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# Excitation of the high energy nuclear continuum in $^{208}$Pb by 22 MeV/nucleon $^{17}$O and $^{32}$S

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The $^{208}$Pb high excitation continuum has been studied using inelastic scattering of 22 MeV/nucleon $^{17}$O and $^{32}$S. The spectra, taken with a magnetic spectrograph, show no evidence for peaks in the 30—100 MeV region of excitation in contrast to published results. The $^{17}$O spectra are found to be remarkably similar to those from medium energy proton scattering.

## I. INTRODUCTION

Over the past several years the spectrum of non-spin-flip, giant resonances in $^{208}$Pb has been established using inelastic scattering of various projectiles. In addition to the well known giant dipole resonance located at 13.6 MeV, measurements have led to the establishment[1] of various multipolarity isoscalar giant resonances with excitation energies up to $\sim 30$ MeV. Recently, a large number of peaks were observed[2,3] in the inelastic scattering spectra of $^{36}$Ar + $^{208}$Pb at 11 MeV/nucleon and $^{20}$Ne + $^{208}$Pb at 30 MeV/nucleon which have been suggested to arise from excitation of states in $^{208}$Pb at excitation energies between 30 and 150 MeV. The width [full width at half maximum (FWHM)] of the peaks was found to vary from $\sim 3$ MeV at lower excitation energy up to $\sim 20$ MeV for the peak observed at an excitation energy of $\sim 138$ MeV. Maximum cross sections for these peaks were found to be $\sim 1$ mb/sr. The peaks appear at the same excitation energy when observed in the two different reactions, and this has been interpreted[2,3] as evidence for the excitation of states in $^{208}$Pb.

The structures reported in Ref. 2 have not been observed in a recent experiment[4] using inelastic scattering of 30-MeV/nucleon $^{20}$Ne from $^{208}$Pb. Furthermore, such structure has also not been observed in measurements using light ions. However, it has been well established[5,6] that heavy ion reactions provide large cross sections for excitation of giant resonances along with a good resonance peak to continuum "background" ratio. In particular, the high excitation continuum is significantly smaller than in light ion scattering. This fact may explain why weak, high-lying giant resonance peaks that have not heretofore been seen might be observed in heavy ion inelastic scattering. An explanation of the structures seen in Refs. 2 and 3 has been given[3] in terms of multiphonon excitation of giant resonances.

Two difficulties that arise when utilizing heavy ions to search for giant resonances are the excitation of states in the projectile and the nucleon pickup and subsequent decay of the projectile. Peaks from these sources may hinder the interpretation of the spectra and could lead to incorrect identification of peaks as arising from excitation of giant resonances in the target nucleus. Reference 6 provides a good example of each of these projectile related problems. It should be noted that the work of Refs. 2 and 3 shows that the high excitation structure was observed at the same energy when two different heavy ion probes were used. The authors used that observation to suggest that the peaks do not arise from projectile pickup but rather are from excitation of states in $^{208}$Pb.

We present in this paper the results of an experiment to search for the peaks reported in Refs. 2 and 3. We used inelastic scattering of $^{17}$O and $^{32}$S to excite states in $^{208}$Pb. Since the neutron binding energies are very different for these two probes, one might expect to observe different effects in the inelastic spectra from projectile excitation. The neutron binding energy in $^{17}$O is only 4.1 MeV, and only one level below the neutron separation energy (0.871 MeV, $\frac{1}{2}^+$) should be strongly excited. Thus, the $^{17}$O inelastic spectra should be relatively free from "contamination" by excitation of the probe. Our results show this to be the case. Furthermore, the low neutron separation energy minimizes effects in the spectrum from projectile pickup and subsequent decay back into the inelastic channel. Apart from these differences, the dynamics of the reactions discussed in Refs. 2 and 3, and those of the present work, are very similar.

