Giant Resonances

First Experiments:

G.C.Baldwin and G.S. Klaiber, Phys.Rev. 71, 3 (1947)

General Electric Research Laboratory, Schenectady, NY

Theoretical Explanation:

M. Goldhaber and E. Teller, Phys. Rev. 74, 1046(1948)

University of Illinois   University of Chicago

It is an oscillation of the neutrons against the protons!

Think electric dipole

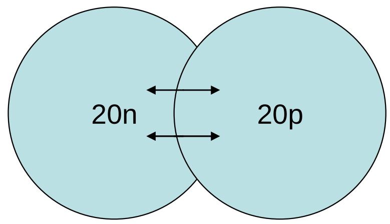
Positive “charge” is the collection of protons.

Negative “charge” is the collection of neutrons.

The Isovector Giant Dipole Resonance

(this E. Teller is Edward Teller – think Hydrogen bomb)

^{40}Ca



Isovector Giant Dipole Resonance

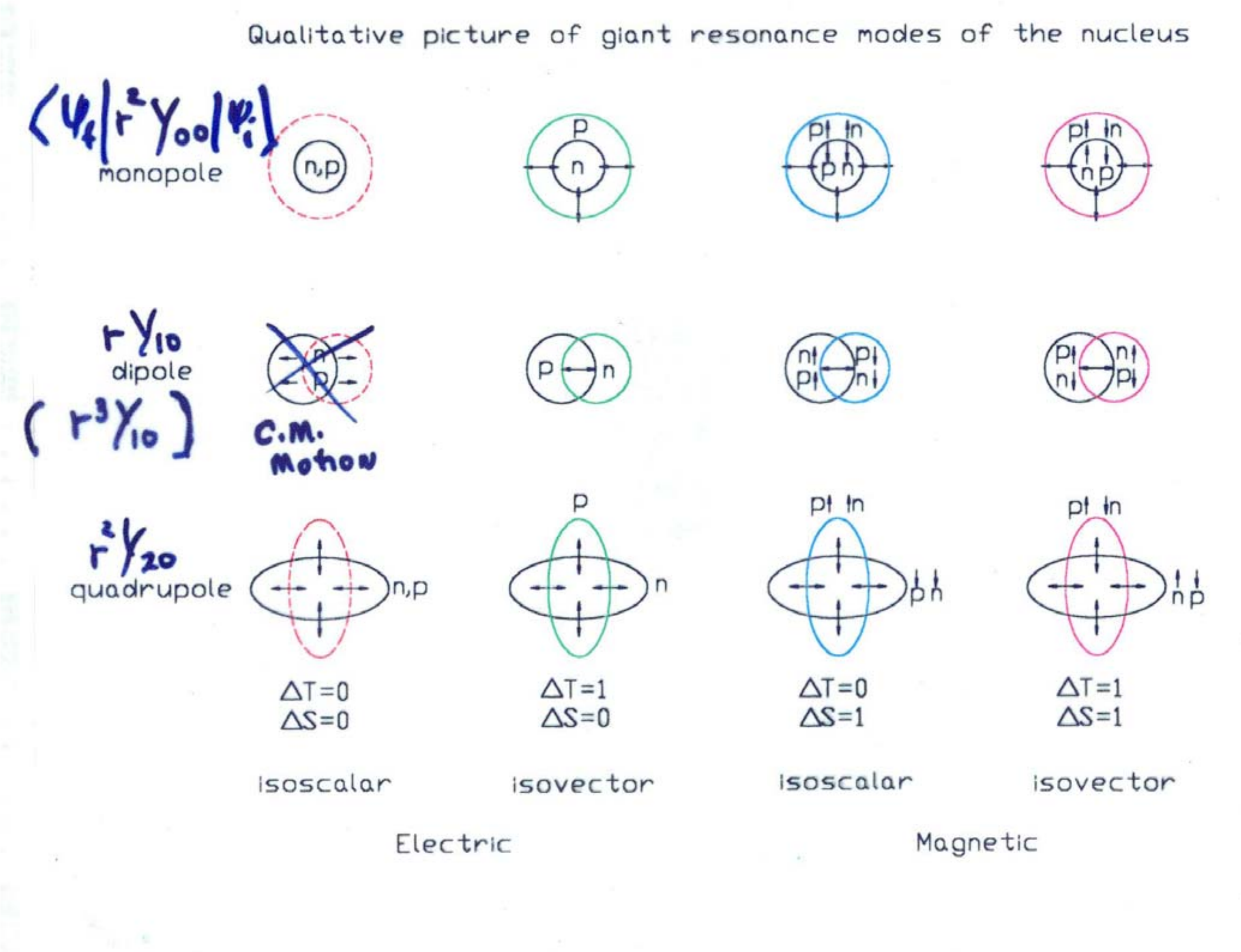
Analogous to charge distributions

Monopole L=0
Dipole L=1
Quadrupole L=2
Octupole L=3
Etc.

