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Highest spin *n*-*p* states in heavy nuclei via the (α,d) reaction at 218 MeV

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Strong transitions to high spin states are observed in the study of the (α,d) reaction at 218 MeV on closed shell heavy nuclei. It is shown that the highest spin valence valence *n-p* strength in the residual nuclei ^{92}Nb, ^{122}Sb, ^{146}Eu, and ^{210}Bi is shared between a first strongly excited fragment and higher lying groups. The valence plus outer shell $(\nu_{13/2}\times\pi h_{11/2})_{12^-}$ strength is tentatively identified in ^{122}Sb.

Neutron and proton stripping reactions have been extensively used to investigate the single-particle strength distributions in medium and heavy nuclei. The higher energy beams available in recent years have revealed themselves as powerful tools for studying the high l orbitals belonging to the valence shell and to the first outer shell. In the case of spherical nuclei, the spectra from high energy $(^3\text{He},d)$, (α,t), or $(\alpha,^3\text{He})$ reactions exhibit only one or few strongly populated low-lying levels together with more or less pronounced higher lying structures.[1-4]

Another approach to the simple excitation modes is the investigation of two-particle states via two-nucleon transfer reactions. Except for the experiments on Zr, Mo,[5] and Pb (Ref. 6) isotopes with the (α,d) reaction, neutron-proton states in heavy nuclei have only been studied over a limited excitation energy range. The previous studies were performed with α beams of energy $E_\alpha \leq 50$ MeV, and bear mainly on light[7-9] and medium weight nuclei.[10] The (α,d) reaction was shown to selectively populate few levels, namely the high spin stretched states.

We have taken advantage of the high-energy beam of the Orsay Synchrocyclotron to study the (α,d) reaction at 218 MeV on heavy nuclei. We have chosen the neutron and/or proton closed-shell targets ^{90}Zr, ^{120}Sn, ^{144}Sm, and ^{208}Pb so that the resulting strongly excited levels and structures could possibly be related to those observed in single neutron and proton stripping experiments.[1-4] The population of known levels in ^{92}Nb and ^{210}Bi and of strongly excited levels in ^{122}Sb and ^{146}Eu allows the investigation of the (α,d) reaction mechanism for the first time at such high energy.

The experiment was performed using the beam transport system and the associated high resolution spectrometer Montpellier set in the achromatic mode. The deuteron particles were detected in the focal plane by two multiwire proportional chambers. Two plastic scintillators giving ΔE information allowed a clean identification of the deuterons. A current of typically 500 nA was used. Under these conditions an overall energy resolution of ~ 100 keV was achieved at 3.4° for the four nuclei with target thickness of about 2–3 mg/cm^2. The angular distributions of the strongly excited or well separated levels in ^{92}Nb, ^{122}Sb, and ^{210}Bi residual nuclei have been obtained from 3° to 18° lab using thicker targets (5.4 to 12 mg) leading to poorer energy resolution (up to ~ 220 keV). The low excitation energy part of the spectra was carefully decomposed into individual levels or groups using a multipeak analysis computer code. The excitation energy spectra obtained at 3.4° with the thin targets are displayed in Fig. 1. The ^{122}Sb spectrum obtained at 3.4° up to $E_x = 18$ MeV with the thick target is displayed in Fig. 2.

Below an excitation energy of ~ 3 MeV all spectra are dominated by only one strong peak. The corresponding angular distributions display a steep decrease of the cross section with angle, as shown in Fig. 3. In addition to the few other states significantly populated in the same region, one observes higher lying groups (up to ~ 5 MeV) and broader structures especially in the ^{122}Sb residual spectra.

Two-nucleon transfer cross sections depend critically on the correlation of the transferred nucleons in the final state. The (α,d) structure amplitudes[11] favor the stretched states especially those with the highest spins. In addition, angular momentum matching conditions, which favor intermediate spin states at lower incident energy, favor the highest spin states at $E_\alpha = 218$ MeV. In this last case the best matched L transfer (typically $L \sim 12$ and $L \sim 16$ for Zr and Pb targets, respectively) would be larger than the maximum available L_{np} shell model value. This feature explains the further simplification of the (α,d) excitation energy spectra at 218 MeV shown in Fig. 1 compared with the corresponding spectra at $E_\alpha \leq 50$ MeV incident energy. A number of intermediate spin levels exhibit negligible or very small cross sections at 218 MeV. Only the levels at 2.58 MeV