We show $^{208}$Pb spectra obtained with the two heavy ion probes and provide a comparison with results obtained using inelastic scattering of medium-energy protons and $^{16}$O. It has been previously shown[5,6] that the cross section for the excitation of giant resonances by inelastic scattering of oxygen and other heavy ions is consistent with distorted-wave calculations and with light-ion results. For this reason we do not concern ourselves with complete angular distributions or cross sections, but rather emphasize spectra having high statistical accuracy at a few angles.

 

## II. EXPERIMENT

Measurements were made using inelastic scattering of 22 MeV/nucleon $^{17}$O (376 MeV) and $^{32}$S (700 MeV) provided by the coupled operation of the tandem and cyclotron at the Holified Heavy Ion Research Facility (HHIRF). The $^{208}$Pb target was an enriched (>99%) self-supporting foil 500 mg/cm$^2$ thick. Inelastically scattered particles (and products from transfer reactions that are not discussed here) were detected in the HHIRF broad-range spectrograph (BRS) facility. The focal plane detector system[7] of the BRS provided the particles' position, charge, and mass. Position was measured in a vertical drift chamber (VDC), while the charge and mass of the scattered particles were determined from measurement of the energy loss and total energy deposited in an ionization chamber which followed the VDC. The energy resolution of the $^{17}$O data was ~200 keV (FWHM) and that for the $^{32}$S measurements was ~400 keV. The mass identification in this experiment was unequivocal. The dispersion of the BRS is such that for a single setting of the magnetic field and a 38 cm long VCD, an excitation energy range of ~80 MeV is obtained for $^{17}$O and ~140 MeV for $^{32}$S. Data were measured at four spectrograph angle settings, each with a 3° angular acceptance, spanning the angular range $\theta_{lab}=4.5°-13.5°$ for $^{17}$O ($\theta_{grazing}\approx 11.5°$) and $\theta_{lab}=7.5°-13.5°$ for $^{32}$S ($\theta_{grazing}\approx 11.6°$). The number of incident particles was determined by measuring the charge deposited by the incident beam in a Faraday cup that was biased to −300 V for electron suppression. Measurements were made with a blank target frame to ensure that the spectra were free from scattering from the frame of the target. Subsequent measurements of the response of the detector system to incident beam at 0° showed no spurious response of the focal plane detector system. However, as will be discussed in the following section, the VDC was found to have defective wires in two position regions during this experiment. These very small regions were identified by observing anomalous effects from the same wires (same focal plane position) in several reaction channels and in spectra obtained by sweeping the elastic peak across the length of the detector by ramping the spectrograph magnetic field. The geometry of the VDC is such that four or five wires are triggered by each projectile crossing the focal plane. Focal plane position and angle information are calculated using a weighted linear least-squares fit to the VDC drift times. The weights of the drift times from the defective wires were reduced relative to the weights for the unaffected wires. Therefore, the data in the regions of the defective wires were recovered with minimal effect on the precision of the focal plane position and angle determinations.

## III. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 1 shows spectra from the three angles at which data were obtained for $^{17}$O and the two angles used for $^{32}$S measurements. The angular acceptance was 3.0° for the spectra in Fig. 1. We have also studied the spectra in 0.5° angle bins, and find no significant structure that is not present in the full 3.0° acceptance spectra. For this reason and since we wish to maximize the statistical significance of the spectra, the data are shown in 3.0° angle bins.

The spectra in Fig. 1 are plotted on a multicycle semilogarithmic plot in order to provide a general view of the spectra over the entire excitation energy range. We used only a single spectrograph magnetic field setting for each run and for this reason the $^{32}$S spectra extended to nearly twice the excitation energy as the $^{17}$O spectra (the dispersion in the focal plane is nearly twice as large for 700 MeV sulfur as for 376 MeV oxygen). At low excitation energies the good energy resolution permits the observation of peaks from excitation of several low-lying bound states (often offscale on Fig. 1). In order to reduce the count rate in the focal-plane detectors, the elastic scattering peak and the peak from excitation of the 2.61-MeV, $3^-$ state were set off one end of the detectors. For this reason the spectra shown on Fig. 1 and succeeding figures

