Excitation of Giant Resonances in ^{90}Zr and ^{122}Sn by Inelastic ^{6}Li Scattering

R. Pardo, R.G. Markham, W. Benenson, A.I. Galonsky, and E. Kashy

Inelastic scattering experiments using a variety of light projectiles have been extremely useful in the study of giant resonances in the past. We have extended this work into the heavy-ion region recently by studying the inelastic scattering of 74-MeV ^{6}Li particles from targets of ^{90}Zr and ^{122}Sn.

Heavy ions are expected to have two advantages over lighter ion studies of giant resonances with L>2. First, the larger angular momentum possible for a given excitation energy will favor the formation of high L giant resonances, and second, the lower background yield from evaporation and other three body continuum reactions should yield favorable conditions for observing these possible resonances.

The experiments were performed using the Enge split-pole spectrograph with a charge-division wire counter in the focal plane. The targets used were 1.0 mg/cm^2 ^{90}Zr(97.8%) and 5.29 mg/cm^2 ^{122}Sn. ^{6}Li beam currents of 5-30 na (electrical) were realized.

Figure 1 shows the spectrum of ^{6}Li-ions inelastically scattered from ^{90}Zr. In ^{90}Zr and ^{122}Sn, the giant quadrupole resonance (GQR) at $\approx 63\ A^{1/3}$ is seen prominently (13.8 MeV in ^{90}Zr and 12.9 MeV in ^{122}Sn). Both spectra also show a region of enhanced cross section above the GQR. The centroid of this enhanced region in ^{90}Zr is at an excitation energy of 22.3±.6 MeV while the ^{122}Sn spectrum indicates two regions of enhancement with excitations of ∿17.5 MeV and 19.8 MeV. The ^{90}Zr spectrum gives some indication of a splitting of the strength in the 22.3-MeV region but the data does not allow this to be determined unambiguously. In addition, the ^{90}Zr spectrum shows a region of enhanced cross section in the 6-9 MeV region underlying the sharp structure.

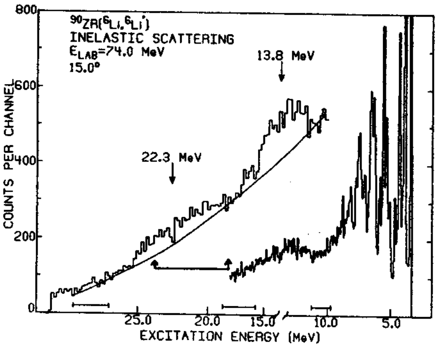

Fig. 1.--Spectra of events observed in ^{90}Zr(^{6}Li, ^{6}Li'). The spectrum spanning the energy region of $E_x \gtrsim 10$ MeV has an average slope of .19 MeV/ch. The spectrum spanning the lower excitation energy region has an average slope of .03 MeV/ch. The region marked with connected arrows is the possible region which can have contributions from ^{90}Zr(^{6}Li, ^{7}Li(7.47))^{89}Zr', ^{7}Li(7.47)→^{6}Li + n .

Angular distributions have been taken for the ^{90}Zr target in the angular range of 11°-25°. The data were analyzed with the DWBA code DWUCK[2] using optical model parameters from elastic scattering at the same energy.[3] These results are shown in Table I and Fig. 2.

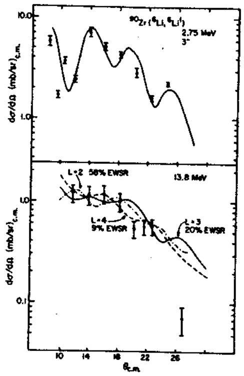

Fig. 2.--Angular distributions obtained in this experiment. The smooth curves are DWBA fits to the data after normalization to the 2.75-MeV state as described in text.

Table I. Giant Resonance paramters obtained in ^{90}Zr(^{6}Li,^{6}Li').

