Low-lying dipole excitations in the heavy, odd-mass nucleus ^{181}Ta

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The strength distribution of low-lying dipole excitations in the heavy odd-mass nucleus ^{181}Ta was studied in nuclear resonance fluorescence experiments performed at the bremsstrahlung beam of the Stuttgart 4.3 MV Dynamitron accelerator. To increase the detection sensitivity in the whole range of excitation energies between 1.8 and 4 MeV two measurements were carried out at different bremsstrahlung end-point energies of 2.7 and 4.1 MeV using two large-volume HPGe detectors of a relative efficiency of 100%. Detailed information on excitation energies, decay widths, transition probabilities, and branching ratios of 37 new low-lying states in the energy range 1.8–3.5 MeV have been obtained. The observed dipole strength is rather fragmented, apart from a strong excitation at 2.297 MeV. The total strength in the investigated range of excitation energies (1.8–4 MeV) is reduced by a factor of ≈ 3.5 as compared to the neighboring even-even nucleus ^{180}Hf. [S0556-2813(98)02308-5]

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I. MOTIVATION

The dipole strength distributions in heavy even-even nuclei, both of electric and magnetic character, were subjects of recent systematic studies in nuclear structure physics (see, e.g., [1,2]). New, rather collective excitations have been observed like the orbital $M1$ ''scissors mode'' in deformed nuclei [3] or $E1$ two-phonon excitations in spherical, semimagic nuclei [4,5]. Comprehensive systematics could be established for these modes, mainly by nuclear resonance fluorescence (NRF) experiments, in even-even nuclei [1,2,6,7]. On the other hand, corresponding experiments on the neighboring odd-mass isotopes provided surprising results.

The coupling of an additional neutron to the two-phonon excitation in ^{142}Nd leads to a $2^+ \otimes 3^- \otimes$ particle multiplet in ^{143}Nd, which could be observed experimentally [8,9]. However, in the nuclei ^{139}La and ^{141}Pr, differing by one proton from the neighboring $N=82$ isotones ^{138}Ba and ^{140}Ce, respectively, only about 40% of the expected dipole strengths could be observed in NRF experiments [10].

The different fragmentation of the $M1$ ''scissors mode'' and the reduction of the experimentally observed total strength in odd-mass rare earth nuclei [11–14] was an open problem for a long time. The puzzle of the lacking strength was able to be solved recently. Statistical fluctuation analyses of the corresponding NRF spectra showed that a considerable part of the strength is hidden in the continuous background of the spectra [15,16].

The $M1$ ''scissors mode'' represents a rather common excitation mode, which is not restricted to deformed rotor nuclei, like the isotopes in the rare earth or actinide region. This is documented by the first observation of this mode in γ-soft nuclei [O(6) nuclei] like ^{196}Pt [17] or ^{134}Ba [18]. In ^{133}Cs, differing by one proton from its even-even neighboring isotope ^{134}Ba, a strong reduction of the detectable total dipole strength was observed in recent NRF experiments [19], resembling the situation in the rare earth nuclei.

The aim of the present investigation was to study the fragmentation of the dipole strength in the mass region near ^{196}Pt, the isotope which is regarded to be one of the best candidates of a γ-soft O(6) nucleus [17,20]. As a target nucleus we have chosen ^{181}Ta since the dipole strength distributions in its even-even neighbors ^{180}Hf and ^{182}W are known from our previous NRF experiments [21,22]. Furthermore, ^{181}Ta is nearly monoisotopic in the natural abundance of the element tantalum. In addition, the odd-odd isotope ^{180}Ta, occurring with a very small relative abundance of 1.2×10^{-4} is a nucleus of fundamental interest. ^{180}Ta is ''stable'' as an isomer ($T_{1/2}\geq 1.2\times10^{15}$ yr), while its ground state decays with a half-life of 8.1 h. The nucleosynthesis of ^{180}Ta remains still a puzzle. The photoactivation of the ^{180}Ta isomer and its depopulation was the subject of several recent experiments [23–26]. The most direct way to study this photoactivation process would be NRF experiments on ^{180m}Ta. However, extremely expensive samples of this isotope are only available in quantities of ≤ 200 mg with a low relative enrichment of about 5%. The present study on ^{181}Ta should also provide, as precise as possible, information on the dipole strength distribution in ^{181}Ta to allow realistic estimations of the feasibility of a direct NRF experiment on ^{180m}Ta.