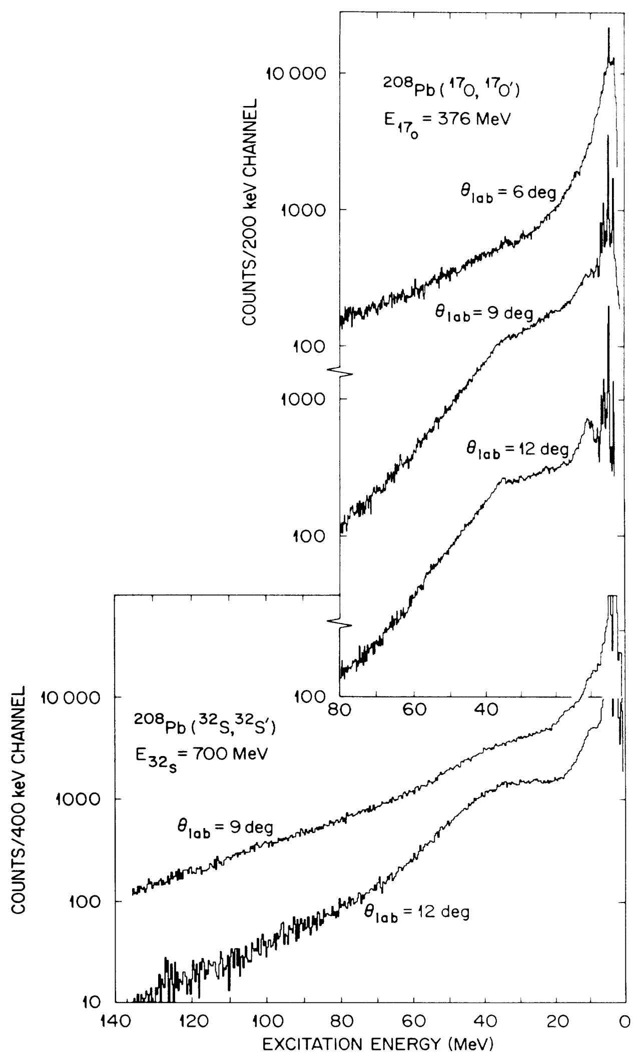


FIG. 1. Inelastic scattering spectra from the reactions $^{208}$Pb($^{17}$O,$^{17}$O′) and $^{208}$Pb($^{32}$S,$^{32}$S′). The peaks from elastic scattering and inelastic scattering to the 2.613 MeV, $3^-$ state are omitted. The angle bin is $\theta_{lab}\pm 1.5°$ and the energy bins are 200 keV for the $^{17}$O spectra and 400 keV for the $^{32}$S spectra.

begin at different excitation energies. In the spectra for the larger angles the giant quadrupole resonance is clearly visible at $\sim 11$ MeV of excitation energy. The data on Fig. 1 are plotted in 200 keV wide energy bins for $^{17}$O and 400 keV wide bins for $^{32}$S.

In Fig. 2 we have plotted spectra expanded over the excitation energy region from $\sim 3$ to $\sim 24$ MeV. Figure 2(a) shows the 12° $^{17}$O inelastic spectra obtained in the present measurements, Fig. 2(b) is the spectrum of $^{208}$Pb from inelastic scattering of 334 MeV protons,[8] Fig. 2(c) is an inelastic scattering spectrum[6] for 400-MeV $^{16}$O on $^{208}$Pb, and Fig. 2(d) is the 9° spectrum from $^{32}$S inelastic scattering from the present measurements. The large peak located at 10.6 MeV in the $^{17}$O spectrum is from excitation of the isoscalar giant quadrupole resonance. In the $^{16}$O spectrum [Fig. 2(c)] the GQR peak is much less clear due to the presence of a larger peak located just below the resonance. The additional peak arises from excitation of $3^-$ and $2^+$ states near 6 MeV in the $^{16}$O projectile. The $^{17}$O spectrum which was obtained with $\sim 200$-keV energy resolution shows the existence of fine structure at excitation energies between $\sim 7$ MeV and the GQR. These peaks are observed also in the (p,p′) spectrum [Fig. 2(b)], which was obtained with about 70-keV resolution. Within the difference in energy resolution, the $^{17}$O spectrum is quite similar to the proton spectrum. The observed fine structure is also consistent with results from 172 MeV alpha particle inelastic scattering[1] and low energy, high resolution, proton scattering data.[9] The most pronounced difference between the $^{17}$O and proton spectra is near 14 MeV, in the region of the giant dipole and giant monopole resonances. This is expected because at the incident energies utilized proton scattering provides stronger excitation of these resonances. The considerable similarity between the spectra from proton and $^{17}$O inelastic scattering is surprising since different types of states could be excited by the two different probes. The $^{17}$O probe excites predominantly isoscalar, non-spin-flip states, whereas in medium-energy proton scattering contributions from spin-flip excitations should be present.[10] The similarity of the fine structure peaks in the $^{17}$O and proton spectra strongly suggests that the peaks arise mainly from excitation of isoscalar states.