There should be lots of "Giant Resonances"

Isovector (n's and p's 180^{o} out of phase)
Isoscalar (n's and p's in phase)
Spin (spin up and down 180^{o} out of phase)

Shape Oscillations



"Giant Resonance"

1. Many Nucleons involved in motion (~ 10 in ^{40}Ca).
2. Contains "most of" strength for that multipole.

Limit on strength for each multipole.

Electromagnetic Operator $Q_L = \sum_i r_i^L Y_{LM}(\theta_i)$

Y_{LM} is a spherical harmonic
for multipole L, magnetic substate M.

$\sum_n E_n |\langle n|Q_L|0\rangle|^2 = S_L$ Energy Weighted Sum Rule

if there are no velocity dependent forces.

E_n is excitation energy of state
$|0\rangle$ represents wave function of ground state
$\langle n|$ represents wave function of excited state

For $L \geq 2$ $S_L = (\hbar^2 L(2L+1)A)/2\pi m * \langle r^{2L-2}\rangle$

"Giant Resonance"

Contains ~90-99% of this strength

Rest of strength in low lying states of nucleus.

1970: Only Dipole had been observed.

Theorists: Came up with reasons why others weren't there!

1971:

Graduate Student: Ranier Pitthan
Advisor: Thomas Walcher

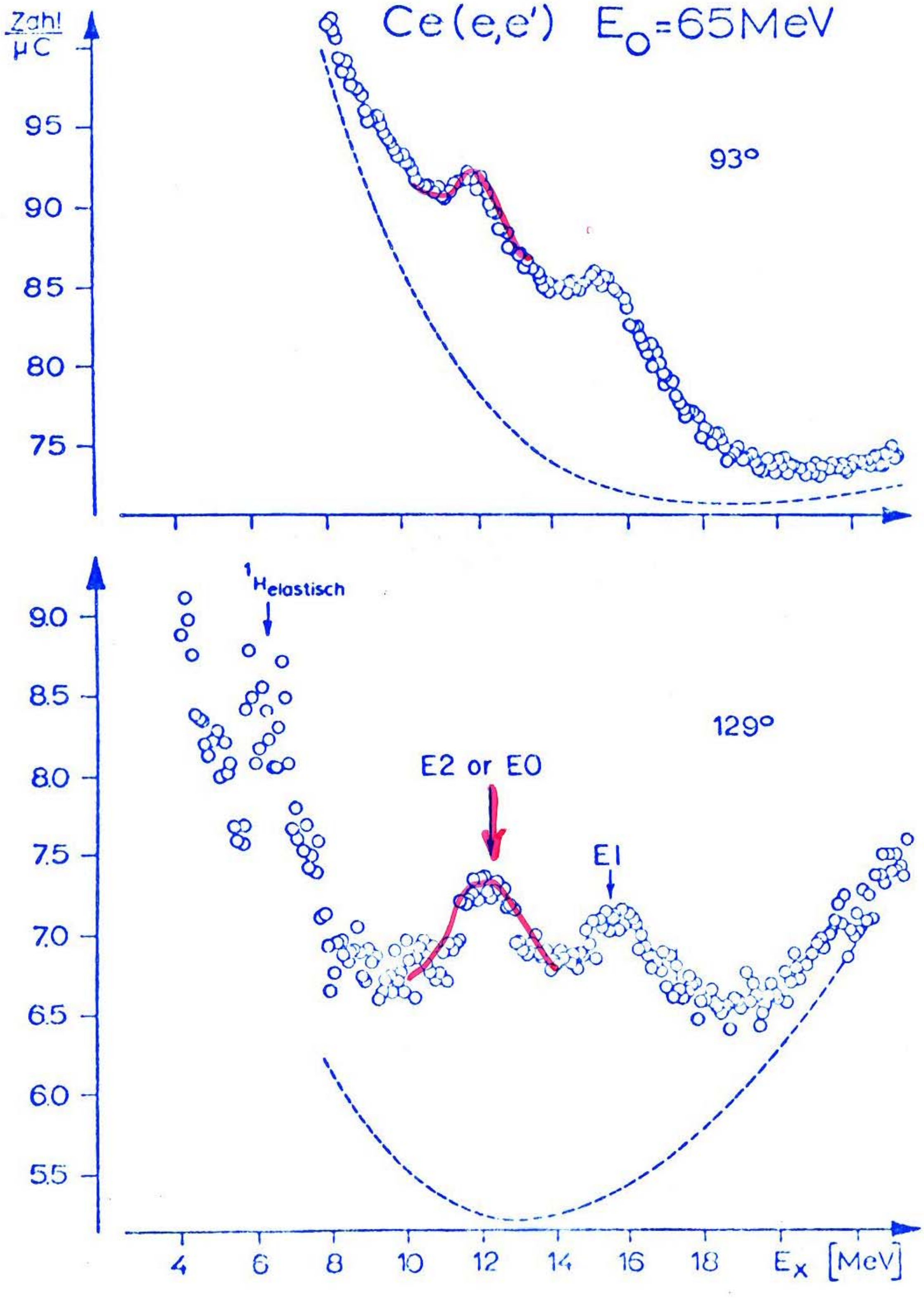
Electron scattering off of Ce, La, Pr targets

