Observation of direct neutron decay of isobar analog processes of a resonant p,n reaction

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An analysis is presented of the published data on the partial cross section of the resonant reactions $^{117,119}Sn(p,n)$ $^{117,119}Sb$ on the basis of a formula that takes into account the contribution of the direct neutron decay of the isobar-analog resonances, and the values of the corresponding partial widths have been determined for the first time.

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Experiments on the excitation of isobar analog resonances (IAR) by neutrons have so far not yielded for the widths $\Gamma_n^\dagger$ of the direct neutron decay any quantitative data that can be compared with the predictions of the theory. [1] This situation is attributed to the smallness of the expected resonance effect and to the complexity of the precision neutron experiment.

More promising are searches for direct neutron decay of analog resonances excited by protons. But even this procedure did not yield data on $\Gamma_n^\dagger$, although the partial cross sections of the resonant (p, n) reaction were investigated in many experiments. The lack of data on $\Gamma_n^\dagger$ is explained primarily by the fact that the interpretation of the experiments was carried out everywhere under the assumption that the neutron decay of the IAR has a purely statistical character, i.e., under the assumption that $\Gamma_n^\dagger = 0$. In this case the resonant partial cross section of the (p, n) reaction takes the form

$$\sigma_{pn}^{\text{res}} = \pi\lambda\!\!\!^{-2} \frac{(2J+1)}{2(2I_0+1)} T_{plj}(E_p) \frac{\sum\limits_{lj} T_{nlj}(E_{ni})}{\sum\limits_{l'j'q'} T_{nl'j'}(E_{nq})} \times \frac{\epsilon^2 - \frac{\Gamma^2}{4} + \Delta^2 - 2\Delta(E_p - E_R)}{(E_p - E_R)^2 + \frac{\Gamma^2}{4}}, \qquad (1)$$

where E_R, Γ, ϵ, and Δ are the IAR parameters, J, I_0, and I are the spins of the resonance, target nucleus, and final-nucleus levels, respectively. The summation is carried out over all the penetrability coefficients $T_{nlj}(E_{ni})$ for the open channels, whose indices l and $j = l \pm 1/2$ satisfy the conditions $|I-j| \leq J \leq |I+j|$ and $(-1)^l \Pi(I) = \Pi(J)$. The factor $F(E_{ni}) = \Sigma_{lj} T_{nlj}(E_{ni}) / \Sigma_{l'j'q} T_{nl'j'}(E_{nq})$ in the Hauser-Feshbach model corresponds to the relative probability of the neutron decay of the resonance with quantum numbers J^π to the ith level of

TABLE I. Experimental and calculated data for $^{119,117}Sb$.

E_{lev} keV	I^{π}	σ_{Ri} rel. un.	T^{opt}_{nlj}	T^{exp}_{nlj}	T^{exp}/T^{opt}	$\Gamma^{\dagger}_{ni}$ keV
^{119}Sb;0	$5/2^+$	70 ± 5	0.756	1.173	1.55 ± 0.11	1.13
644	$1/2^+$	30 ± 4	0.500	0.503[1]	1.0 ± 0.13	–
700	$3/2^+$	27 ± 4	0.326	0.453	1.39 ± 0.21	0.34
1327	$1/2^-$	91 ± 6	0.770	1.307	1.54 ± 0.1	1.46
1339	$3/2^+$	—	0.220	0.220[2)]	1.0	–
1413	$3/2^-$	78 ± 5	0.595	1.308	2.20 ± 0.14	1.93
1487	$1/2^-$	75 ± 5	0.764	1.258	1.65 ± 0.11	1.34
1646	$5/2^+$	31 ± 7	0.338	0.52	1.54 ± 0.35	0.49
1680	$1/2^+$	28 ± 3	0.405	0.47	1.16 ± 0.12	0.18
1750	$3/2^+$	12 ± 3	0.155	0.2	1.30 ± 0.32	0.12
1821	$1/2^+$	23 ± 4	0.390	0.386[1)]	1.0 ± 0.17	–
1875	$3/2^+$	10 ± 6	0.130	0.168	1.29 ± 0.77	0.11
—	$1/2^+$	—	0.356	0.356[2)]	1.0	–
2130	$5/2^+$	35 ± 7	0.190	0.231	1.22 ± 0.21	0.11
^{117}Sb;0	$5/2^+$	111 ± 5	0.436	0.770	1.77 ± 0.08	4.66
720	$1/2^+$	53 ± 3	0.367	0.367[1)]	1.0 ± 0.18	–
925	$3/2^+$	21.5 ± 2	0.077	0.149	1.94 ± 0.18	1.01
1355	$1/2^-$	78 ± 8	0.590	0.540	0.91 ± 0.10	–