The $^{32}$S spectrum shown in Fig. 2(d) is much more complicated than the $^{17}$O spectrum (or proton spectrum). The energy resolution of the sulfur data is $\sim 400$ keV (FWHM). While there is evidence for a GQR peak at 10.6 MeV, there are other peaks—for example, a strong excitation at $\sim 7.5$ MeV—which do not appear in the $^{17}$O spectrum. In the 8-MeV region of both the $^{17}$O and pro-

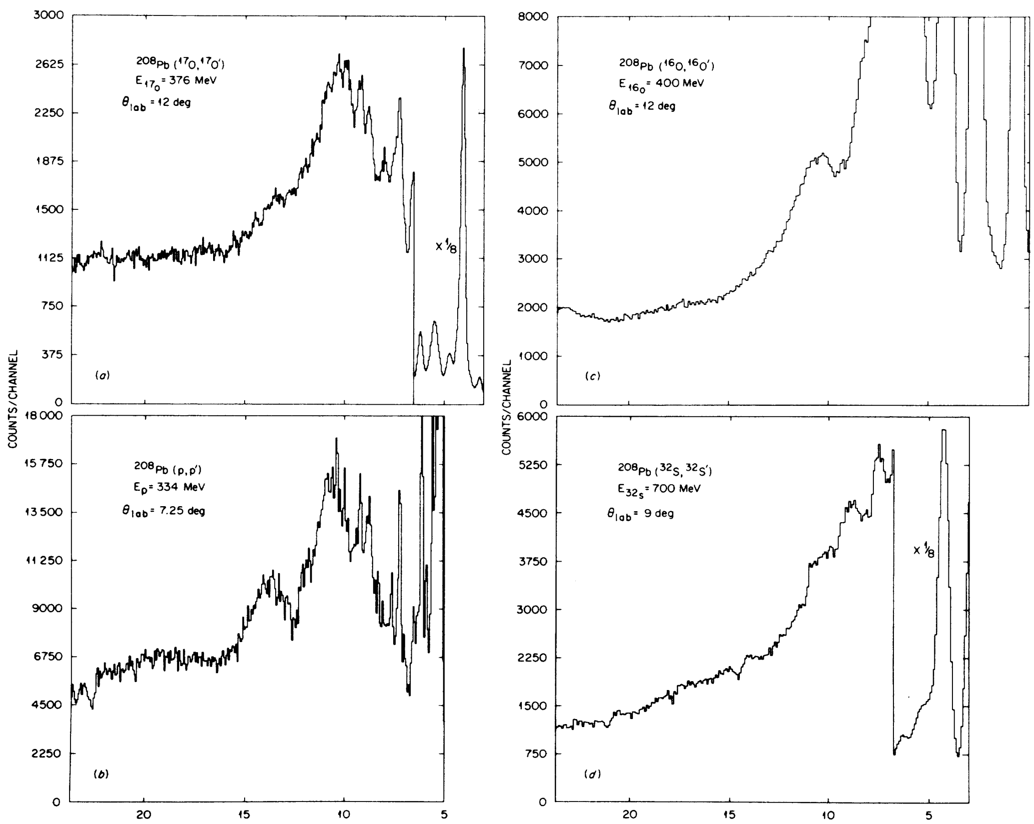


FIG. 2. Inelastic scattering spectra for excitation energies between $\sim 3$ and $\sim 24$ MeV. (a) ($^{17}$O,$^{17}$O′), 12° (present work), (b) (p,p′), 7.25° (Ref. 8), (c) ($^{16}$O,$^{16}$O′), 12° (Ref. 6), and (d) ($^{32}$S,$^{32}$S′), 9° (present work).

