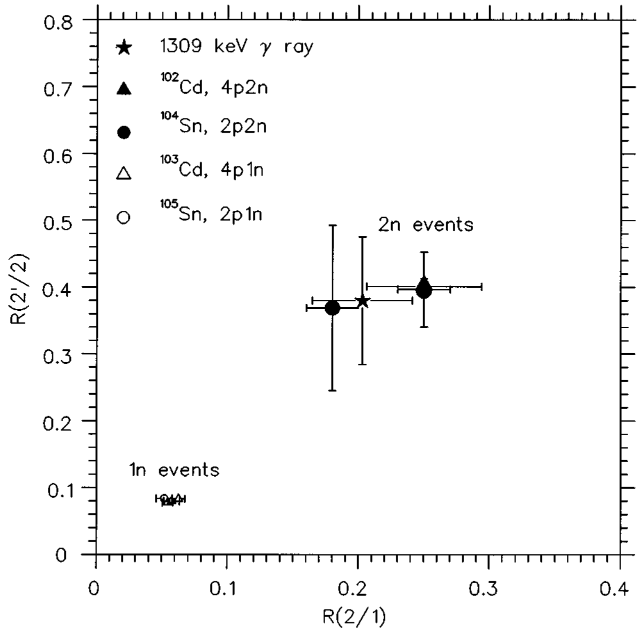

FIG. 2. The figure strengthens the assigment of the 1309 keV line as originating from a $2n$ channel. The abscissa shows the intensity ratio of different γ rays deduced from spectra gated by two and one neutron, respectively. The ordinate shows the intensity ratio for the same γ rays gated by two neutrons with and without rejecting events in which neighboring neutron detectors fired. Except for the 1309 keV γ ray, all γ rays used are known from previous experiments.

principle. In the off line processing we rejected events where two nearest-neighbor neutron detectors fired. By sorting the remaining two neutron events into γ-ray spectra only $\sim$8% of the misidentified one neutron channel remains. At the same time $\sim$40% of the true two neutron channel is preserved. The two neutron channel thus gains, in relative intensity, a factor of 4–5 over the one neutron channel. This approach has the obvious drawback that the total efficiency for detecting the two neutrons is reduced. It does, however, supply a rather powerful tool for identification of two neutron events. These results were confirmed by simulations taking into account the reaction kinematics and the geometry of the neutron detector array [20].

Following the procedure outlined above we found one γ ray at 1309 keV in the $1p1\alpha 2n$ spectrum that exhibits the behavior expected of a transition in ^{101}In (see Fig. 1). Furthermore it does not belong to any other known two neutron channel. For this γ ray the intensity ratio obtained from the two spectra is 0.37 ± 0.12. We also derived the intensity ratio deduced from the spectra gated by $1p1\alpha 2n$ and $1p1\alpha 1n$. As mentioned above this ratio is $\sim$0.05 for one neutron events. For a two neutron event the same ratio is $\sim$0.20. The measured ratio was 0.18 ± 0.02 for the 1309 keV γ ray. After extracting these ratios for several known one and two neutron channels and plotting the result in a graph, one neutron events and two neutron events are easily separable (see Fig. 2).

Identifying the correct charged particle channel is more complicated. One may nevertheless draw certain conclusions from a comparative study of spectra gated by different com-