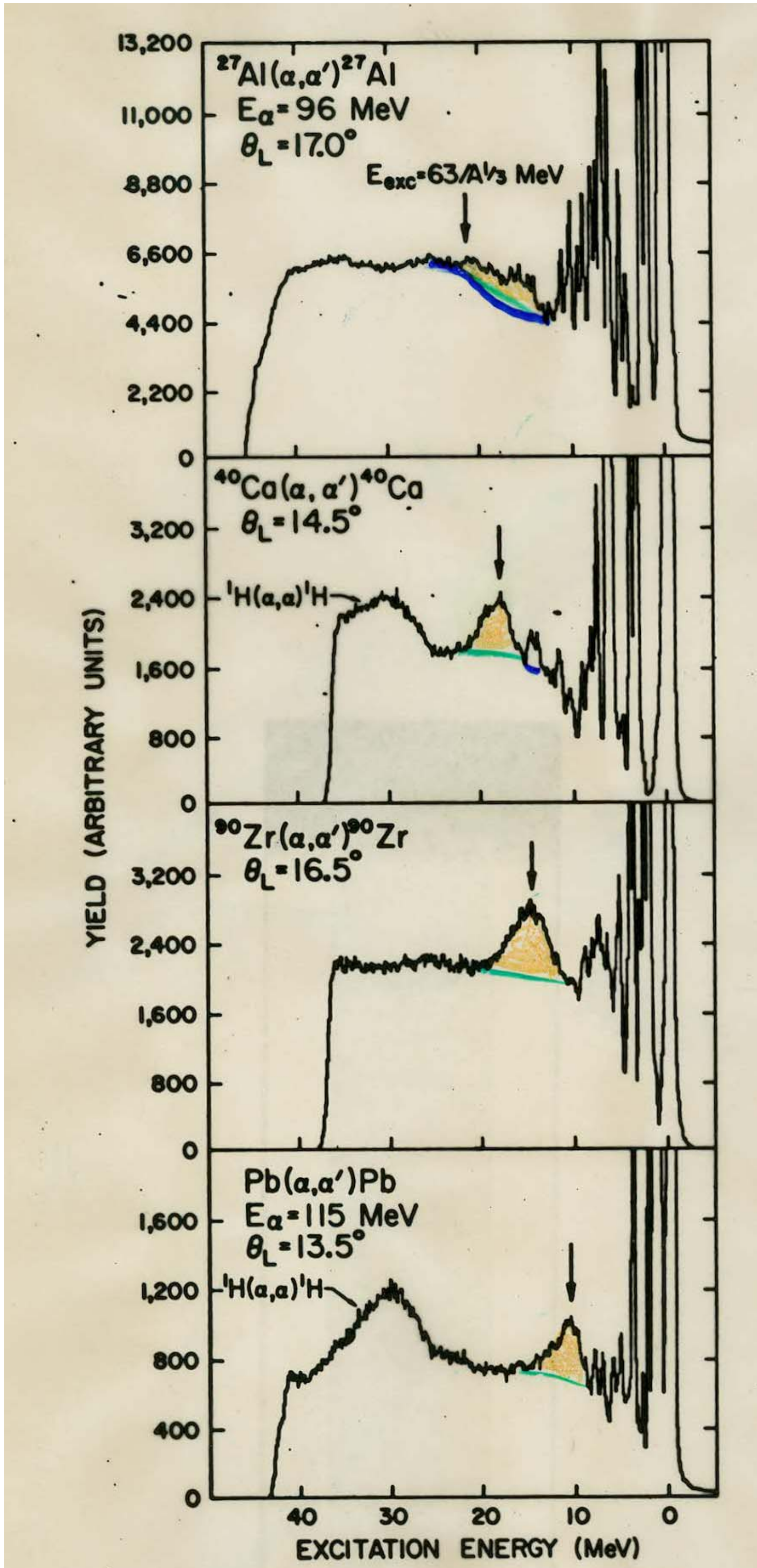
Darmstadt, Germany

Electrons interact only with the protons (no nuclear force)

Excite Isoscalar and Isovector states ~ same.