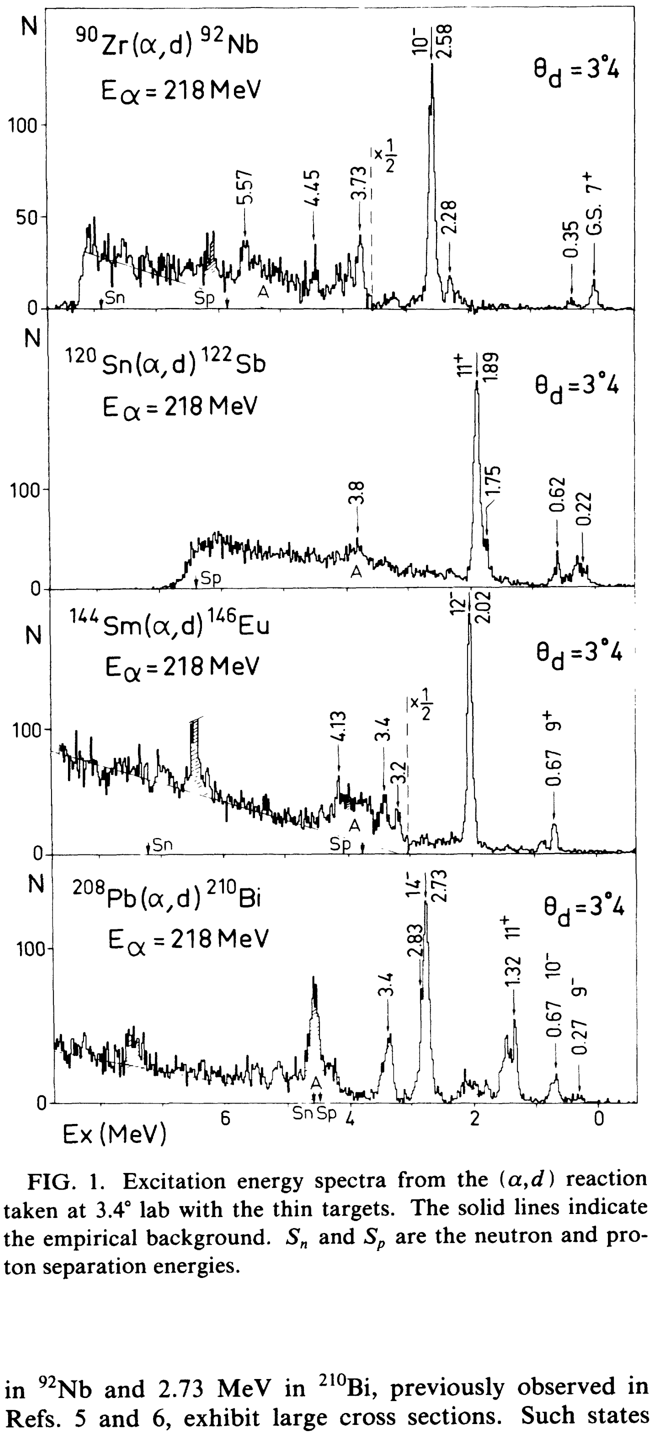

FIG. 1. Excitation energy spectra from the (α,d) reaction taken at 3.4° lab with the thin targets. The solid lines indicate the empirical background. S_n and S_p are the neutron and proton separation energies.

in ^{92}Nb and 2.73 MeV in ^{210}Bi, previously observed in Refs. 5 and 6, exhibit large cross sections. Such states can thus be definitively identified as the most favored states with configurations and spins $(j_n\ \max, j_p\ \max)_{J_{\max}}$, e.g., $(\nu h_{11/2}\times\pi g_{9/2})_{10^-}$ in ^{92}Nb and $(\nu j_{15/2}\times\pi i_{13/2})_{14^-}$ in ^{210}Bi.

Taking into account the observed strong selectivity of the reaction at 218 MeV and the available shell model orbitals, the previously unknown strongly excited levels in ^{122}Sb and ^{146}Eu are attributed to the spins and configurations $(\nu h_{11/2}\times\pi h_{11/2})_{11^+}$ and $(\nu i_{13/2}\times\pi h_{11/2})_{12^-}$, respectively.

The analysis was attempted in the framework of the ZR-DWBA approximation using the code DWUCK4.