II. EXPERIMENTAL METHOD AND TECHNIQUES

A. NRF technique

The NRF process, the resonant absorption of real photons by an atomic nucleus and the subsequent deexcitation of the photoexcited level by γ decay, offers the advantage of an

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extreme selectivity for excitations of low multipolarity, mainly dipole excitations. Therefore, the NRF method represents by far the most sensitive technique to study dipole excitations even in ranges of excitation energies with a high level density, e.g., in odd-mass nuclei or odd-odd isotopes. The formalism describing NRF experiments is summarized in previous publications (e.g., [2,27]). From experiments using continuous bremsstrahlung as the photon source the total cross section integrated over one resonance and the full solid angle can be extracted:

$$I_{s,f}=g\left(\pi\frac{\hbar c}{E_\gamma}\right)^2\frac{\Gamma_0\Gamma_f}{\Gamma}. \tag{1}$$

Here Γ_0, Γ_f, and Γ are the decay widths of the photoexcited state with spin J to the ground state, to a final lower-lying state, and its total width, respectively. The statistical factor $g=(2J+1)/(2J_0+1)$ is called the ''spin factor.'' The product $g\Gamma_0$, which can be directly extracted from the measured scattering intensities, is proportional to the reduced excitation probabilities $B(E1)\uparrow$ or $B(M1)\uparrow$,

$$B(\Pi 1)\uparrow=g\ B(\Pi 1)\downarrow=\frac{9}{16\pi}\left(\frac{\hbar c}{E_\gamma}\right)^3(g\Gamma_0), \tag{2}$$

and in numerical form

$$B(E1)\uparrow=0.955\,\frac{g\Gamma_0}{E_\gamma^3}[10^{-3}\ e^2\ \mathrm{fm}^2], \tag{3}$$

$$B(M1)\uparrow=0.0864\,\frac{g\Gamma_0}{E_\gamma^3}[\mu_N^2]. \tag{4}$$

Here the excitation energies E_x are in MeV and the ground-state transition widths Γ_0 in meV.

Unfortunately, in the case of odd-mass target nuclei the angular distributions of the scattered photons are less anisotropic than in the case of even-even nuclei. Therefore, in particular for odd-mass nuclei with higher ground-state spins like $J_0=5/2$, 7/2, etc. (^{181}Ta has a ground-state spin of $J_0^\pi=7/2^+$), the modest angular resolution of the setup and the limited statistics of the present experiments do not allow one to measure precisely the lower anisotropies to assign unambiguously spins to the photoexcited states. The low anisotropies in the angular distributions in addition lead to rather low degrees of polarization of the scattered photons. As a consequence no parity assignments were possible by polarization measurements in the present experiments in contrast to the case of even-even nuclei. For the comparison with the dipole strengths in even-even nuclei we introduce the quantity $g\Gamma_0^{\mathrm{red}}$:

$$g\Gamma_0^{\mathrm{red}}=g\,\frac{\Gamma_0}{E_\gamma^3}, \tag{5}$$

which is proportional to the reduced dipole excitation probabilities [see Eqs. (3) and (4)].

The decay branching ratio R_{expt} for the decay back to a low-lying excited state and to the ground state, respectively, is defined by

$$R_{\mathrm{expt}}=\frac{B(\Pi L;\ J\rightarrow J_f)}{B(\Pi L;\ J\rightarrow J_0)}=\frac{\Gamma_f}{\Gamma_0}\,\frac{E_{\gamma J_0}^3}{E_{\gamma J_f}^3}. \tag{6}$$

For deformed nuclei the branching ratio R_{expt} provides valuable information on the K quantum number K of the excited state within the validity of the Alaga rules [28].