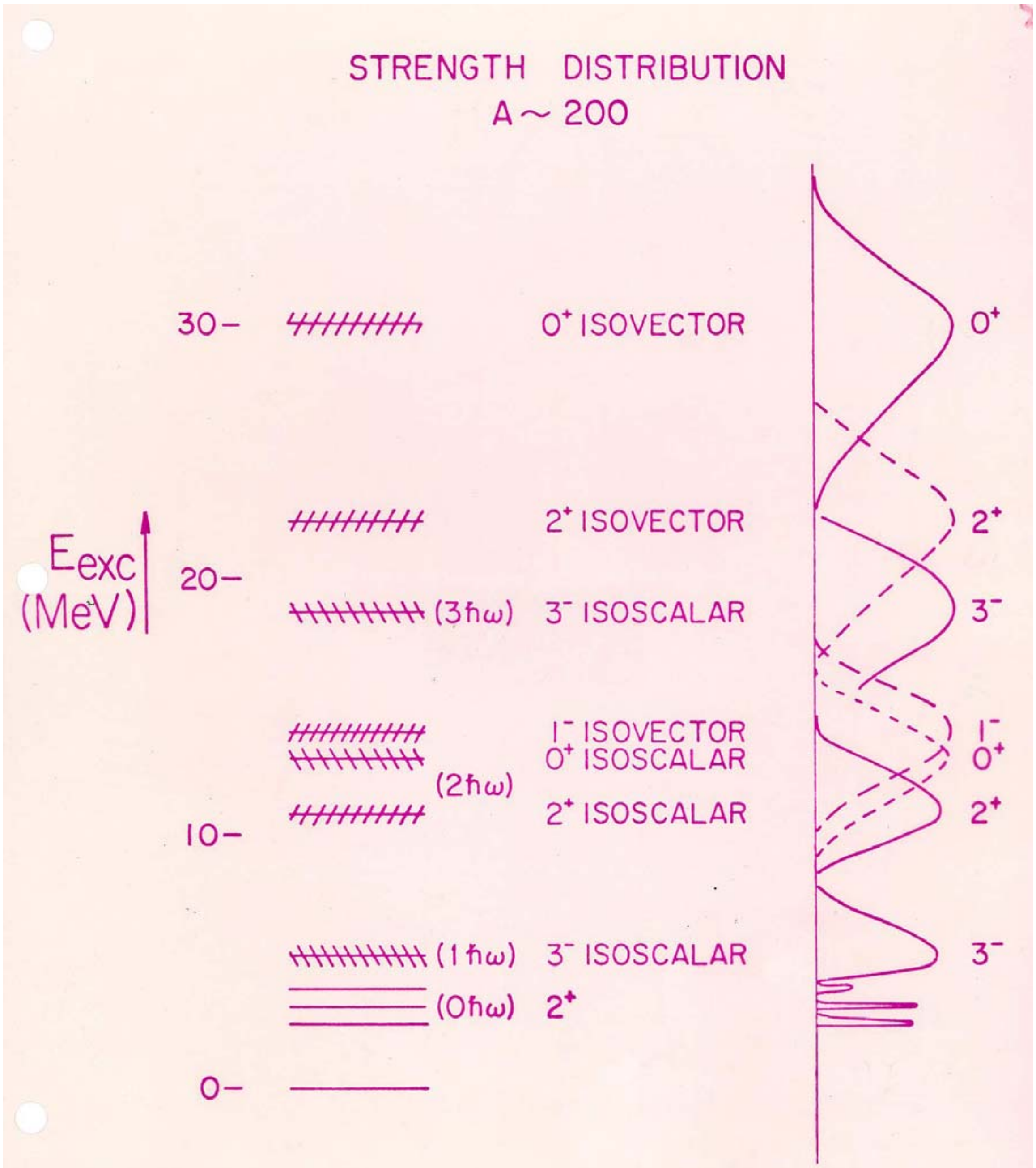
R. Pitthan and T. Walcher, Phys. Lett. 36B 563 (1971)