Excitation Energy	Γ(MeV)	% EWSR			
		E0	E2	E3	E4
13.8 ± 0.3 MeV	3.8 ± 0.4	533%	58%	20%	9%

The structure of 22.3-MeV excitation was originally thought to be a new "giant resonance". Although the kinematic shift from angular distributions was consistent with this interpretation, later experiments at bombarding energies of 60 and 67 MeV indicated that the excitation energy of this structure shifted with bombarding energy. This was especially obvious in the ^{122}Sn case. These observed shifts are consistent with the assumption of the decay of ^{7}Li following neutron pick-up to the 7.47-MeV state in ^{7}Li. This state is unbound to neutron emission by .22 MeV. The resulting ^{6}Li will have a possible energy range of approximately ±2.5 MeV about the central value indicated in Fig. 1, thereby causing a structure similar to a giant resonance in the scattered ^{6}Li spectrum. Although there is some additional strength at an excitation energy above the apparent range of this process, this might be due to additional excitation of the residual nucleus, energy shifts due to the decays of ^{7}Li in the field of the residual nucleus, or possible proton pick-up forming ^{7}Be. The observation of this process in ^{6}Li scattering shows that this reaction is plagued with pick-up problems similar to those encountered in α-scattering.[4]

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The Search for M1 Strength with the ^{58}Ni(p,n) Reaction

L.E. Young, Sam Austin and Aaron Galonsky

The (p,n) reaction has been used to search for 1^+ states in ^{58}Cu. The M1 strength is expected to be relatively large in this region which has a filled j> shell ($f_{7/2}$) and an empty j< shell ($f_{5/2}$). The charge-exchange transition via (p,n) from the 0^+ ground state to a 1^+ state should be correspondingly enhanced. For example, the (p,n) reaction has already been found to excite 1^+ states using a ^{90}Zr target.[1]

Figure 1 shows a spectrum taken with the neutron time-of-flight system, using a 32 meter flight path. A proton beam of 42 MeV was used, and beam sweeping allowing one of three beam bursts to reach the target provided for sufficient dynamic range to see up to 14 MeV excitation energy in ^{58}Cu. Using a 4 mg/cm^2 ^{58}Ni target, and with 0.75 ns overall time resolution for the γ peak, an energy resolution of 160 keV was obtained for IAS peak, with a resolution of 90 keV in the region of 10 MeV excitation energy.

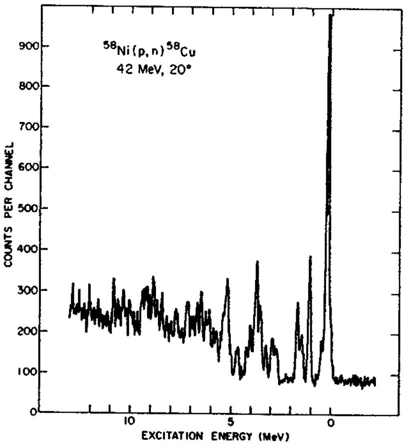

FIG. 1.--Spectrum obtained from the ^{58}Ni(p,n)^{58}Cu reaction with 42 MeV protons and a scattering angle of 20°. The energy resolution ranges from 160 keV for the IAS at 0.202 MeV to about 90 keV for the states in the region of 10 MeV excitation energy.

There is an approximate correspondence in the energies of the individual states in the group of levels at 10.5 MeV to the energies of states identified in ^{58}Ni as 1^+ by (e,e') work.[2] Because of the systematics of energy levels, the group of states at 10.5 MeV has been tentatively identified as T=2, 1^+ states. Since ^{58}Cu is a T=0 nucleus the question arises as to whether any transition strength to T=1 or T=0 1^+ states can be seen. Toward this end, angular distributions are being taken for individual states in the groups of levels seen at 6.5 MeV and 9.0 MeV as well as for the group at 10.5 MeV. These will be compared with the angular distribution from a known 1^+ state at 1.05 MeV excitation energy, and with DWBA calculations.

A preliminary comparison using angular distributions from one level in each region is consistent with there being 1^+ strength in each group. However, the experiments using electron scattering on a ^{58}Ni target[2] should have excited the analogs of the T=1 states at less than 10 MeV excitation energy, but the discovery of these states has not yet been reported.