B. Experiments

The present NRF experiments on ^{181}Ta were performed at the bremsstrahlung facility of the Stuttgart Dynamitron accelerator [2,12,29]. To increase the detection sensitivity in the entire range of excitation energies of interest (1.8–4 MeV), experiments were performed at two different bremsstrahlung endpoint energies of 2.7 and 4.1 MeV. Here electron currents of about 250 μA on the bremsstrahlung production target were used in the present experiments. The scattering target consisted of six metallic Ta sheets (diameter 16 mm) with a total mass of 5459 mg which were alternatively put into layers with six Al sheets of the same diameter and a total mass of 1527 mg. The isotope ^{27}Al has several excited states at low energies with absolutely and rather precisely known decay widths [30]. Therefore, the Al sheets served as an internal standard for the absolute photon flux calibration, a technique which is nowadays a common normalization method in all low-energy NRF experiments [31,32]. The scattered photons were detected by three high-resolution Ge γ-ray spectrometers installed at angles of about 90°, 127°, and 150° with respect to the incoming bremsstrahlung beam. The two high-efficiency detectors with efficiencies of $\approx$100% [relative to a standard 7.6 cm$\times$7.6 cm NaI(Tl) detector] were set up at 90° and 127°, respectively. Under 150° a third detector was installed with a moderate relative efficiency of 22%. The total time of data collection was 104 h at a bremsstrahlung end-point energy of $E_0=4.1$ MeV and 34 h for the measurements with $E_0=2.7$ MeV.

III. RESULTS AND DISCUSSION

In Figs. 1 and 2 the spectra of the scattered photons are depicted as measured with bremsstrahlung end-point energies E_0 of 2.7 and 4.1 MeV, respectively. The low-energy part (up to 2.7 MeV) is shown in Fig. 1 in two panels, documenting the increased sensitivity of the measurement with a lowered bremsstrahlung end-point energy (upper part) due to a considerable reduction of the continuous background from nonresonant scattering. The spectra represent the sum spectra taken by the two 100%-efficiency Ge detectors installed at scattering angles of 90° and 127°. Obviously, the low-energy spectra are dominated by a strong excitation at 2297 keV. Besides the labeled ^{27}Al peaks (photon flux calibration) and a background line (^{208}Pb) some weak excitations can be seen around 2250 keV in the upper spectrum ($E_0=2.7$ MeV). Another concentration of fragmented strength could be observed at higher excitation energies (3000–3100 keV) as shown in Fig. 2, where the high-energy part of the spectrum is depicted.

The observed intensity ratios $W(90°)/W(127°)$ agree within their errors with unity, corresponding to a nearly iso-

