carrying out such an experiment. Clearly, this and other types of correlation studies will do much toward improving our understanding of the central collision processes.

It is hoped that the results of the present communication will add further stimulus to both the experimental study of relativistic central nuclear collisions and the much needed complementary theoretical development.

We wish to thank the Bevalac operating crew and James Brannigan for his continuous support. This work is supported by the U. S. Department of Energy under Contract No. DE-AT03-80-ER-10626.

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Decay of the Giant Gamow-Teller Resonance in ^{208}Bi

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(Received 12 November 1980)

In coincidence with tritons from the ^{208}Pb(^{3}He, t)^{208}Bi reaction proton spectra corresponding to decay into definite final states in ^{207}Pb have been measured. The coincidence yield is described as exclusively coming from the decay of two resonances, the isobaric analog state (IAS) and the Gamow-Teller (GT) resonance. An analysis in terms of a formation cross section times a branching ratio gives a good description for the IAS and for the shape of the GT resonance. The yield from the GT resonance is, however, an order of magnitude larger than calculated.

PACS numbers: 21.60.-n, 24.30.-v, 25.40.+k

Recent (p,n) experiments[1,2] have demonstrated that a significant part of the total Gamow-Teller (GT) strength in heavy nuclei is collected in a state with an energy somewhat above the isobaric analog state (IAS) and a width around 4 MeV. The structure of the state is believed to be characterized by a coherent sum of proton-particle–neutron-hole states. In this paper we report on the decay of the GT state in ^{208}Bi. The 1^+ state is formed in the ^{208}Pb(^{3}He,t)^{208}Bi reaction. In coincidence with the tritons measured at $\theta = 0°$, we measure the emitted protons leaving the ^{207}Pb nucleus in definite final states.

The experiments were performed at the cyclotron facility of the Kernfysisch Versneller Instituut, Groningen. The ^{3}He beam energy was 81 MeV, the highest energy practical for bending the relevant tritons in the QMG/2 magnetic spectrograph.[3] The tritons were recorded in the focal-plane detector[3] with the spectrograph placed at θ_t

$=0°$ with a solid angle of 7.5 msr. The protons were detected in two ΔE-E telescopes with solid angles of 70 msr each and placed at $\theta_p = 130°$ and 155° and in a separate run at $\theta_p = 90°$ and 130°. The target was a self-supporting foil of ^{208}Pb of around 0.5 mg/cm^2. The energy resolution for the tritons was 50 keV and for the protons around 250 keV. The ^{3}He beam was stopped inside the first dipole of the spectrograph several meters from the target, and this allowed a beam current of ~100 nA mainly limited by a proton count rate from the (^{3}He; xp,yn) reaction in the target. The data were recorded event by event to facilitate further analysis.

The decay into definite states in ^{207}Pb is characterized by events where $E_t + E_p$ is constant. Figure 1 shows the yield of t-p coincidences for protons at $\theta_p = 130°$. The data are obtained in several independent runs with different field settings. The data shown in Fig. 1 correspond to a collected charge of 20 000 μC or around 80 h of effective beam on target. The contribution from random coincidences fulfilling the different conditions for being accepted as protons decaying into definite final ^{207}Pb states is very small, and the error bars given in the figure are mostly statistical.

We note that all the one-hole states in ^{207}Pb up to and including the $h_{9/2}$ hole state are populated, the yield for decay into the $h_{9/2}$ hole state at $E_x = 3.4$ MeV being an upper limit since the present proton-energy resolution does not allow a separation of yield into near-lying levels.

The data are consistent with an assumption of formation and subsequent decay of two resonances in ^{208}Bi, namely the 0^+ IAS at $E_x = 15.2$ MeV and a 1^+ GT resonance at 15.6 MeV with $\Gamma = 4.1$ MeV. The latter numbers are from recent ^{208}Pb(p,n)-^{208}Bi experiments by Horen *et al.*[2] with proton energies $E_p = 120$–200 MeV. The singles spectrum given in Fig. 1 shows that in the (^{3}He,t) reaction at this energy the GT resonance is completely buried in the continuum. This is similar to the situation for (p,n) reactions below $E_p = 45$ MeV,[4] whereas the GT resonance in (p,n) spectra at $E_p > 120$ MeV is large compared to the continuum.