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Giant Fermi and Giant Gamow-Teller Transitions in the (^{3}He,t) Reaction at 130 MeV

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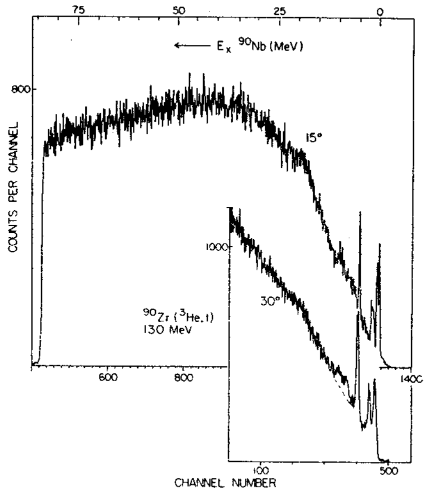
Giant resonances in charge exchange (T=1) reactions have been seen as analogs of the ground states of target nuclei (IAS) since the work of Anderson and Wong. In these transitions, giant Fermi transitions, S=0. A giant Gamow-Teller (G-T) (S=T=1) transition producing a broad peak near the sharp Fermi peak has been observed at MSU in the (p,n) reaction on ^{90}Zr with 45-MeV protons.[1] The resonance is built upon ($\pi g_{7/2}$, $\nu g^{-1}_{9/2}$) particle-hole excitations. As the resonance (in ^{90}Nb) has T=4, whereas ^{90}Zr has T=5, it may also be considered the anti-analog of the giant M1 resonance in ^{90}Zr. As the T=5 analog state should be at higher excitation and more weakly excited, it was not seen in the (p,n) experiment.

Using a Si-Ge, ΔE-E telescope and targets of ^{90}Zr, ^{120}Sn, and ^{208}Pb, we have studied charge-exchange transitions via (^{3}He,t) with the 130-MeV ^{3}He beam at the Jülich cyclotron. Data were taken from about 10° to 35° at 1° intervals.

The figure shows representative triton spectra obtained with the ^{90}Zr target. The Fermi (or IAS) peak is the most prominent feature of the spectra. For all 3 targets we are analyzing the IAS data with the aid of the DWBA code DWUCK in order to determine the strength of the charge-exchange reaction. Up to 70 MeV the strength is a decreasing function of bombarding energy[2].

There is also a broad, structured peak near the Fermi peak. The location and width of the broad peak agree with what was seen in the neutron spectra and interpreted as the giant G-T transition. In ^{120}Sn spectra, however, there is only the slightest hint of a broad peak under the IAS, and in the ^{208}Pb spectra the only peak is the IAS.

An important feature of these spectra is that they run to very high excitation energies and that they exhibit almost no structure beyond the IAS or G-T. In the ^{90}Zr spectra, however, there is a slight bump around 19 MeV excitation energy. Conceivably, it is the $T_>$ part of the G-T transition, that is, the T=5 component, whose existence is a necessary part of the giant G-T interpretation of the (p,n) and (^{3}He,t) data. The isospin splitting would then be ~10 MeV, somewhat above earlier estimates.[2] Its energy above the Fermi IAS, ~13.5 MeV, is ~3.3 MeV below the energy for the analog of the T=1, E1 resonance in ^{90}Zr.[3]



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The Observation of Hole States at High Excitation in (p,t) Reactions

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The spreading of simple states, which are embedded in a host of more complex states, into the underlying background remains one of the important questions in nuclear physics. One method of studying such states is by pick-up reactions particularly at high excitation energy where the level density is substantial. Hole states with spin parity $9/2^+$, $1/2^-$ and $3/2^-$ and with significant spectroscopic factors have been observed at about 5 MeV of excitation in the odd tin isotopes in single neutron pick-up reactions[1,2,3]. In the present experiment, which was motivated by a search for high-lying pairing resonances[4], a peak was observed at an excitation energy of about 8 to 9 MeV in a number of tin isotopes. One plausible explanation for this peak is that it arises from two neutron hole states in the major shell consisting of $1g_{9/2}$, $p_{1/2}$, $p_{3/2}$ and possibly $1f_{5/2}$ levels.

Because the pairing-resonances were predicted to occur at $70/A^{1/3}$ MeV, i.e. about 14.1 MeV for ^{122}Sn, the first measurements were carried out using a ^{122}Sn target at a proton bombarding energy of 45 MeV, and the tritons were detected in a standard counter telescope consisting of three Si detectors. This arrangement permitted the study of ^{120}Sn up to an excitation energy of about 17 MeV. No structure was observed near 14 MeV, but a substantial "bump" was observed around 8.7 MeV excitation.