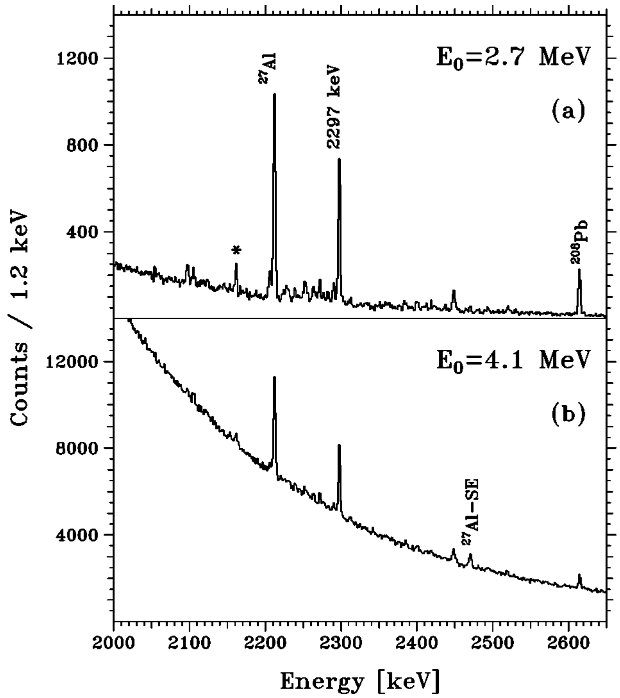

FIG. 1. Upper panel: spectrum of photons scattered off ^{181}Ta in the energy range 2.0–2.7 MeV measured at a bremsstrahlung end-point energy of 2.7 MeV. The spectrum represents the sum of the spectra taken by the two 100%-efficiency Ge detectors installed at scattering angles of 90° and 127°, respectively. Labeled peaks stem from the photon flux standard ^{27}Al, from background (^{208}Pb), or are single escape (SE) peaks. The peak marked by an asterisk corresponds to the decay of the 2297 keV level to the low-lying excited state at 136.3 keV. Lower panel: spectrum of photons scattered off ^{181}Ta in the energy range 2.0–2.7 MeV measured at a bremsstrahlung end-point energy of 4.1 MeV. For explanations see above.

tropic angular distribution, as expected for ^{181}Ta with its high, half-integer ground-state spin $J_0^\pi = 7/2^+$.

In Table I the results of the present experiment are summarized. Excitation energies E_x (uncertainties $\leqslant 1$ keV), integrated scattering cross sections $I_{s,0}$, and the products $g\Gamma_0$ of the spin factor g and the ground-state decay width Γ_0 are

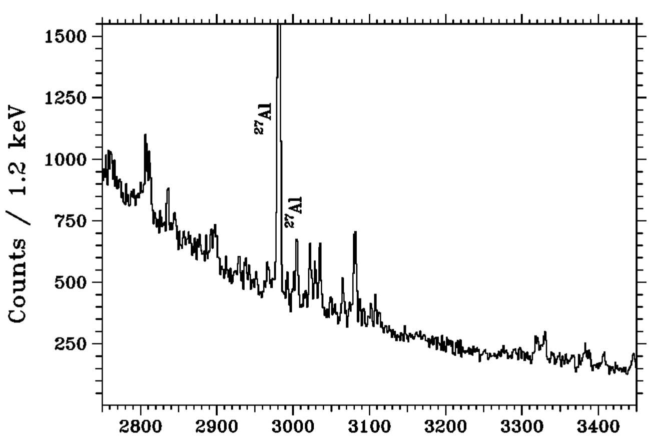

FIG. 2. Spectrum of photons scattered off ^{181}Ta in the energy range 2.8–3.4 MeV measured at a bremsstrahlung end-point energy of 4.1 MeV. For explanations see caption of Fig. 1.

given. The decay branching ratios $R_{\rm expt}$ are quoted in cases where a decay to the first excited state at 6.2 keV ($J^\pi = 9/2^-$, bandhead of the low-lying $K = 9/2$ band) or to the second excited state at 136.2 keV ($J^\pi = 9/2^+$ of the $K = 7/2$ ground-state rotational band) could be observed. In all other cases where no decay branching could be detected the quantity $g\Gamma_0$ has been deduced assuming an exclusive ground-state transition ($\Gamma_0 = \Gamma$).

In Fig. 3 the dipole strength distribution in ^{181}Ta is depicted in the lower panel and compared to the strength distribution in the neighboring even-even nucleus ^{180}Hf [21]. For ^{181}Ta the products of the reduced transition probability $\Gamma_0^{\rm red}$ and the spin factor $g = (2J+1)/(2J_0+1)$ are plotted as a function of the excitation energy. For ^{181}Ta the spin factor g can be 3/4, 1, or 5/4 for dipole excitations to levels with spins $J = 5/2$, 7/2, or 9/2, respectively. For the even-even nucleus the spins of the excited levels are 1 and therefore the spin factor is known and amounts to $g = 3$. The product $g\Gamma_0^{\rm red}$ is proportional to the reduced transition probabilities [see Eqs. (3) and (4)].