Part of the continuum in the triton spectra comes from elastic breakup of ^{3}He followed by a (d,t) reaction and such a process will also contribute to a t-p coincidence yield, but this yield will be extremely forward peaked.[5] In the coincidence proton spectra with $\theta_p = 90°$ we do observe a nonresonant yield especially in the decay into the $\frac{1}{2}^-$ and $\frac{3}{2}^-$ hole states in ^{207}Pb, and this favoring of low-angular-momentum states is consis-

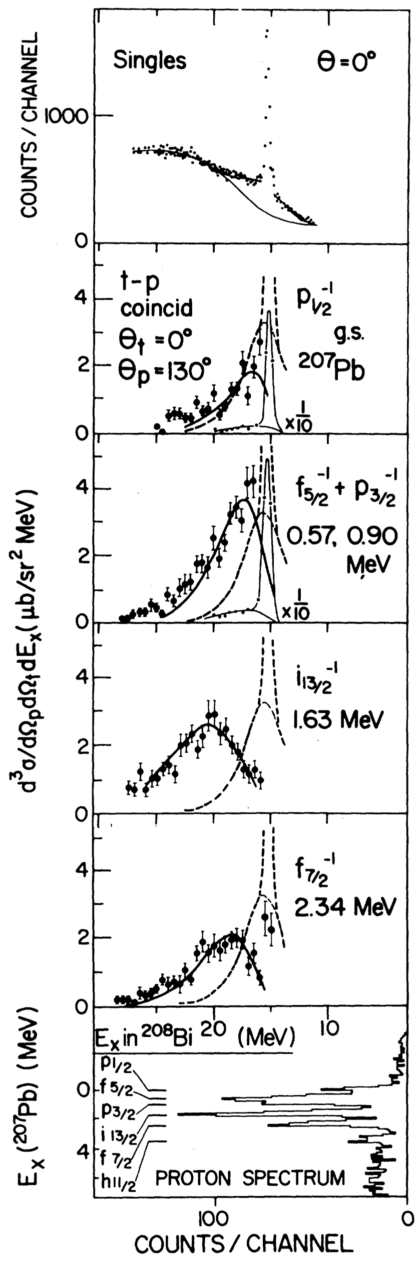

FIG. 1. Singles and coincidence spectra. In the singles spectrum a resonance is shown with a width of 4.1 MeV (Ref. 2) and an area of 3 mb/sr. In the coincidence spectra this resonance is used as the common formation cross section (dashed). The full drawn curves are obtained as the formation cross section folded with the single-particle widths, and normalized in accordance with the numbers in Table I. The bottom part shows a coincidence spectrum projected onto the proton energy axis for triton energies corresponding to E_x (^{208}Bi) 17–25 MeV (i.e., not including IAS).

tent with assigning this nonresonant yield to the breakup process. At $\theta_p = 130°$ and $155°$ the nonresonant yield is very small, and we shall in the following analysis assume that it can be neglected or rather that interference effects with possible nonresonant amplitudes are small. In this connection we note that the neutron decay from low-spin compound states in the excitation region considered is favored over proton decay by a factor larger than 300. It is therefore the special particle-hole structure for the IAS and GT resonances that favors the decay into the hole states in ^{207}Pb.

The angular correlation for the protons relative to the tritons (observed at 0°) is $1 + A_2 P_2(0)$ for a 1^+ state, and the data are within statistics consistent with this assignment. For the decay from the 0^+ IAS we observe isotropy for the decay protons. The yield at $\theta_p = 130°$ (where $P_2 \sim 0$) for decay into a definite hole state $|i\rangle$ is written as a product of a formation cross section and a branching ratio:

$$\frac{d^3\sigma^{(i)}(E_x)}{dE_x d\Omega_p d\Omega_t} = \frac{d^2\sigma(E_x)}{dE_x d\Omega_t} \frac{1}{4\pi} \frac{\sum_m \Gamma_{mi}(E_p)}{\Gamma_{\text{tot}}}. \qquad (1)$$

Here the indices m and i label the different particle-hole components of the GT resonance; the widths Γ_{mi} we write as $\Gamma_{\text{s.p.}}(m) a_{mi}^2$ corresponding to emission of a proton particle with an amplitude a_{mi}. For decay, e.g., into the $i_{13/2}^{-1}$ state, the significant contributions are from the $\pi i_{11/2} \nu i_{13/2}^{-1}$ and $\pi i_{13/2} \nu i_{13/2}^{-1}$ components of the 1^+ state. The single-particle widths $\Gamma_{\text{s.p.}}(m)$ are calculated from scattering in a real potential well, with parameters determined from elastic scattering data.[6]