Texas A&M

1973



STRENGTH DISTRIBUTION
A ~ 200
E exc (MeV)
30 –
20 –
10 –
0 –
(3ħω)
(2ħω)
(1ħω)
(0ħω)
0+ ISOVECTOR
2+ ISOVECTOR
3− ISOSCALAR
1− ISOVECTOR
0+ ISOSCALAR
2+ ISOSCALAR
3− ISOSCALAR
2+
0+
2+
3−
1−
0+
2+
3−

One in particular:

Isoscalar Giant Monopole Resonance

The “breathing mode”

A 3 dimensional harmonic oscillator

SHO: $\omega=(k/m)^{1/2}$ **and** $E=\hbar\omega$

Liquid drop model of nucleus:

$$E_{GMR}=(\pi\hbar/3r_oA^{1/3})*(K_A/m)^{1/2}$$

r_o is nuclear radius

A is #(protons + neutrons)

m is mass of nucleon

K_A is compressibility of nucleus

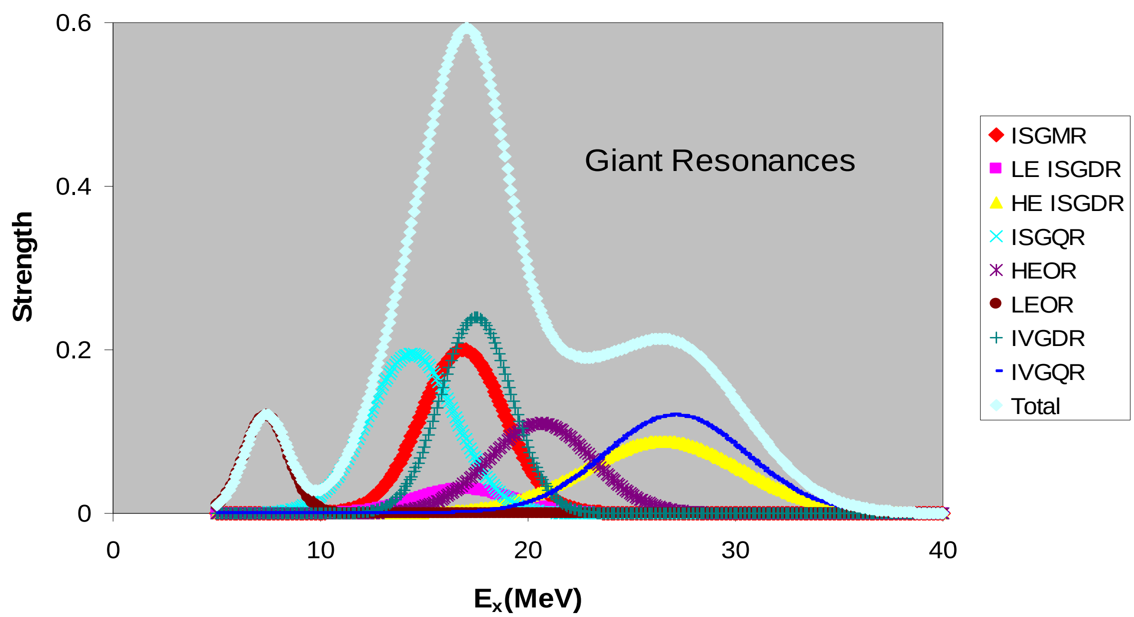
Can get compressibility of nucleus from ISGMR

IF WE CAN FIND IT!

Strength of Giant Resonances

Light Blue is what you see (the sum of strengths).