[1)]Normalized values of T^{exp}

[2)]Assumed values of T^{exp} for one member of the doublet.

the final nucleus with I^{π}. The statistical character of the IAR decay into neutron channels is governed by the mechanism of the "external" mixing of the analog state with the set of neighboring compound-nucleus states that decay statistically in all the open neutron channels. It follows from (1) that for all the transitions from a given IAR we have $\sigma_{Ri} = \sigma(E_{ni}, E_p = E_R) = c\Sigma T_{nlj}(E_{ni})$. This simple connection between the resonant enhancement and the optical-model set of $T_{nlj}(E)$, which takes place only for purely statistical neutron decay of the IAR, served as the starting point for a large number of investigations, in which the dependence of T_{nlj} on J^{π} and I^{π} was used to determine the unknown values of I^{π}.

An analysis of our experimental data[2] and the values of σ_{Ri} from the published papers[3,4] has revealed two cases in which the statistical-decay condition $\sigma_{Ri} = c\Sigma T_{nlj}(E_{ni})$ is not satisfied, namely, an "excess" enhancement of σ_{Ri} is observed and can be attributed to the contribution of the direct neutron decay of the IAR. Indeed, the partial widths $\Gamma^{\dagger}_{ni}$ are determined by the structure of simple states (such as analog, configuration, etc.), so that their distribution can differ greatly from statistical. By virtue of this difference, a distinction must be made between the statistical and direct neutron decays, and the partial cross section must be represented in the form $(E_p = E_r)$

$$\sigma_{Ri} = 4\pi\lambdabar^2 g \Gamma_p \Gamma^{-2} (\Gamma_n^{\downarrow} F_{ni} + \Gamma_{ni}^{\uparrow}). \tag{2}$$

After summing over all the open channels $(\Sigma_i F_{ni} = 1)$ we obtain the known expression for the total cross section:

$$\sigma_R = \sum_i \sigma_{Ri} = 4\pi\lambdabar^2 g \Gamma_p \Gamma^{-2} (\Gamma_n^{\downarrow} + \Gamma_n^{\uparrow}), \quad \Gamma_n^{\downarrow} + \Gamma_n^{\uparrow} = \Gamma - \Gamma_p, \tag{3}$$

which is obtained in the IAR theory[5] in the case of small T_p and Δ. The difference $\Gamma - \Gamma_p$ corresponds to the total spread width of the IAR, which can be subdivided into $\Gamma_n^{\downarrow}$ (statistical decay) and $\Gamma_n^{\uparrow}$ (direct decay).

We consider now by way of example the results of an analysis, by formulas (2) and (3), of the experimental data of[3], where the values of σ_{Ri} were measured in the reactions ^{117,119}Sn(p,n) ^{117,119}Sb in the region of IAR with $J^{\pi} = 0^+ (E_R = 4.491$ MeV and 4.642 MeV), which are analogs of the ground states of the nuclei ^{118,120}Sn. In the decay of the 0^+ resonance, only one value $j = 1$ is realized, so that each transition corresponds to only one value of T_{nlj}.