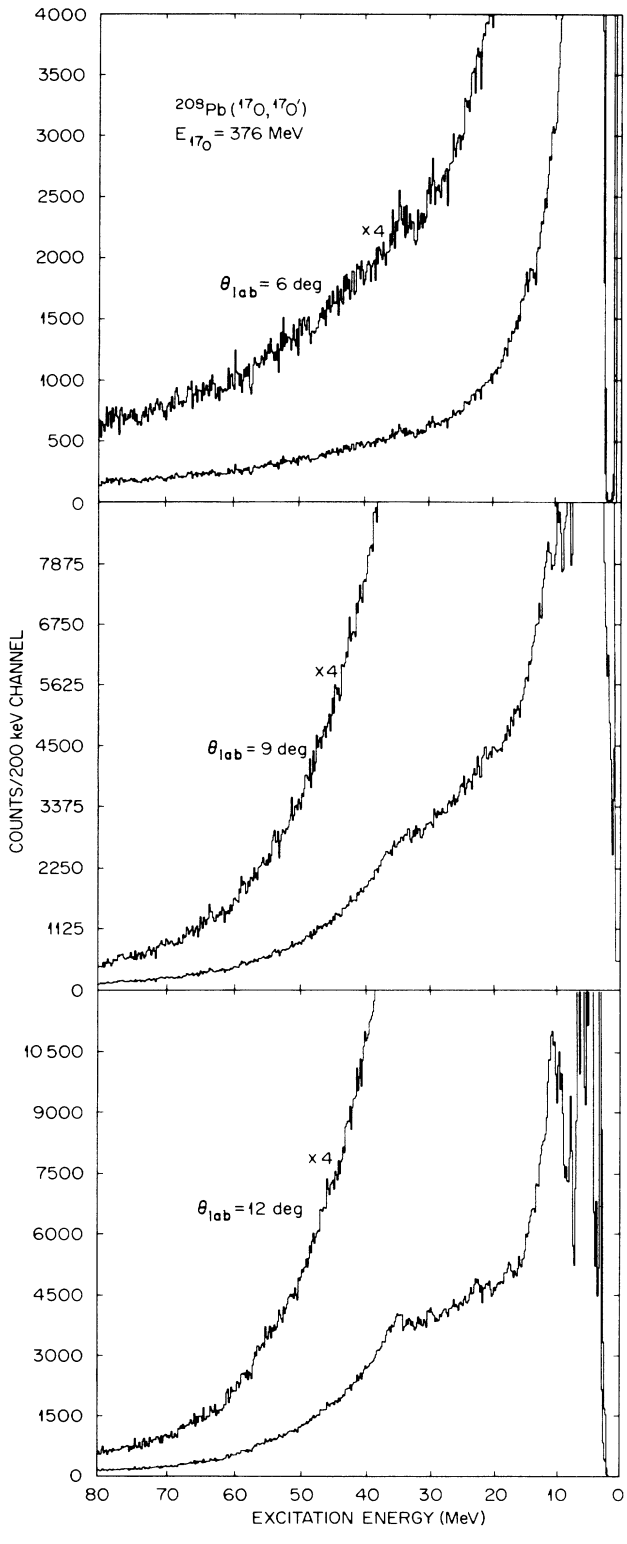


FIG. 3. Spectra from the $^{208}$Pb($^{17}$O,$^{17}$O$'$) reaction for $E_{^{17}\mathrm{O}}=376$ MeV at 6°, 9°, and 12°. For each angle the high excitation energy region is shown multiplied by 4.

ton spectra the narrow states are considerably weaker than the GQR. In addition, there is more structure in the region between 15 and 24 MeV of excitation energy in the $^{32}$S spectrum than is seen in the proton or $^{17}$O spectra. It is likely that the additional peaks in the $^{32}$S spectrum arise from excitation of states in the $^{32}$S projectile.

