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Blocking effect in the $16^+ \rightarrow 16^+$ (p,t) transition on the isomeric $^{178}\mathrm{Hf}^{m2}$ target

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The availability of a target of $^{178}\mathrm{Hf}$ in its aligned four-quasiparticle, $J^\pi = 16^+$ isomeric state, has allowed to measure the effect of blocking of the aligned-quasineutron orbitals in the (p,t) reaction. The experimental ratio of cross sections $R = \sigma_{(16^+ \rightarrow 16^+)} / \sigma_{(0^+ \rightarrow 0^+)}$ agrees with a predicted value deduced from the known (p,t) cross section on odd Hf isotopes.

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The (p,t) reaction is known [1] to be a probe of pair correlations. The lowering of the $L = 0$ reaction strength observed [2–4] on odd N targets has been explained [2] by the blocking of the single-particle orbital. This lowering is systematically observed in deformed as well as in spherical nuclei far from N shell closure. The same effect should be expected on an even-even target in a neutron quasiparticle aligned state.

The production rate [5,6] of the long-lived $^{178}\mathrm{Hf}^{m2}$ isomer ($E_x = 2446$ keV, $T_{1/2} = 31$ yr, $J^\pi = 16^+$) makes possible using it as a target. The isomer is known [7] to be of a $K = 16$ aligned four-quasiparticle nature:

$$(\pi \tfrac{7}{2}[404])(\pi \tfrac{9}{2}[514])(\nu \tfrac{7}{2}[514])(\nu \tfrac{9}{2}[624]) \ .$$

Phenomenological [8] and microscopic [9] calculations support this interpretation. A $K = 16$ band with the same configuration is known [10] also in $^{176}\mathrm{Hf}$. We expect that the cross section for the $L = 0$ (p,t) transition from $^{178}\mathrm{Hf}^{m2}$ to the $K = 16$ bandhead in $^{176}\mathrm{Hf}$ ($J^\pi = 16^+$, $E_x = 3266$ keV) should be weaker than for the ground state to ground state transition, due to the blocking of the two orbitals of the aligned neutrons.

The effect of blocking of each of the two orbitals has been observed in (p,t) reactions on the odd Hf targets, $^{177}\mathrm{Hf}_{\mathrm{g.s.}}\ (\tfrac{7}{2}^-, \tfrac{7}{2}[514]) \rightarrow {}^{175}\mathrm{Hf}_{321}(\tfrac{7}{2}^-, \tfrac{7}{2}[514])$ and $^{179}\mathrm{Hf}_{\mathrm{g.s.}}(\tfrac{9}{2}^+, \tfrac{9}{2}[624]) \rightarrow {}^{177}\mathrm{Hf}_{348}(\tfrac{9}{2}^+, \tfrac{9}{2}[624])$ (see third column in Table I).

An estimation of the $(16^+ \rightarrow 16^+)$ cross section can be deduced from the known [3] $L = 0$ reaction cross section on Hf isotopes in their ground state: the ground state to ground state (p,t) cross section on an even-even target results from coherent contributions of many amplitudes and can be written as $\sigma_{(0^+ \rightarrow 0^+)} = (a_{7/2} + a_{9/2} + a_r)^2$ where $a_{7/2}$ and $a_{9/2}$ stand for the amplitude contributions for the transfer of a pair coupled to zero in the $\tfrac{7}{2}[514]$ and in the $\tfrac{9}{2}[624]$ orbitals respectively, and a_r for the contribution of all the remaining orbitals. Since a neutron pair cannot be transferred from an orbital occupied by a single particle, the cross section for reaction on the odd and on the metastable targets can be written as $\sigma_{(7/2^- \rightarrow 7/2^-)} = (a_{9/2} + a_r)^2$, $\sigma_{(9/2^+ \rightarrow 9/2^+)} = (a_{7/2} + a_r)^2$, $\sigma_{(16^+ \rightarrow 16^+)} = (a_r)^2$. By assuming that the amplitudes vary only smoothly with the target mass number, the variations can be neglected and the following relation is deduced:

$$\sigma_{(16^+ \rightarrow 16^+)} \simeq \left[\sqrt{\sigma_{(7/2^- \rightarrow 7/2^-)}} + \sqrt{\sigma_{(9/2^+ \rightarrow 9/2^+)}} - \sqrt{\sigma_{(0^+ \rightarrow 0^+)}} \right]^2 .$$

The expected cross section ratio can then be predicted to be

$$R = \sigma_{(16^+ \rightarrow 16^+)} / \sigma_{(0^+ \rightarrow 0^+)} = 0.32 \pm 0.05 \ .$$

The experiment on the $^{178}\mathrm{Hf}^{m2}$ target was performed by using a proton beam from the Orsay MP tandem accelerator. An incident energy of 19 MeV was chosen, since the (p,t) reaction cross section for the various isotopes of hafnium has already been measured [3] at this energy. The target was prepared by electrospraying of a 5 mm diameter deposit onto a 40 $\mu\mathrm{g/cm}^2$ carbon backing. The quantity of $^{178}\mathrm{Hf}^{m2}$ isomer in the target was deter-

TABLE I. Measurement of isotopic composition of the target.