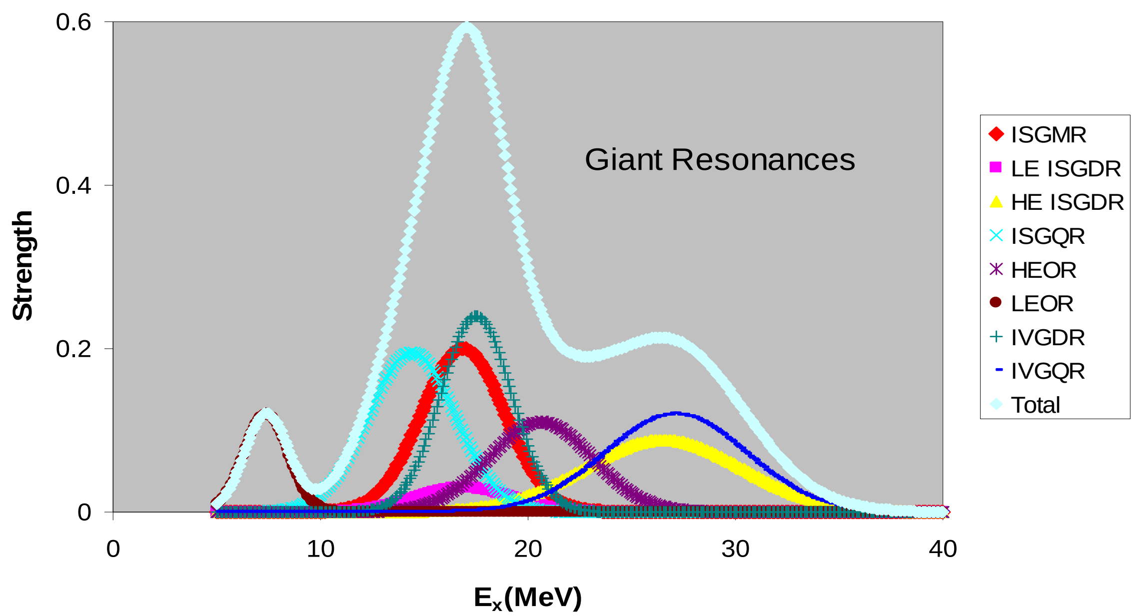
Red is the Isoscalar Giant Monopole Resonance
(what you want to measure)

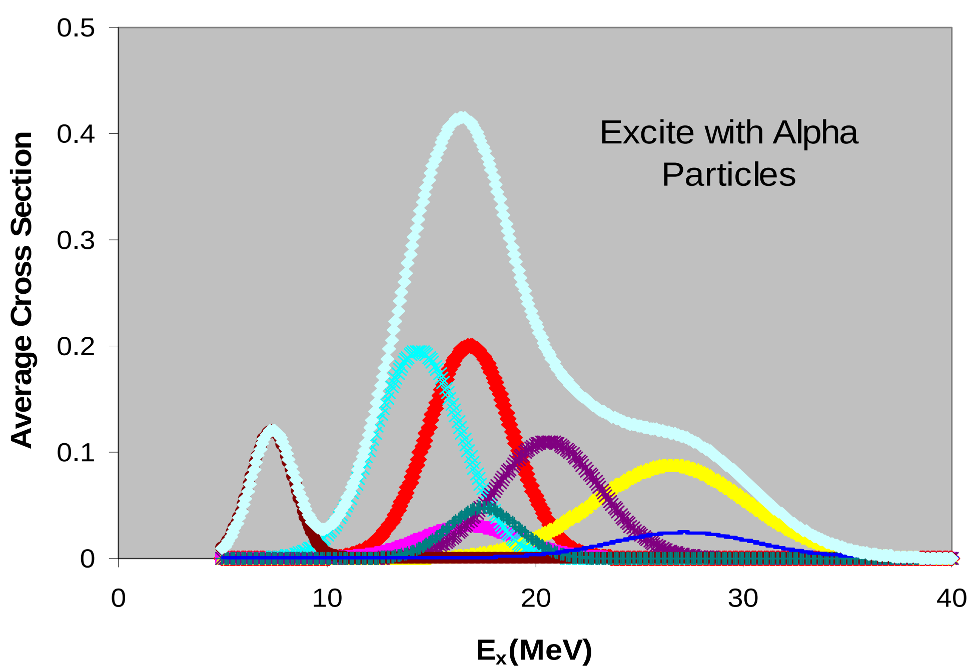


How do you separate out the Monopole??

Use an alpha particle beam to excite them!

Alpha particle (2p, 2n): excites Isoscalar states strongly. Isovector states weakly.





Need to do more!

Diffraction Model of α inelastic Scattering

Due to highly absorptive nature of α-Nucleus interaction, can treat it as scattering by a black disc. (Fraunhofer scattering)

See Bernstein (Adv. Nucl. Phys. 3 1969)

This is Blair Model (1959, 1965).