Surprisingly for an odd nucleus, a very strong dipole excitation was observed at 2.297 MeV in ^{181}Ta, which clearly dominates the strength distribution. Its strength amounts to about $B(M1)\uparrow \approx 0.28\mu_N^2$ or $B(E1)\uparrow \approx 3.1\times 10^{-3}\ e^2\ {\rm fm}^2$ depending on the parity of the level. Unfortunately, both the spin J and the parity of this 2297 keV level are unknown. Comparing the measured decay branching ratio $R_{\rm expt} = 0.24 \pm 0.03$ (for the decay to the ground state and the $J^\pi = 9/2^+$ state of the $K = 7/2$ ground-state rotational band) with the prediction of the Alaga rules the assignments $(J,K) = (7/2, 7/2)$ or $(9/2, 9/2)$ are possible. Besides this strong excitation at 2.297 MeV the strength distribution shows a strong fragmentation with some strength concentrations around 2.4 and 3.1 MeV, respectively. In the energy range above 3.4 MeV no dipole excitations could be observed in ^{181}Ta in contrast to the results for ^{180}Hf. The reason for that probably is an increased strength fragmentation in the odd-mass nucleus.

For a deformed even-even nucleus like ^{180}Hf the observed dipole excitations can be classified by the decay behavior of the excited states which can be used for a K number assignment. Empirically it was shown that all strong $\Delta K = 0$ dipole excitations have $E1$ character [6] whereas strong $\Delta K = 1$ dipole transitions correspond to $M1$ transitions as shown in all our previous polarization measurements [2]. Therefore, parities can be tentatively assigned from the deduced K numbers within the validity of these ''rules'' supported by systematical experimental findings. In the upper panel of Fig. 3 the dipole strength distribution in ^{180}Hf now can be separately given for $\Delta K = 1$ excitations (solid bars) and transitions with $\Delta K = 0$ or excitations to spin-1 levels without an observed decay to the first excited state (open bars). The figure shows that there is no distinctly different behavior of the strength distribution patterns of $E1$ and $M1$ excitations in the even-even nucleus ^{180}Hf.

In the following we want to discuss the total dipole strength observed in ^{181}Ta and to compare it with the results for the neighboring even-even nucleus ^{180}Hf. The total strength observed in ^{181}Ta (1.8–4 MeV; all errors were added linearly) amounts to $\Sigma_{1.8-4\ {\rm MeV}}\, g\Gamma_0^{\rm red} = (14.9 \pm 2.2)$

TABLE I. Results of the present ^{181}Ta(γ,γ') experiment: Excitation energies E_x, integrated elastic resonance scattering cross sections $I_{s,0}$, the products $g\Gamma_0$ of the spin factor g and the ground-state decay widths Γ_0, the products $g\Gamma_0^{\rm red}$ of the spin factor g and the reduced ground-state decay widths $\Gamma_0^{\rm red}$, and observed experimental decay branching ratios $R_{\rm expt}$ are given. In cases where no decay branching could be detected the quantity $g\Gamma_0$ has been deduced assuming $\Gamma_0=\Gamma$.