Target Hf isotope	$\sigma\times N/10^{16}$ a	σ b	$N/10^{16}$
176	713±35	≤435±34	≥1.64±0.15
177	4380±100	≤342±14	≥12.8±0.6
178	1587±100	464±15	3.42±0.24
179	220±17	230±15	0.96±0.10
180	360±17	501±25	0.72±0.05

[a] N is the local isotopic thickness (number of atoms per square centimeter), σ is the maximum differential cross section (at $\theta_{\mathrm{lab}}=27°$) in μb/sr.

[b] From Ref. [3]; the upper limit is assimilated to the real value in our estimation of the expected R value.

mined by activity measurement to be 2.1×10^{14} atoms. Isomeric ratio (i.e., the numbers of hafnium nuclei in the isomeric state as compared to that in the ground state) and isotopic composition of the target shall be discussed below. Details about production of the isomer, chemical separation of Hf, and preparation of the target are given in Refs. [5,6].

Triton spectra were measured at five angles (4°, 12.5°, 27°, 42.5°, 55°) corresponding to the maxima and minima of the $L=0$ angular distributions [3], using a split-pole spectrometer and a position-sensitive, 75 cm long, 128 wires drift chamber. A partial spectrum is shown in Fig. 1. The overall energy resolution is 15 keV full width at half maximum. All peaks in the spectra have been identified. Impurities such as Zr and Pt are clearly present in the target. The $(16^+\rightarrow16^+)$ transition (known Q value: -6348.0 keV) is indicated by a vertical arrow (measured Q value: -6350.7 ± 4.0 keV). It can be stated from kinematical calculations, that this peak is free from any contamination originating from (p,t) reaction on another hafnium isotope or any identified impurity of the target, except the 4_1^+, 811 keV level of ^{194}Pt. The $^{196}\mathrm{Pt}(p,t)^{194}\mathrm{Pt}$ reaction has not been studied at 19 MeV, but the cross section for the population of the 4_1^+ level has been measured to be only 1% of the ground state cross section at 26 MeV [11] and at 35 MeV [12]. According to Ref. [13], one can deduce that this relative cross section is not larger at 17 MeV. Therefore, the contribution of this level to the observed peak is estimated to be less than a tenth of the observed intensity.

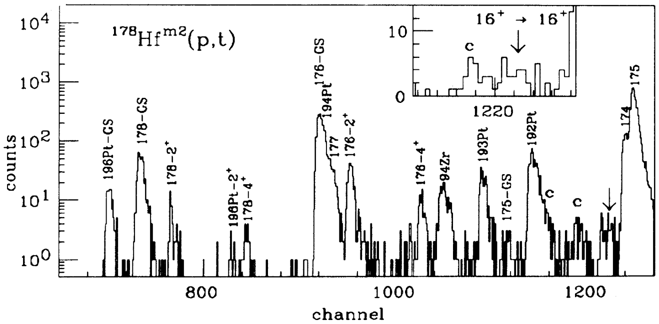

FIG. 1. Partial spectrum observed at 27°. The expected location of the $16^+\rightarrow16^+$ transition is indicated by a vertical arrow. All observed peaks are due to Hf isotopes or identified contaminants; the largest ones are labeled by their final state mass number and eventually their spin parity. Label c means identified contaminants.

The angular distribution obtained for the $(16^+\rightarrow16^+)$ transition together with the main $L=0$ transition on each Hf isotope present in the target are compared in Fig. 2 with typical experimental shapes [3] at the same energy. In spite of low statistics, the $(16^+\rightarrow16^+)$ angular distribution is reasonably well reproduced by this $L=0$ shape.

The knowledge of the isomeric ratio in the target is crucial for the measurement of the $R=\sigma_{(16^+\rightarrow16^+)}/$