In order to study this phenomenon in more detail, the ^{122}Sn(p,t) reaction was repeated at a proton bombarding energy of 42 MeV using a 50 cm long resistive wire proportional counter backed by a plastic scintillator in the focal plane of the Enge spectrograph. This arrangement gave very clear separation of the tritons but was restricted to measuring a range of triton energies from about 32.5 MeV to 21.5 MeV. Again a structure was observed at around 8.7 MeV in ^{120}Sn, quite consistent with the observations at 45 MeV using the silicon counter telescope.

The (p,t) experiment was carried out at 42 MeV using the Enge spectrometer on the even tin isotopes, ^{124}Sn, ^{122}Sn, ^{120}Sn, ^{118}Sn and ^{116}Sn. The raw spectra obtained from these measurements at a laboratory angle of 16° are plotted in Fig. 1, using the same absolute energy scale. A peak, about 2 MeV wide at an excitation energy between 8 and 9 MeV is observed in all the Sn isotopes studied. In addition the reactions ^{106}Cd(p,t), ^{104}Pd(p,t) and ^{208}Pb(p,t) were examined. No enhanced structure was observed in ^{206}Pb, but enhancement was seen in ^{104}Cd and ^{102}Pd at a lower excitation energy. In these two cases, fine structure was evident on top of an overall increase in cross section (Fig. 2).

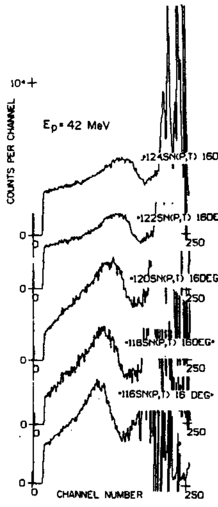

Fig. 1.--Spectra from the (p,t) reaction on six tin isotopes at 16° and 42 MeV. The absolute energy scale is the same for all spectra.

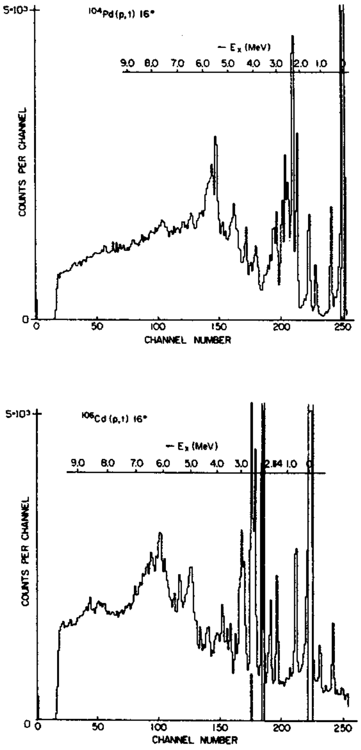

Fig. 2.--Spectra from the (p,t) reaction on ^{104}Pd and ^{106}Cd at 16° and 42 MeV.

The excitation energies and Q-values for the peak of the broad structure are given in Table I. The excitation energy of the peak increases with the addition of neutrons. In addition, the width of the peak increases from about 1.9 MeV in ^{114}Sn to 2.6 MeV in ^{122}Sn, and the peak becomes more asymmetric for the heavier tin isotopes.

A possible explanation of this feature is that it arises from pickup of two neutrons from the lower lying filled major shell which contains the single particle orbits $1g_{9/2}$, $p_{1/2}$, $p_{5/2}$ and $1f_{5/2}$. This explanation is consistent with the observed increase in excitation energy with increasing neutron number since one must reach deeper below the fermi surface to extract the two neutrons for the heavier isotopes. It is also consistent with the fact that no structure was observed in ^{208}Pb(p,t) since in this reaction two major shells have to be crossed to pick out the two neutrons. The two neutron hole states should occur at approximately twice the excitation energy of the single neutron hole states observed in the single neutron pick-up experiments *viz*, 11 MeV, minus the energy due to residual interactions between the two neutrons. For the pairing interaction the residual interaction was estimated by Broglia and Bes[4] to be about 1.4 MeV. The observed excitation energy of the peak in the tin isotopes of between 8 and 9 MeV is in reasonable agreement with this estimate particularly in view of the uncertainty in the residual interaction. Hopefully the present observations may stimulate theoretical calculations of the expected energies of such states including the variation in excitation energy observed from isotope to isotope.