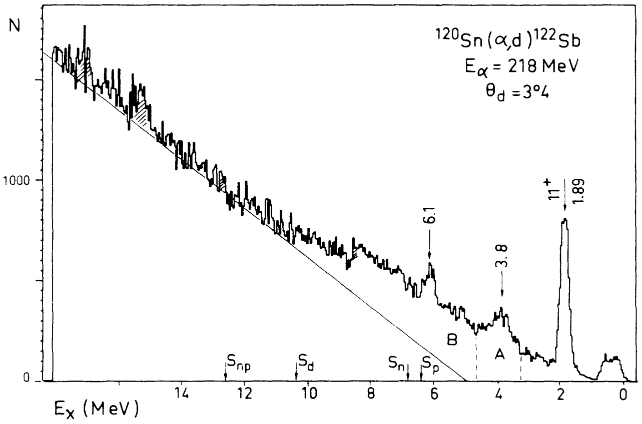

FIG. 2. Deuteron energy spectrum for the reaction ^{120}Sn$(\alpha,d)^{122}$Sb (thick target). The solid line indicates the empirical background. S_n, S_p, and S_d are the neutron, proton, and deuteron separation energies.

Several optical potentials taken from the literature were tried to describe the entrance and exit channels. Microscopic form factors were used for the different configurations. The main conclusions are summarized as follows.

The relative cross sections calculated at forward angles for the strongly excited peaks do not depend much upon the optical parameter choice. For each configuration the stretched state cross section is at least a factor of 10 to 20 above those of all other states with $J<J_{\max}$. It is also

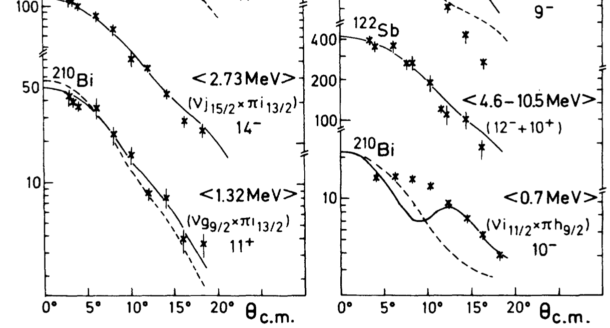

FIG. 3. Angular distribution for the (α,d) reaction at 218 MeV. The curves are zero range (solid line) and finite range (dashed line) DWBA calculations for the indicated spins and configurations. ^{122}Sb ⟨4.6–10.5 MeV ⟩: Experimental cross sections of the structure B, background subtracted (see Fig. 2), and DWBA calculations (see Table I).

TABLE I. Neutron-proton particle states strongly populated in the $(A+2)$ nuclei via the (α,d) reaction and data on the single neutron and proton states in the $(A+1)$ nuclei. The excitation energies and the indicated C^2S are mean values taken from the Nuclear Data Tables and from Refs. 1–4 especially for the high-lying structures. Poorly established or estimated C^2S values are given within parentheses.

$A+2$	*N-P*	Configuration			Neutron	$A+1$	Proton	$A+1$	$\sigma_{\mathrm{exp}}/\sigma^{\mathrm{b}}_{\mathrm{calc}}$
	E_x (MeV)	*N*	*P*	$J^{\pi\mathrm{a}}$	E_x (MeV)	C^2S_n	E_x (MeV)	C^2S_p	
^{92}Nb	2.58[c]	$h_{11/2}$	$g_{9/2}$	10^-	2.19	0.46	0	0.9	0.77
	3.5–6.8	$(h_{11/2}$	$g_{9/2})$	(10^-)	3.5–6.0	(0.5)	0	0.9	1.12
^{122}Sb	1.89 ∓ 0.05	$h_{11/2}$	$h_{11/2}$	11^+	0.008	0.42	1.42	(0.75)	1.28
	3.25–4.6	$(h_{11/2}$	$h_{11/2})$	(11^+)	0.008	0.42	2.0–4.2	(0.25)	3.6 (1.1)[d]
	4.6–10.5	$(h_{9/2}$	$h_{11/2})$	(10^+)	4.0–7.0	0.92	1.42	(0.75)	1.5
		$(i_{13/2}$	$h_{11/2})$	(12^-)	5.4–10.0	0.46	1.42	(0.75)	
^{146}Eu	2.02 ∓ 0.03	$i_{13/2}$	$h_{11/2}$	12^-	1.10	0.46	0.72	0.9	1.04
	3.05–4.70	$(i_{13/2}$	$h_{11/2})$	(12^-)	2.5–3.5	0.4	0.72	0.9	0.95
^{210}Bi	2.73[e]	$j_{15/2}$	$i_{13/2}$	$14^{-\mathrm{e}}$	1.43	0.58	1.61	(0.74)	0.85

[a] Proposed spin and parities for the *n-p* states in $(A+2)$ nuclei.

[b] $\sigma_{\mathrm{Calc}}=N\times C^2S_p\times C^2S_n\times\sigma_{\mathrm{DWUCK}}$ with $N=330$.

[c] Reference 5.

[d] Peak only.