Cross-section given by square of Bessel function:

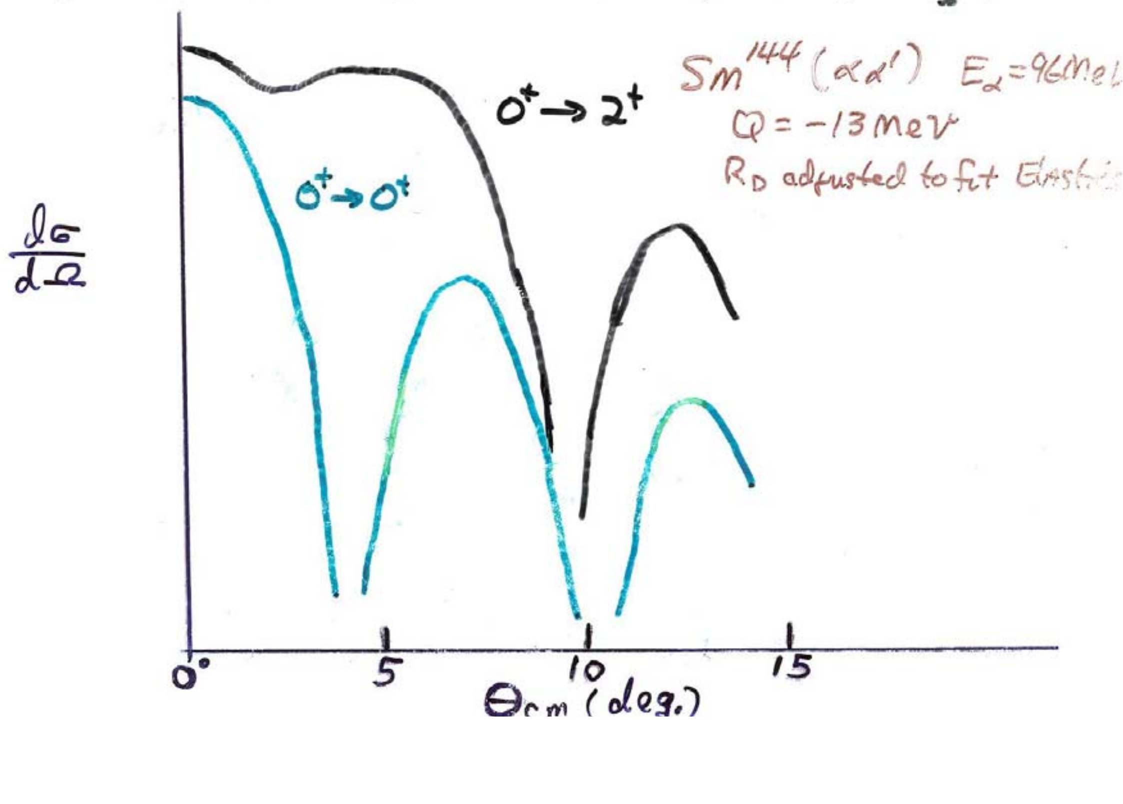
$$\left(\frac{d\sigma}{d\Omega}\right)_{elastic} \propto \left|J_1(qR_D)\right|^2$$

q is momentum Transf.