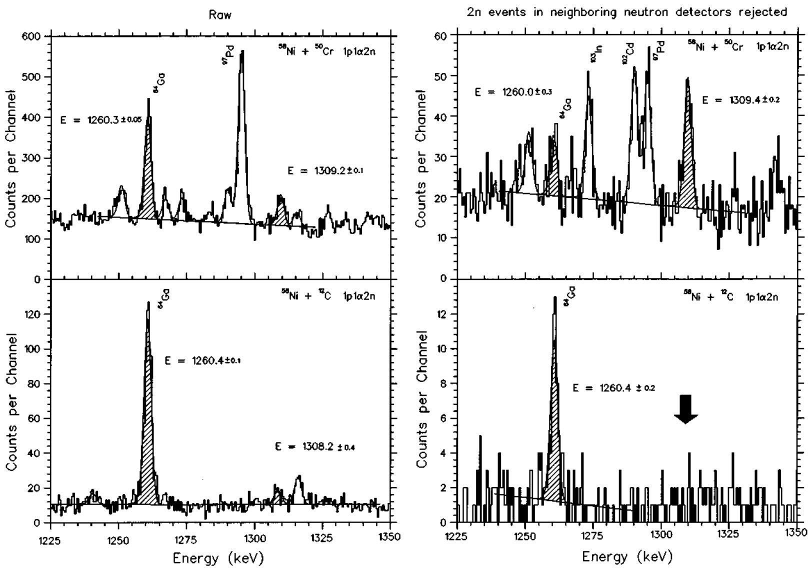

FIG. 3. The spectra on top were obtained from the reaction on ^{50}Cr. The left one is again the raw spectrum obtained by gating on $1p1\alpha2n$. To the right the same spectrum is shown when two neutron events from neighboring neutron detectors were excluded. The lower spectra were collected during a complementary run on a ^{12}C target. Performing the same analysis on these spectra shows that the line at 1309 keV is unlikely to originate from the contaminant. Compare for instance the relative intensities of the 1309 keV line and the known contaminant from ^{64}Ga. Note that the 1308 keV peak in the lower spectrum has an intensity ratio corresponding to a one neutron channel.

binations of charged particles and neutrons. An immediate conclusion is that no more than one α particle is emitted since the 1309 keV γ ray is not present in any spectrum gated by two or more α particles. On the other hand, if no α particle at all is evaporated the only possibility is that one or more protons are misidentified as an α particle. This would mean the 1309 keV γ ray would have to be one of the strongest γ rays in the spectra gated by two neutrons and two or more protons. This is not the case. It is possible, though, to identify some of the strongest lines from the $3p2n$ and $4p2n$ channels in the $1p1\alpha2n$ spectrum. The only remaining possible misidentification would be if the 1309 keV γ ray was in coincidence with $1\alpha2n$ but with more than one proton, but the 1309 keV γ ray is not present in such a spectrum. One may thus be fairly confident that the 1309 keV γ ray does belong to the $1p1\alpha2n$ channel and that its presence in the spectrum gated by this particle combination is not a result of a misidentification.

To firmly establish the origin of the emitted γ ray one must also exclude any contaminant as its source. Unfortunately, a straightforward exclusion of this possibility was hampered by contaminating carbon inside the target chamber. We therefore made a run substituting the ^{50}Cr target with a thin, backed, ^{12}C target. The fundamental assumption is that the population patterns in the two runs are sufficiently equal so that an identification of the residual nuclei from the reaction on the contaminating ^{12}C, in the main run, is possible. In the reaction on ^{12}C the $1p1\alpha2n$ channel leads to ^{63}Ga [21], a nucleus that already has been identified in-beam. None of the γ rays known from that study was found in the $1p1\alpha2n$ spectrum in the reaction on ^{50}Cr. Lines from ^{64}Ga are visible, however [22]. Performing the same analysis as described above of the spectra collected from the latter run makes it possible to rule out reactions on ^{12}C as the source (see Fig. 3). We are thus, under the difficult circumstances described above, quite certain that the observed γ ray emanates from ^{101}In.

Despite the low number of events in the spectrum it is still possible to get a notion of further excited states by gating on the 1309 keV γ ray in the collected γ-γ matrices. In Fig. 4 the summed spectrum resulting from a gate on the 1309 keV peak in the matrices gated by $1p1\alpha2n$ and $1\alpha2$n is shown together with a corresponding background gate. It is evident that the 341 keV γ ray rides on practically no background and that the dominant background comes from ^{101}Cd [3], which is a one neutron channel. None of the γ rays belonging to ^{101}Cd exhibits the behavior expected of a two neutron channel, leading to the conclusion the 341 keV γ ray comes from the same residual nucleus as the 1309 keV γ ray.