[e] Reference 6.

found that the high spin stretched states with a configuration $(j_\nu=l_\nu+\frac{1}{2},\ j_\pi=l_\pi+\frac{1}{2})_{J\,\mathrm{max}}$ are enhanced compared both with those having the configurations $(j_\nu=l_\nu\mp\frac{1}{2},\ j_\pi=l_\pi\pm\frac{1}{2})_{J\,\mathrm{max}}$ and those with $(j_\nu=l_\nu-\frac{1}{2},\ j_\pi=l_\pi-\frac{1}{2})_{J\,\mathrm{max}}$ and the same total orbital angular momentum. The cross sections range typically as 10, ~2, ~0.7, (if $l_\pi\neq l_\nu$). In each nucleus the largest cross section is obtained from the $(j_\nu\,\mathrm{max},\ j_\pi\,\mathrm{max})_{J\,\mathrm{max}}$ state. These features agree very well with the recorded spectra shown in Fig. 1.

The shapes of the angular distributions for the highest spin states and for the known 11^+ level at 1.32 MeV in ^{210}Bi are well reproduced (see Fig. 3) with the same α optical potential used successfully for the $(\alpha,{}^6\mathrm{He})$ reaction.[12] The best fit is obtained with an adiabatic deuteron potential (adding the neutron and proton potentials as given in Ref. 13, for $E_{n,p}=E_d/2$). The theoretical angular distribution shapes depend neither on the value of the range parameter (1.3 to 1.7 fm) nor on configuration mixing.

The cross sections of the weakly excited levels could not be confidently separated out except for the measurements at 3.4° taken with the thin targets. The angular distributions obtained for three low-lying groups studied in ^{122}Sb and ^{210}Bi are displayed in Fig. 3. From simple multiplet energy considerations the two groups in ^{122}Sb are expected to be dominated by stretched 8^- and 9^- states belonging, respectively, to the configuration $(\nu h_{11/2},\pi d_{5/2})$ and $(\nu h_{11/2},\pi g_{7/2})$. The ZR-DWBA analysis fails to reproduce the experimental angular distribution shapes. The agreement is very much improved if finite-range effects are taken into account in the calculation of the *n-p* cluster transfer amplitudes (using the same microscopic form factors as for the ZR calculation), especially for the first group which comprises the known 8^- level at $E_x=0.163$ MeV. The relative cross sections at 3.4° are not very much changed. On the other hand, a specific discrepancy still stands for the peak dominated by the well known $(\nu i_{11/2},\pi h_{9/2})_{10^-}$ level at $E_x=0.69$ MeV in ^{210}Bi.

Turning to the discussion of the absolute cross sections, we first consider the highest spin state in each residual nucleus. These states would have pure *n-p* configurations if the coupling with the collective degrees of freedom were small. This is not the case, in particular, for high *l* orbitals in the case of closed-shell nuclei. We have used the measured spectroscopic factors to account for the lack of concentration of the single-particle neutron and proton strengths into one level (or closely spaced group of levels) in the corresponding odd-*A* nuclei. The necessary data and the results are summarized in Table I. It is found that the highest spin state cross sections are reproduced by the DWBA calculations within $\mp30\%$ in all four nuclei using the same mean empirical normalization factor. Taking into account all uncertainties about the C^2S values and the large dispersion of the (α,d) reaction normalization factors for different targets and incident energies, this overall agreement is rather promising.

It is very encouraging that such comparison also holds at forward angles within 40% to 60% for the 11^+ and 12^+ levels, respectively, at 1.32 and 1.47 MeV in ^{210}Bi and even for lower spin levels such as the 9^+ state at 0.67 MeV in ^{146}Eu and the 9^- state at 0.270 MeV in ^{210}Bi. The above procedure has been used for all other levels and structures. In the following, we concentrate on the discussion of the high-lying structures.

The high excitation energy part (10–18 MeV) of the residual spectra measured with the ^{120}Sn target exhibits a constant slope without pronounced structures. Wu *et al.*[14] have shown that breakup processes give an important contribution to the reaction cross section of fast α particles (≥40 MeV/*n*). They have also shown that the inelastic breakup processes where one or more of the projectile constituents are absorbed by the target while the others act as spectators were necessary to account for the continuum cross section, together with the elastic breakup reaction. This is consistent with the fact that the continuum observed in the present experiment does not seem to vanish at the *n-p* or deuteron thresholds.

In the region of interest the breakup and stripping contributions to the continuum would have to be considered together. No background shape attributed to the breakup reactions can thus be confidently calculated. In order to evaluate the cross sections of the structures observed in ^{122}Sb the background has been obtained by extrapolating the high excitation energy continuum as a straight line. Purely empirical backgrounds have been chosen for the other nuclei as indicated in Fig. 1.