In order to more closely examine the data for structure at high excitation energies, we show in Figs. 3 and 4, respectively, the $^{17}$O and $^{32}$S inelastic spectra on various linear scales. The $^{17}$O data are plotted in $\sim$200 keV wide energy bins and the $^{32}$S data are in $\sim$400 keV energy bins. While the general shape of the spectra are the same as

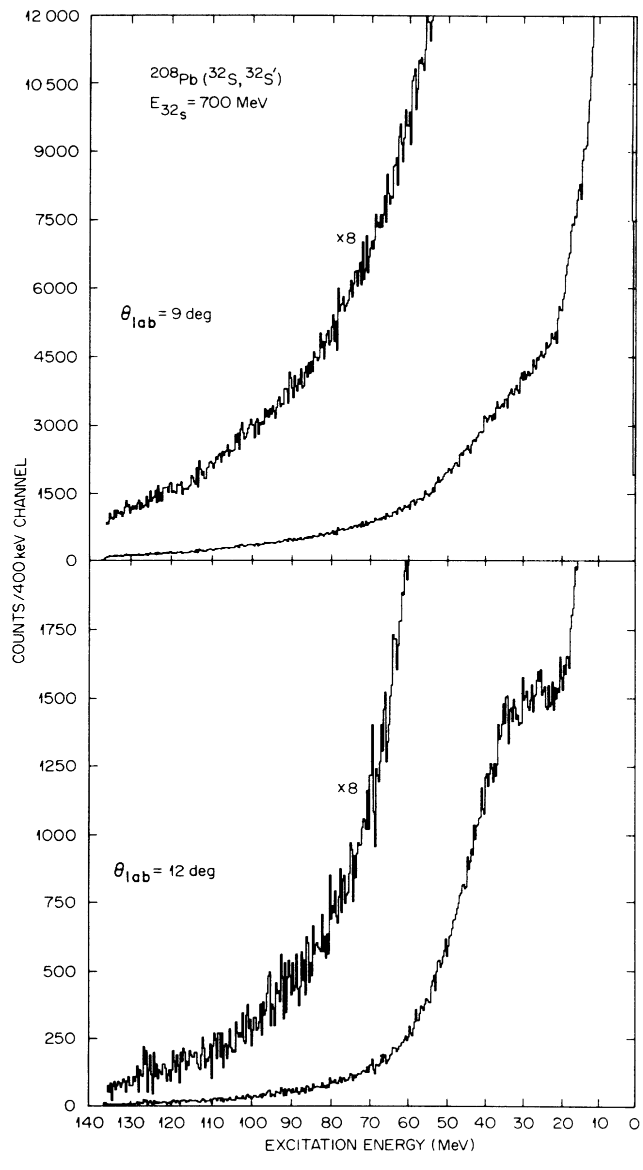


FIG. 4. Spectra from inelastic scattering of 700-MeV $^{32}$S from $^{208}$Pb for 9° and 12°. For each angle the high excitation energy region is shown multiplied by 8.

those reported in Ref. 2, we find no evidence for statistically significant peak structure with a width of 2–10 MeV in the high excitation ($E_x \gtrsim 40$ MeV) spectra, for either the oxygen or sulfur data, that cannot be explained as statistical fluctuations. Plotting the data in 1 MeV energy bins smoothes out the statistical fluctuations and still yields an essentially structureless continuum spectrum at all angles for both probes.