E_x [keV]	$I_{s,0}$ [eV b]	$g\Gamma_0$ [meV]	$g\Gamma_0^{\rm red}$ [meV/MeV^3]	$R_{\rm expt}$
1866	5.43±0.86	4.92±0.78	0.76±0.12	
1935	4.23±0.64	4.12±0.63	0.57±0.09	
2097	2.21±0.52	2.53±0.60	0.27±0.06	
2105	3.65±0.68	4.21±0.79	0.45±0.08	
2240	2.15±0.49	2.81±0.64	0.25±0.06	
2253	2.88±0.53	3.81±0.71	0.33±0.06	
2272	3.62±0.59	4.86±0.79	0.41±0.07	
2289	3.25±0.55	4.43±0.75	0.37±0.06	
2297	23.65±2.52	39.00±3.91	3.22±0.32	0.24±0.03[b]
2400	2.41±0.45	7.65±1.18	0.55±0.09	1.33±0.28[b]
2418	2.11±0.44	5.28±0.96	0.37±0.07	0.65±0.18[a]
2448	5.45±0.72	11.95±1.53	0.81±0.10	0.48±0.09[b]
2519	2.40±0.43	3.96±0.71	0.25±0.04	
2761	1.64±0.35	3.25±0.70	0.15±0.03	
2800	1.07±0.31	2.18±0.64	0.10±0.03	
2807	3.76±0.53	7.71±1.08	0.35±0.05	
2812	3.07±0.46	6.32±0.95	0.28±0.04	
2835	2.49±0.41	5.21±0.87	0.23±0.04	
2845	1.57±0.35	3.31±0.73	0.14±0.03	
2892	1.68±0.35	3.66±0.77	0.15±0.03	
2898	3.14±0.46	6.86±1.00	0.28±0.04	
2929	1.50±0.34	3.35±0.75	0.13±0.03	
2967	3.02±0.42	6.92±0.96	0.26±0.04	
3016	1.34±0.31	3.17±0.73	0.12±0.03	
3023	4.65±0.56	11.06±1.34	0.40±0.05	
3029	4.06±0.51	9.70±1.23	0.35±0.04	
3035	5.75±0.65	13.79±1.55	0.49±0.06	
3054	1.24±0.29	6.55±1.13	0.23±0.04	1.18±0.29[a]
3065	2.88±0.41	7.04±1.01	0.24±0.04	
3074	1.43±0.31	8.49±1.37	0.29±0.05	1.62±0.36[b]
3081	8.99±0.95	22.21±2.35	0.76±0.08	
3086	2.37±0.38	5.87±0.94	0.20±0.03	
3092	1.46±0.31	3.63±0.78	0.12±0.03	
3108	2.58±0.40	12.17±1.55	0.41±0.05	0.88±0.14[a]
3320	2.99±0.44	8.58±1.26	0.23±0.03	
3329	3.17±0.45	9.14±1.29	0.25±0.04	
3407	2.13±0.37	6.44±1.11	0.16±0.03	

[a]Branching to the excited $9/2^-$ state at 6.2 keV (bandhead of the low-lying $K=9/2$ band).
[b]Branching to the excited $9/2^+$ state at 136.3 keV (first excited state in the $K=7/2$ ground-state rotational band).

meV/MeV^3. This value would correspond to total reduced transition probabilities of $\Sigma_{1.8-4\,\rm MeV}\,B(E1)\uparrow=(14.3\pm2.1)\times10^{-3}\,e^2\,\rm fm^2$ or $\Sigma_{1.8-4\,\rm MeV}\,B(M1)\uparrow=(1.29\pm0.19)\mu_N^2$, assuming exclusively $E1$ or $M1$ excitations, respectively. These total strengths are about a factor of 3.5 lower than those observed in the neighboring even-even nucleus ^{180}Hf [21].

In a recent publication [6] we proposed a consistent summing procedure for the total $M1$ strength that should be attributed to the $M1$ scissors mode. From this considerations, the strength added up in the energy interval 2.4–3.7 MeV should be regarded for nuclei with an atomic number $Z\geqslant68$. The total strength observed for ^{181}Ta in this energy range is $\Sigma_{2.4-3.7\,\rm MeV}\,g\Gamma_0^{\rm red}=(8.3\pm1.3)$ meV/MeV^3. This value would correspond to total reduced transition probabilities of $\Sigma_{2.4-3.7\,\rm MeV}\,B(E1)\uparrow=(7.9\pm1.2)\times10^{-3}\,e^2\,\rm fm^2$ or