The amplitudes a_{mi} we calculate in a Tamm-Dancoff (TD) approximation with a particle-hole interaction $g_0' \vec{\sigma}_1 \cdot \vec{\sigma}_2 \vec{\tau}_1 \cdot \vec{\tau}_2 \delta(\vec{r}_1 - \vec{r}_2)$. If we adjust g_0' to reproduce the GT resonance energy we find $g_0' = 245$ MeV fm^3 and the particle-hole amplitudes as given in Table I. These amplitudes also determine the coefficients A_2 in the angular correlation. The measured angular correlations are consistent with the calculated numbers but the poor statistics and the nonresonant yield at 90° do not allow a more quantitative analysis.

With use of Eq. (1), the full drawn curves in Fig. 1 have been obtained as a product of the common formation cross section (dashed curve) and the single-particle widths. The latter quantity varies strongly in the energy region in question through the dependence of the penetrability on decay energy and orbital angular momentum but the figure shows that the shapes of the experimental spectra are well reproduced. The normalizations of the individual curves have been adjusted to correspond to the numbers in column 4 of Table I.

The present experiment is only sensitive to the high-excitation-energy part of the resonance, but the shape of the formation cross section is consistent with the (p,n) results.[2] We can rewrite Eq. (1) as

$$4\pi \int \frac{d^3\sigma^{(i)}}{dE_x d\Omega_p d\Omega_t} \frac{1}{\Gamma_{\text{s.p.}}(E_p)} dE_x = \frac{\sum_m a_{mi}^2}{\Gamma} \int \frac{d^2\sigma}{dE_x d\Omega_t} dE_x. \qquad (2)$$

TABLE I. Particle-hole structure and decay of GT resonance.

$\|mi\rangle$	a_{mi}	$\Sigma_m a_{mi}^2$	$4\pi\int(d^3\sigma^{(i)}/dE_x\, d\Omega_p\, d\Omega_t)\Gamma_{\text{s.p.}}^{-1}(E_p)dE_x$ [a]	$\Gamma^{-1}\Sigma_m a_{mi}^2\int(d^2\sigma/dE_x\, d\Omega_t)dE_x$ [b]
$p_{3/2}p_{1/2}^{-1}$	0.091	0.009	0.02 ± 0.01	0.03×10^{-1}
$p_{1/2}p_{1/2}^{-1}$	-0.034			
$f_{7/2}f_{5/2}^{-1}$	0.144	0.030	$0.12^{\text{c}} \pm 0.04$	0.09×10^{-1}
$f_{5/2}f_{5/2}^{-1}$	-0.094			
$p_{3/2}p_{3/2}^{-1}$	0.111	0.023	0.03 ± 0.02	0.07×10^{-1}
$p_{1/2}p_{3/2}^{-1}$	-0.104			
$i_{13/2}i_{13/2}^{-1}$	0.232	0.40	6.6 ± 1.5	1.2×10^{-1}
$i_{11/2}i_{13/2}^{-1}$	-0.588			
$f_{7/2}f_{7/2}^{-1}$	0.142	0.058	0.27 ± 0.09	0.17×10^{-1}
$f_{5/2}f_{7/2}^{-1}$	-0.195			
$h_{9/2}h_{9/2}^{-1}$	-0.182	0.032	< 2.0	0.09×10^{-1}
$h_{9/2}h_{11/2}^{-1}$	-0.562	0.32		

[a] The numbers in this column have been obtained from the experimental triple differential cross section by numerical integration of this expression. The unit is mb/sr MeV.

[b] Calculated with $d\sigma(1^+, \theta = 0)/d\Omega = 3$ mb/sr and $\Gamma = 4.1$ MeV.

[c] The values for the decay to the $f_{5/2}^{-1}$ and $p_{3/2}^{-1}$ hole states are based on a separation in the energy region 17–20 MeV. In Fig. 1, only the summed yield is shown.

TABLE II. Decay of IAS.