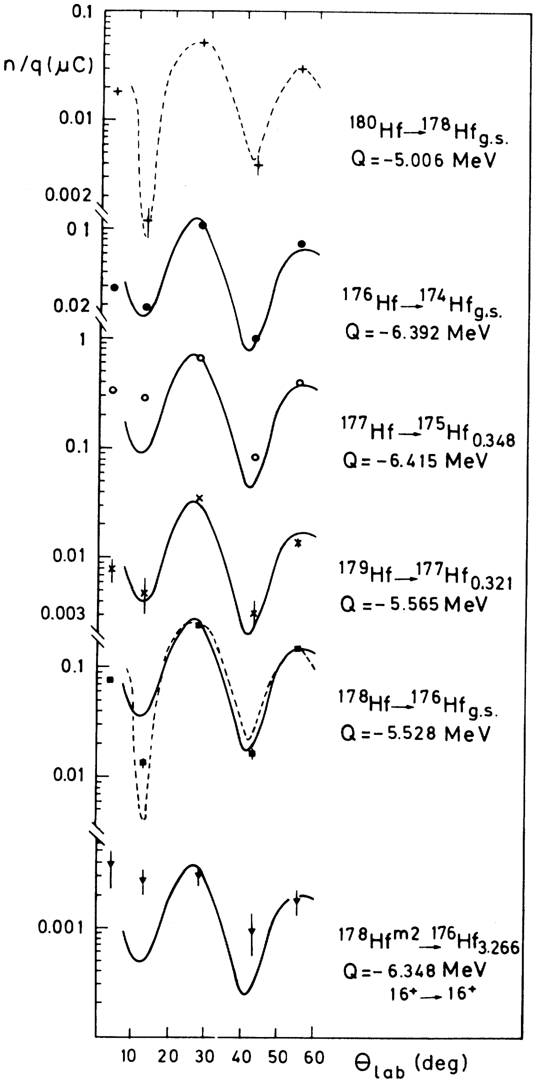

FIG. 2. Angular distribution obtained for the main $L=0$ transition on each Hf target. Curves are experimental shapes taken from Ref. [3], and obtained on Yb targets. As the distinctive $L=0$ oscillatory pattern is damped when the Q value becomes more negative, two shapes are shown for comparison; the dashed line corresponds to $Q=-4.216$ MeV, the continuous to $Q=-6.862$ MeV.

$\sigma_{(0^+\rightarrow 0^+)}$ ratio. The ^{178}Hf^{m2} isomer was produced [6], together with other Hf, by α bombardment of a ^{176}Yb target. The production rate of each hafnium isotope produced in the reaction was calculated [5,6]. For the radioactive isotopes, the calculated yields agreed with the results of activity measurements. From the calculated yield of stable ^{178}Hf, and from the measured activity of the ^{178}Hf^{m2}, the isomeric ratio was found to be 5.4% [6].

The ^{178}Hf lines observed in the present experiment (see Fig. 1) indicate that an unexpected quantity of ^{180}Hf isotope is present in the target. An estimation of the target isotopic composition is then necessary. As the number of counts measured for each transition is proportional to the product of the cross section and the target thickness, we deduce the *local* thickness from our measurements, and from the cross sections measured in Ref. [3]. The results are reported in Table I.

If it is supposed (assumption 1) that the unexpected quantity of ^{180}Hf observed in the target is due to some contamination by natural Hf, the corresponding added quantity of ^{178}Hf is easily deduced from natural abundance. If it is also supposed that the isomeric ratio of the originally produced ^{178}Hf^{m2} has the calculated value [6] (5.4%), the deduced isomeric ratio in the target is 4.5% and the ratio of the $(16^+\rightarrow 16^+)$ transition to the $(0^+\rightarrow 0^+)$ transition cross section is

$$R_1 = 0.27 \pm 0.05 \; .$$

Another estimation may be considered: if the target thickness is uniform (assumption 2), the product of the local thickness by the target area gives the total number of atoms for each isotope. With the above given number of isomer atoms in the target, the estimated isomeric ratio is 3.1% and the ratio of the $(16^+\rightarrow 16^+)$ transition to the $(0^+\rightarrow 0^+)$ transition cross section is

$$R_2 = 0.39 \pm 0.08 \; .$$

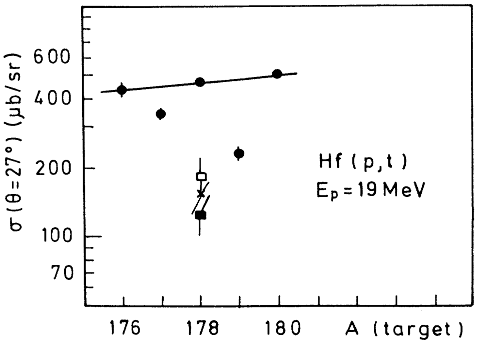

FIG. 3. Blocking effect in Hf(p,t) reaction. The black circles are values taken from Ref. [3]. The points corresponding to odd isotopes are quite under the straight line linking even isotopes points. The cross represents the deduced cross section for the $(16^+\rightarrow 16^+)$ transition. Measured cross section is represented by black square (assumption 1) or open square (assumption 2).

Neither of the two estimations of the isomeric ratio is really a measure, but their comparison indicates that they give a good estimation of the order of magnitude. As shown in Fig. 3, the experimental cross section for the (p,t) transition from the 16^+ isomeric state ^{178}Hf^{m2} is in agreement, within uncertainties, with the expected value.

In conclusion, the present study has allowed to measure the extent of blocking observed in the (p,t) reaction on a target of ^{178}Hf in the 16^+ isomeric aligned-quasiparticle state. The result is in agreement with the predicted value deduced from the (p,t) reaction on odd Hf isotopes. Other transfer reactions on ^{178}Hf in this isomeric state are planned with a new target which will be made free from contamination by using an isotopic separation of the hafnium material.

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