In the energy region below 40 MeV the oxygen data of Fig. 3 exhibits a shoulder at 35 MeV that appears weakly at 9° and becomes stronger at 12°. This shoulder has the same shape as observed[11] in inelastic scattering of $^{20}$Ne from $^{58}$Ni, and may arise from projectile pickup and decay processes. There is also a weak peak near 22 MeV in the 12° spectrum. The weak, narrow peaks at 30 and 35 MeV in the $^{17}$O spectra are caused by defective wires in the VDC. These weak peaks are not as apparent in the 9° spectrum, which was obtained near the start of the experiment before the wires in question became defective.

Using a kinematical analysis, similar to those used by Bohlen *et al.*[11] and by Blumenfeld *et al.*,[2] we have calculated the expected energy for maximum cross section from the projectile pickup and decay process (given in terms of excitation energy in $^{208}$Pb) for various channels. (The threshold for the pickup-decay process is, of course, much lower. See Ref. 11 for a complete treatment of this question.) We have assumed only that the decay is symmetric with respect to 90° in the c.m. frame of the ejectile, and that the target is in the ground state. For the neutron pickup channel we calculate an energy for the maximum pickup decay cross section of ~29 MeV for the $^{17}$O and $^{32}$S projectiles. For the proton channel we calculate the energy of maximum cross section to be ~36 and 31.9 MeV for the $^{17}$O and $^{32}$S projectiles, respectively. These calculated values are in generally good agreement with the observed energy of the shoulders in the data and, as has been noted in Ref. 11, lends support to the conjecture that the shoulders arise from the pickup-decay process. However, it is unlikely that this process will produce narrow structures, due to the fact that many of the pickup channels should have comparable cross sections and therefore would probably result in a broad background. Nevertheless, experimental evidence exists for the observation of single or, at most, a few pickup decay channels in the $^{16}$O + $^{208}$Pb reaction,[6] leading to structure around 20 MeV of clearly secondary nature (i.e., nontarget excitation).

## IV. CONCLUSIONS

In order to search for numerous states recently reported in $^{208}$Pb at high excitation energies (30–150 MeV), we have measured inelastic spectra from reactions of 22 MeV/nucleon $^{17}$O and $^{32}$S on $^{208}$Pb. Our use of a magnetic spectrograph, high resolution focal plane detector, and unequivocal mass identification yielded very clean high excitation energy spectra.

Our results show that $^{17}$O, in which the neutron is loosely bound, provides an extremely clean heavy-ion probe for excitation of giant resonances, and because of this $^{17}$O should be especially useful in the search for weak, high excitation states in the target nucleus. The $^{17}$O spectrum in the region of giant resonances in $^{208}$Pb is surprisingly similar to that obtained using inelastic scattering of medium energy protons.

The $^{17}$O inelastic scattering data on $^{208}$Pb show no evidence for peaks at high excitation energy. A shoulder is found at ~35 MeV in the $^{17}$O spectra, which we conjecture arises from projectile pickup and decay processes. A rather small peak is found at 22 MeV in only the 12° $^{17}$O inelastic spectra. We have no suggestions as to the origin of this weak peak. At excitation energies between ~20 and 35 MeV we find peaks in the $^{32}$S inelastic spectra that are not observed in the $^{17}$O inelastic data. As we discussed earlier, because of the high particle binding energy of the projectile we would expect to see more peaks in the $^{32}$S spectra than in the $^{17}$O spectra which seem to be nearly free from projectile effects. We find no evidence for peaks in the $^{32}$S spectrum between 40 and 140 MeV.

Our results are in disagreement with those from Refs. 2 and 3. In those works the authors report the existence of approximately 13 peaks extending to ~140 MeV of excitation energy which they attribute to population of states in $^{208}$Pb. In the present experiment we have obtained spectra with small statistical fluctuations that do not exhibit such structure in the 40–140 MeV excitation range. Our spectra are consistent with recent results[4] from measurements of $^{20}$Ne + $^{208}$Pb inelastic scattering in which no structure was observed in the $^{208}$Pb high excitation energy continuum.

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