Table I.

Reaction	E_x of Maximum enhancement (MeV)	Full Width at Half Maximum (MeV)
^{116}Sn(p,t)^{114}Sn	8.00±0.04	1.93±0.07
^{118}Sn(p,t)^{116}Sn	8.40±0.04	2.12±0.07
^{120}Sn(p,t)^{118}Sn	8.51±0.04	2.16±0.07
^{122}Sn(p,t)^{120}Sn	8.53±0.08	2.58±0.10
^{124}Sn(p,t)^{122}Sn	8.65±0.08	2.72±0.10

To test further the assumption that the structure observed arises from pickup of two neutrons from the g,p,f shell, a number of DWBA calculations were carried out using the code DWUCK. All four orbits $1g_{9/2}$, $2p_{1/2}$, $2p_{3/2}$ and $1f_{5/2}$ were included, and all states with spin from 0^+ to 8^+ which could be formed by picking up two neutrons from these orbits were included. The assumption was made that these orbits were completely filled so that the total pickup strength was therefore calculated. The results are shown in Fig. 3 along with the experimental angular distribution for the "bump" extracted from the ^{116}Sn(p,t) experiment. The value of D_0^2 was set equal to 22.0 MeV^2/fm for all the states calculated. The total cross section predicted on this simple model is rather structureless, and the general slope matches very well the experimental angular distribution. However, the absolute magnitude of the predicted summed cross section is about twice as high as the experimental cross section. On the other hand, in the Sn(d,t) reactions about 30% of the $g_{9/2}$ and 20% of the $p_{1/2}$, $p_{3/2}$ sum rule limit is observed experimentally.[1] For the (p,d) reactions[2,3] less than 20% of the sum rule limit is observed. One might expect that about the same fraction of the total strength would be seen in the two neutron and in the one neutron pickup reactions. Thus the 50% of the total predicted cross section for the gpf shell which is observed experimentally is already surprisingly large.

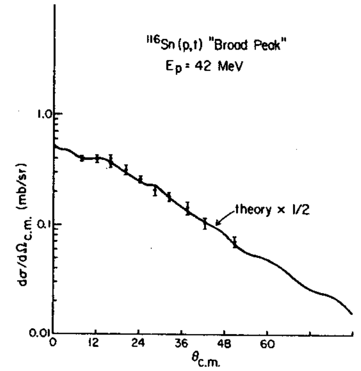

Fig. 3.--Angular distribution for ^{116}Sn(p,t) for the broad peak at Ex ~8 MeV. The curve is a DWBA calculation described in the text.

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Search for α-emitting High-Spin Isomers

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At very high spins ($I>30\hbar$) some nuclei are expected[1] to become oblate, with the spins of the yrast states then being generated by alignment of nucleon orbits. Under such circumstances, yrast traps may arise.[1] α-emission may compete with electromagnetic transitions in the decay of such high-spin isomers. Using beams from the MSU cyclotron, we have searched for high-spin α-emitters with the following projectile-target (natural unless otherwise indicated) combinations: 70 MeV ^{12}C+Sm; 103 MeV ^{14}N+Sm, Pr, Lu; 60 MeV ^{16}O+^{82}Se; 89 MeV ^{16}O+Ba, Sm, Nd, ^{146,148}Nd; 128 MeV ^{16}O+Ba, Sm. The targets were typically $\sim$60 μgm/cm^2, evaporated on C foils of $\sim$40 μgm/cm^2 thickness. The beam was incident on the target near grazing angle ($\sim 7^{\circ}$) whereas the α's entering the detector left the target at around 90°. In this fashion the effective target thickness to the beam was about eight times the actual thickness, while α's emitted from recoils stopped in the C foil penetrated only a small thickness en route to the detectors.

The α-particles were detected in either a single Si detector (170 μ thick; sensitive principally to α's when the energy of the detected particle is 6 - 17 MeV) or a ΔE-E telescope. The entire detection system was checked by detecting delayed α's from ^{208}Pb(^{12}C,xn) reactions.