$\vert mi\rangle$	$a_{mi} = [(2j+1)/2T_0]^{1/2}$	$a_{mi}^2\Gamma_{s.p.}$ (keV)		Γ_p(expt)/$\Sigma\Gamma_p$(expt)	Γ_p(expt) (keV)
$p_{1/2}p_{1/2}^{-1}$	0.213	46[a]	54[b]	0.36 ± 0.03[c]	51 ± 6
$f_{5/2}f_{5/2}^{-1}$	0.369	27	28	0.18 ± 0.04	26 ± 6
$p_{3/2}p_{3/2}^{-1}$	0.302	49	66	0.43 ± 0.04	61 ± 8
$f_{7/2}f_{7/2}^{-1}$	0.42	6	4	0.023 ± 0.003	3.3 ± 0.5

[a] $\Gamma_{s.p.}$ calculated from scattering in a real well; parameters from Ref. 6.
[b] Calculated, from Ref. 9.
[c] Uncertainties are smaller on the relative widths.

The left-hand side can be obtained from the experimental data by numerical integration, while the right-hand side is calculated from the formation cross section, the width, and, in addition, the amplitudes a_{mi} with which the different proton-particle–neutron-hole components occur in the GT wave function. Values obtained for the left- and right-hand side quantities are listed in Table I. For the calculation of the latter a formation cross section of 3 mb/sr has been assumed. This is an upper limit. If it had been larger, the GT resonance would have been visible in the singles spectrum above the background. The width has been taken to be 4.1 MeV in accordance with Ref. 2. The coefficients a_{mi} are from our time-dependent calculation. They are listed in Table I. In calculating $\Gamma_{s.p.}(E_p)$ we have assumed that the emitted protons have the same orbital angular momentum as the neutron hole state in ^{207}Pb to which the resonance decays. It is assumed that only these 1p-1h components are important.

It is seen from Table I that there is an order of magnitude discrepancy between the values based on the left- and right-hand side of Eq. (2). This discrepancy can only be removed by assuming an integrated formation cross section of about 30 mb/sr which undoubtedly would stand out in the singles spectrum.

The larger coincidence yield could possibly come from a process where the transferred proton in a (^{3}He; d,t) or (^{3}He; α,t) reaction is emitted again from the surface region. The transmission probabilities could therefore be larger than the ones entering the $\Gamma_{s.p.}$'s in Eqs. (1) and (2). The (^{3}He; d,t) reaction gives in a finite-range second-order distorted-wave Born approximation a significant contribution to the (^{3}He,t) cross section[7] and does probe the one-particle, one-hole structure of the final state. A more quantitative estimate of the coincidence yield has not been attempted.

Another possible contribution to the coincidence yield especially at excitation energies higher than $E_x \simeq 17.0$ MeV may come from the IAS of ^{208}Pb. Although these are expected to be weakly excited at 0° because of their high-spin values, they can nevertheless favorably proton decay because of their particle-hole and isospin characters to the high-spin hole states of ^{207}Pb with low-angular-momenta protons (thus having large penetrabilities).

We note that the decay of the IAS is a very nice built-in calibration in this experiment. We find $d\sigma(0^+, \theta=0°)/d\Omega = 1.29 \pm 0.25$ mb/sr for the formation cross section and $\Gamma^{-1}\sum\Gamma_p = 0.61 \pm 0.06$ in agreement with resonance measurements.[8,9] In Table II, we give the ratios together with widths calculated by the procedure described above. These numbers are in fair agreement with values obtained by a more elaborate model.[10] We mention that this is the first measurement of $\Gamma_{f_{7/2}}$ (IAS), the decay width into $p + {}^{207}\mathrm{Pb}(f_{7/2}^{-1})$.

In conclusion, we have measured the decay of the GT resonance and IAS in ^{208}Bi using the (^{3}He, t) reaction. The coincidence yield into the one-hole states in ^{207}Pb can at backward angles be described as exclusively coming from the decay of the two resonances. An analysis in terms of a common formation cross section times a branching ratio gives a good description for the shape of the GT resonance, and points to the special significance of the $i_{13/2}$ hole component in the resonance. The yield is however much larger than calculated.

The authors acknowledge the participation of E. H. L. Aarts, R. J. de Meijer, and A. van der Woude in certain parts of this experiment. We thank T. Døssing and B. Nilsson for helpful discussions. This work was supported in part by funds from the Danish Natural Science Research Council.

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