Within our simple model, in all four nuclei the high spin *n-p* strength built on the first neutron and proton levels (or closely spaced levels) of the relevant valence orbitals is found to be approximately exhausted below $E_x \sim 3$ MeV. It is thus tempting to relate the groups and structures observed beyond that energy to the *n-p* strength associated with the single neutron and/or proton strength missing from the first levels, then to configurations involving one particle in an external shell. The results are summarized in Table I together with the relevant data concerning the single neutron and proton states. In the discussion we first rely on the comparison of the forward angle experimental cross sections with the ZR-DWBA predictions calculated for the stretched states belonging to the different configurations which may be expected in the excitation energy region of interest.

Starting from the neutron closed-shell targets ^{90}Zr and ^{144}Sm, the high-spin single-neutron valence strength is fragmented while the single proton strength is not. Only the $(\nu h_{11/2}\pi_{9/2})_{10^-}$ strength in ^{92}Nb and the $(\nu i_{13/2}\pi h_{11/2})_{12^-}$ strength in ^{146}Eu are able to account for the large experimental cross section of the high-lying groups and structures as shown in Table I. Moreover, this strong fragmentation of the 10^- and 12^- *n-p* valence-valence strengths first observed in ^{92}Nb and ^{146}Eu compares well with simple energy predictions based on the $h_{11/2}$ and $i_{13/2}$ neutron fragmentation in ^{91}Zr and ^{145}Sm. High-lying structures attributed to proton external orbitals only occur beyond $E_x \sim 4.5$ MeV in ^{91}Nb and ^{145}Eu.

The ^{122}Sb residual spectra have been studied up to higher excitation energy. Beyond $E_x \sim 3$ MeV they exhibit two broad peaks and smoother structures with angular distributions which are similar to those of the strongly excited 11^+ level (see Fig. 3). The $h_{11/2}$ proton strength is known to be fragmented in ^{121}Sb (see Table I) whereas nearly all the neutron strength (reduced by the occupation number) is concentrated in the first $\frac{11}{2}^-$ level in ^{121}Sn. Taking into account energy considerations and DWBA cross sections, the peak around $Ex = 3.8$ MeV is tentatively suggested to contain the missing valence strength. On the other hand, the ^{120}Sn(α,^{3}He)^{121}Sn spectra of Ref. 1 exhibit pronounced structures beyond $E_x \sim 4.5$ MeV attributed to the $h_{9/2}$ and $i_{13/2}$ neutron external orbitals, whereas external proton states show no such clustering in ^{121}Sb. We thus tentatively attribute the second peak and the whole structure in ^{122}Sb mainly to the $(\nu i_{13/2}\pi h_{11/2})_{12^-}$ strength with a smaller contribution of the unfavored $(\nu h_{9/2}\pi h_{11/2})_{10^+}$ strength.

High-lying groups which may be attributed to the 14^- strength are also observed in ^{210}Bi. As both the $j_{15/2}$ neutron and the $i_{13/2}$ proton states in the $A = 209$ nuclei are strongly fragmented, a detailed discussion based on these fragmentations taken separately would not be justified. Moreover, the gaps between the high *l* valence and outer orbits are relatively small.

In summary, the (α,d) reaction at 218 MeV has proven to be a powerful specific tool to study the $(j_{n\,\max}, j_{p\,\max})_{J\,\max}$ stretched states belonging to the valence-valence and valence-outershell orbital configurations in heavy nuclei, both at low and high excitation energy.

The present study has concentrated on single and double closed-shell heavy targets. It is shown for the first time that the highest spin valence-valence *n-p* strength is shared between a first strongly excited fragment and higher lying groups and structures. The observed strong fragmentation which is found to be qualitatively related to those of the single neutron and/or proton orbitals in the neighboring odd nuclei, reveals the important role of the coupling with the surface vibrations. A higher lying structure is tentatively identified in ^{122}Sb as resulting from the highest spin valence plus first outer shell strength. Theoretical calculations are needed, taking into account the collective vibrations, for a better understanding of the high spin *n-p* strength distributions both at low and high excitation energy, as well as further experimental studies with improved energy resolution.

The ZR-DWBA analysis was fairly successful in describing the strongly excited states. Further studies of the experimental angular distributions of other more weakly excited levels, with intermediate spins or unfavored configurations $(j_1 = l_1 - \frac{1}{2},\ j_2 = l_2 \mp 1)_{J\,\max}$ are needed together with an improved description of the reaction. Finite-range calculations taking also into account the α particle *D* state, and possibly two-step processes would be especially useful.

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