With the above projectile-target combinations, no unambiguous evidence has been found for delayed α-particles in the 6-17 MeV energy range. Preliminary analysis of the data yielded upper limits ranging from 0.5 to 30 μb for the different cases. For half-lives longer than several hours or shorter than $\sim$10 ns, the upper limits are larger. We can conclude that no α-emitting isomers were found in the relatively small number of residual nuclides made in the search. A more systematic search covering a larger portion of the periodic table would be desirable before more general conclusions could be drawn. It would also be preferable to use heavier projectiles than employed in this study in order to bring in a larger amount of angular momentum.

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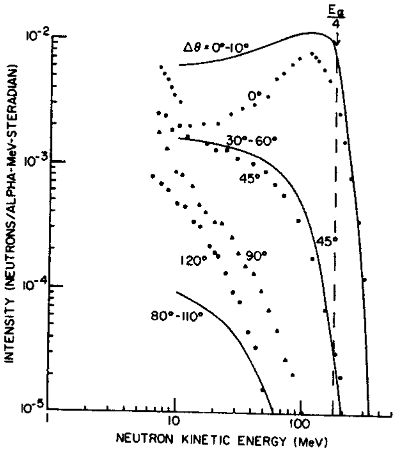
Neutron Production with 180 MeV/A α Particles

Aaron Galonsky, Peter Miller, Larry Young, Richard Madey,[*] Bryan Anderson,[*]
Alan Baldwin,[*] Bob Cecil,[*] and Frank Waterman[+]

Originally motivated by a wish to intelligently design radiation shielding for the heavy-ion cyclotrons, we have measured absolute neutron spectra produced by 710-MeV α particles (~180 MeV/nucleon) stopping in several different materials. Perhaps the most hazardous beams our superconducting cyclotrons will produce are of the lighter heavy ions having 200 MeV per nucleon. To the extent that an α particle may be considered as 1/3 of a carbon ion, insofar as neutron production is concerned, the measurements we have made should suffice for the shielding design. The data will also be used for comparison with models of nucleon production in heavy-ion collisions.

The data were obtained at the Space Radiation Effects Laboratory in Newport News, Virginia. From their synchrocyclotron, a slow-spill α-particle "beam", reduced in intensity to $\lesssim 10^5$/sec, was transported to our target. Neutrons were detected in plastic scintillators, and their energies were determined by the time-of-flight method. The detectors and associated electronics were a variant of standard Kent State University equipment. Because a synchrocyclotron does not produce very sharp bursts, neutron pulses were timed not against the cyclotron rf signal, but against signals from individual α particles in the beam. These signals were derived from the second of two thin scintillators near the target used to geometrically define the α-particle "beam".

Data were taken at 0°, 6°, 15°, 30°, 45°, 90°, 120°, and 150° five angles at a time. Four different targets were used -- carbon, water, iron, and lead. A run with the lead target was made with the "beam" energy reduced to 640 MeV. By subtraction from 710-MeV spectra, it is hoped to obtain the equivalent of thin-target spectra.



A sample of preliminary spectra is shown in the figure. The data are for neutron angles of 0°, 45°, 90°, and 120°. The curves result from an unpublished calculation by Hugo Bertini at Oak Ridge for the case of 200 MeV/nucleon ^{12}C ions bombarding a thin target of ^{16}O. With a few simplifying assumptions Bertini's spectra were integrated thru a thick water target by Kashy and Ledebuhr to form a basis for the first shielding estimates for the heavy-ion facility. With a slight adjustment to 180 MeV/nucleon their results are the curves in the figure. The factor-of-3 shorter range of carbon ions in comparison to α particles is cancelled by the assumption that one carbon = three alphas.

Bertini's model[1], an intranuclear cascade-plus-evaporation model utilizing a Monte Carlo computer calculation, is obviously very good. It does have a systematic error of predicting too-steep a fall-off of neutron flux with increasing angle. However, where the bulk of the neutrons are, in the forward direction, the discrepancy is small. Furthermore, in its favor is the agreement with (and advance prediction of) observation of a significant number of neutrons at small angles with energies well in excess of $E_\alpha/4$ = 180 MeV/nucleon.

Another model for which we do not yet have comparison calculations is the so-called fireball model[2], a model using thermodynamics and straightforward geometric concepts.

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[*] Kent State University
[+] University of Chicago

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