Table I lists the energies of the levels of ^{119,117}Sb, their quantum numbers, the experimental values of σ_{Ri}, the calculated values of T_{nlj}^{opt}, the experimental values T_{nlj}^{exp} obtained from σ_{Ri} by normalization to the data for the levels $\frac{1}{2}^+ (T_{nlj}^{\text{exp}} = T_{n0}^{\text{opt}} \sigma_{Ri}/\sigma_{R0})$, the ratios $T^{\text{exp}}/T^{\text{opt}}$, and the values of $\Gamma_{ni}^{\uparrow}$ calculated from formulas (2) and (3). The level energies E_{lev} and the values of I^{π} were refined and supplemented to agree with the latest spectroscopic data,[6] since an exact knowledge of all the levels and their quantum numbers is a mandatory condition for an unambiguous separation of $\Gamma_{ni}^{\uparrow}$. The values of $T_{nlj}^{\text{opt}}(E_{ni})$ were calculated by us on the basis of the optical potential described in[7], and their relative course duplicates the data of[3]. In contrast to[3], however, we carried out a single normalization of all the values of σ_{Ri} relative to the value of T_{n0} for each resonance. The choice of the $1/2^+$ levels for the normalization is not accidental: they have been reliably identified in direct reactions and γ decays, they have relatively large values of σ_{Ri}, and at the same time the ratios $\sigma_{Ri}/T_{nlj}^{\text{opt}}(E_{ni})$ for them are minimal.

The ratios $T^{\text{exp}}/T^{\text{opt}}$ are a measure of the resonant enhancement. For eight levels of ^{119,117}Sb (including the two normalization levels), the deviations from one do not exceed the measurement errors, but the other eight levels are characterized by an excess enhancement: an average value $T^{\text{exp}}/T^{\text{opt}} = 1.7$ and a maximum value 2.2.

To obtain the absolute values of $\Gamma_{ni}^{\uparrow}$ and $\Gamma_n^{\uparrow}$ we used the known data[4] on the total cross section $\sigma_R(E_p = E_R)$ and on Γ, namely $\sigma_R = 8.8$ mb and $\Gamma = 35$ keV for $E_R = 4.642$ MeV (^{120}Sb) and $\sigma_R = 5.5$ mb and $\Gamma = 32$ keV for $E_R = 4.491$ MeV (^{118}Sb). Substituting these values in (3) we find that $\Gamma_n^{\downarrow} + \Gamma_n^{\uparrow} = 32.65$ keV (for ^{120}Sb) and 30.75 keV (for ^{118}Sb). The ratio $\Gamma_n^{\uparrow}/\Gamma_n^{\downarrow} = \Sigma(T^{\text{exp}} - T^{\text{opt}})/\Sigma T^{\text{opt}}$, where the summation is over all the open channels, is 0.283 for ^{120}Sb and 0.226 for ^{118}Sb, and consequently $\Gamma_n^{\downarrow} = 25.45$ keV, $\Gamma_n^{\uparrow} = 7.21$ keV (^{120}Sb), and $\Gamma_n^{\downarrow} = 25.08$ keV and $\Gamma_n^{\uparrow} = 5.67$ keV (^{118}Sb). The partial widths

$$\Gamma^{\uparrow}_{ni} = \Gamma^{\uparrow}_{n} \frac{\Delta T^{\exp}(E_{ni})}{\Sigma \Delta T^{\exp}}$$

are given in Table I. The average value is $\overline{\Gamma}^{\uparrow}_{ni} = 1.11 \pm 0.21$ keV and the maximum is 4.66 keV. The obtained $\Gamma^{\uparrow}_{n}$ and $\Gamma^{\uparrow}_{ni}$ are essentially lower bounds of the widths, since it was assumed in the normalization that $\Gamma^{\uparrow}_{ni} = 0$ for the transitions $0^{+} \to 1/2^{+}$. If, however, these $\Gamma^{\uparrow}_{ni} > 0$, then the widths $\Gamma^{\uparrow}_{ni}$ must be increased for the remaining transitions. The accuracy of the widths is determined both by the error of $T^{\exp}$ and by the possible systematic error in the calculation of ΣT^{opt} over all the open channels, owing to the lack of exact data on the levels with large excitation energies.

Direct neutron decay of the 0^{+} IAR of ^{118,120}Sb has a selective character: it populates most intensively the single-particles $5/2^{+}$ and $3/2^{+}$ states in excess of the filled $Z = 50$ shells, and also the states with negative parity, which apparently have a structure proton $(d^{3/2}, d^{5/2})$ + phonon (3^{-}).

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