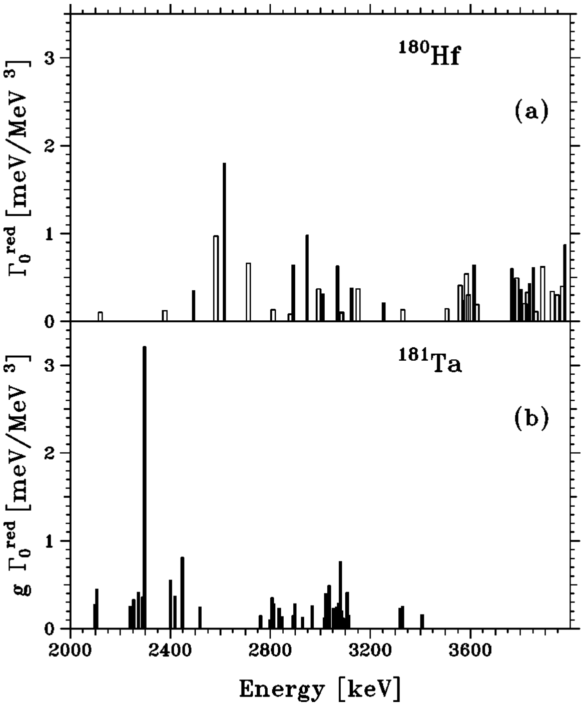

FIG. 3. Comparison of dipole strength distributions in ^{180}Hf [upper panel (a)] and ^{181}Ta [lower panel (b)]. Plotted as a function of the excitation energy are the quantities $\Gamma_0^{\rm red}$ for the even-even nucleus ^{180}Hf, where the spin factor is known to be $g=3$, and $g\Gamma_0^{\rm red}$ for the odd-mass nucleus ^{181}Ta. Here $g\Gamma_0^{\rm red}$ is proportional to the reduced excitation probabilities $B(E1)\uparrow$ or $B(M1)\uparrow$. In the upper panel solid bars correspond to $\Delta K=1$ transitions; the open bars correspond to $\Delta K=0$ transitions or to transitions with unknown ΔK (see text and Ref. [21]).

$\Sigma_{2.4-3.7\ \rm MeV}\ B(M1)\uparrow=(0.72\pm0.11)\mu_N^2$, assuming exclusively $E1$ or $M1$ excitations, respectively. In the neighboring nucleus ^{180}Hf the $E1$ and $M1$ fractions are about equal. Therefore, following the systematic investigations to explain the missing strengths of the $M1$ scissors mode in odd-mass nuclei [15,16], we assume that only about 50% of the observed strength in ^{181}Ta can be attributed to the scissors mode (about $0.35\mu_N^2$). This value is about a factor of 3–4 lower than expected from the systematics of the scissors mode strengths for even-even nuclei [6]. This fact suggests the assumption that the overwhelming part of the $M1$ strength in the heavy odd-mass nucleus ^{181}Ta is hidden in the continuous background of the NRF spectra, even more as shown for odd-mass rare earth nuclei [15,16].

To come back to the astrophysical problem of the photoactivation process of ^{180m}Ta, one has to state that the observed strong fragmentation of the dipole strength in ^{181}Ta into many weak excitations seems to prevent the highly desired direct NRF experiment on ^{180m}Ta, at least in the energy range 2–4 MeV investigated in the present experiments. Since the rare odd-odd isotope ^{180m}Ta is only available in small quantities (some mg's) of rather low enrichment ($\approx5\%$), representing the world's stock, it would be very difficult to assign unambiguously weak excitations observed in direct NRF studies to photoexcitations of ^{180m}Ta. Therefore, inclusive photoexcitation experiments of enriched Ta samples by measuring activation yield curves in bremsstrahlung experiments seem to be the only choice at present to study this interesting problem.

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