Within the shell model ^{101}In is interpreted as having two neutrons and one proton hole outside the doubly closed shell. Following systematics, the ground state has spin and parity of $9/2^+$, from the proton hole in the $g_{9/2}$ orbital. The first excited state in ^{101}In is thought to be the 2^+ state in ^{102}Sn coupled to this proton hole, giving a state with spin and parity $13/2^+$. Our candidate for this state is thus a state at 1309 keV. Due to the low number of collected events we are not able to say anything about the multipolarity of the transition. The 341 keV γ ray could possibly correspond to the deexcitation from the $17/2^+$ state to the $13/2^+$ state. The

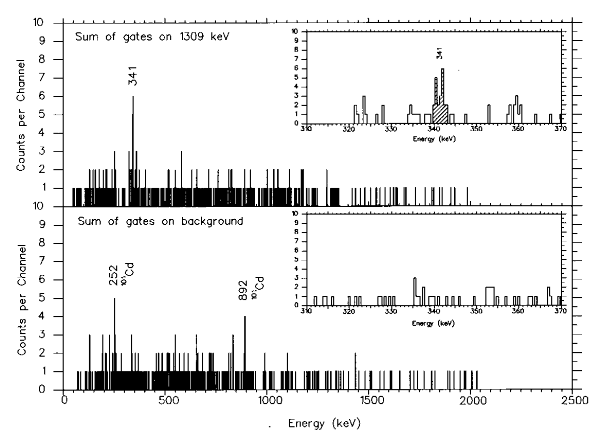

FIG. 4. A gate on the 1309 keV peak obtained from a sum of the $1p1\alpha2n$ and $1\alpha2n$ matrices. Note that around 341 keV there is virtually no background present and that the remaining peaks in the background come from the one neutron channel ^{101}Cd.

number of counts in this line does not admit a determination of its multipolarity either. A quantitative shell-model calculation of the excited states in ^{101}In is hampered by the fact that empirical two-body matrix elements and single-particle energies are not known for a ^{100}Sn core. Following a recent approach using combined empirical and realistic two-body matrix elements and single-particle energies from ^{88}Sr and ^{90}Zr, the $13/2^+$ and $17/2^+$ states in ^{101}In are calculated to have an energy of 1530 and 1825 keV, respectively. The theoretical γ-decay scheme below the $21/2^+$ state is consistent with an almost exclusive population of the $21/2^+ - 19/2^+ - 17/2^+ - 13/2^+ - 9/2^+$ decay sequence. The $21/2^+$ state is the highest spin state available in the $\pi(p_{1/2},\ g_{9/2})\ \nu(d_{5/2},\ g_{7/2},\ s_{1/2},\ d_{3/2},\ h_{11/2})$ model space, without invoking a $\nu h_{11/2}$ excitation. In accordance to previous observations in the open proton and neutron shells [3,5,23,24], the ground state is calculated to be overbound, resulting in a too high energy for the $13/2^+$ state. The systematics of the odd In and even Sn isotones show a strong correlation between the energies of the $13/2^+$ and 2^+ states. The energy of the $13/2^+$ state in the light In isotopes, down to ^{105}In, is roughly a factor 1.15 of the energy of the 2^+ state in the corresponding Sn isotone. This is readily explained in a simple $Q_{2^+} q_{j=9/2}$ coupling scheme, using a prolate intrinsic quadrupole moment. The trend is, however, broken for the ^{103}In and ^{104}Sn pair of isotones as the energies of the $13/2^+$ and 2^+ states are almost equal. Following the systematics the situation may even be reversed for a lower neutron number implying that the energy of the 2^+ state in ^{102}Sn is approximately equal to or larger than the indicated 1309 keV of the $13/2^+$ state in ^{101}In. An energy of the 2^+ state in ^{102}Sn larger than 1309 keV would, according to the model, imply a change in the sign of the quadrupole moment going from ^{104}Sn to ^{102}Sn as well as an inversion of the $13/2^+$-$11/2^+$ sequence of states in ^{101}In. It may be noted that the mentioned shell-model approach, which neglects particle-hole excitations, shows a drop in the quadrupole moment of the 2^+ state in ^{102}Sn by a factor of 4 as compared to the 2^+ state in ^{106}Sn. The calculation does not, however, indicate any change in the sign of the quadrupole moment.

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