Rd is diffraction Radius

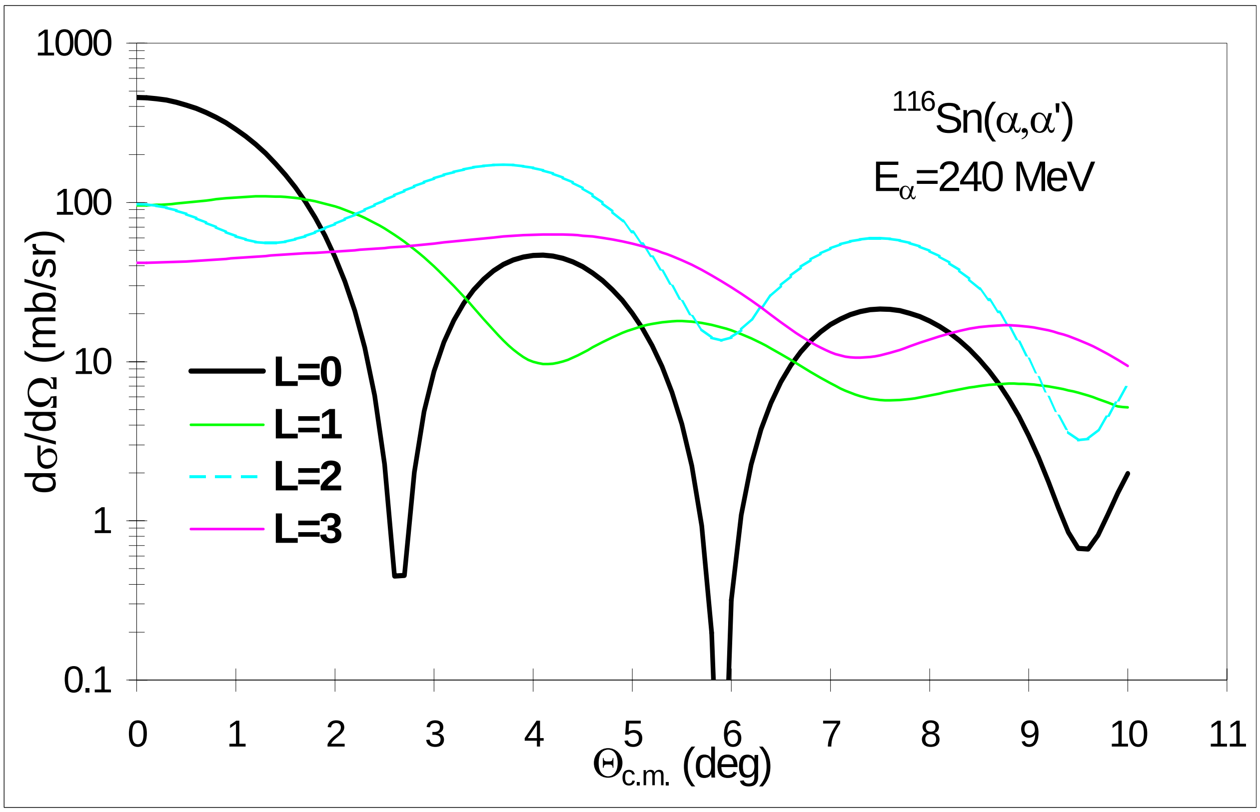
$$\left(\frac{d\sigma}{d\Omega}\right)_{0^+\to 0^+} \propto \left|J_0(qR_D)\right|^2$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{0^+\to 2^+} \propto \left[\tfrac{1}{4} J_0^2(qR_D) + \tfrac{3}{4} J_2^2(qR_D)\right]$$



Distorted Wave Born Approximation Calculation

Inelastic α scattering E_α=240MeV

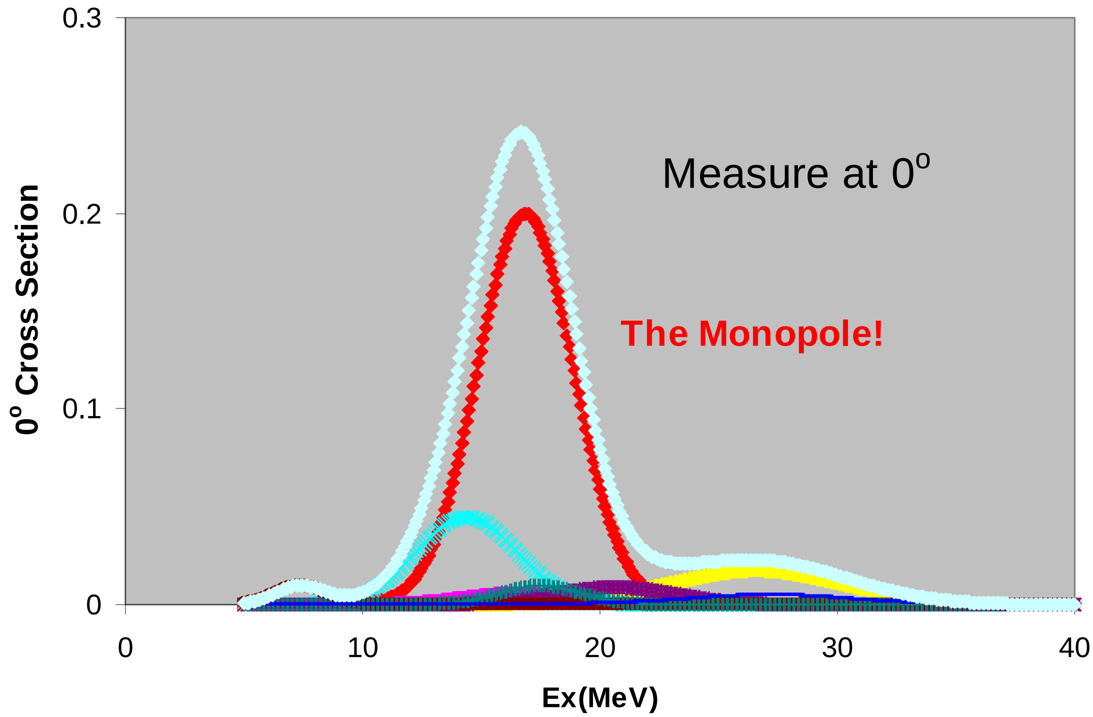


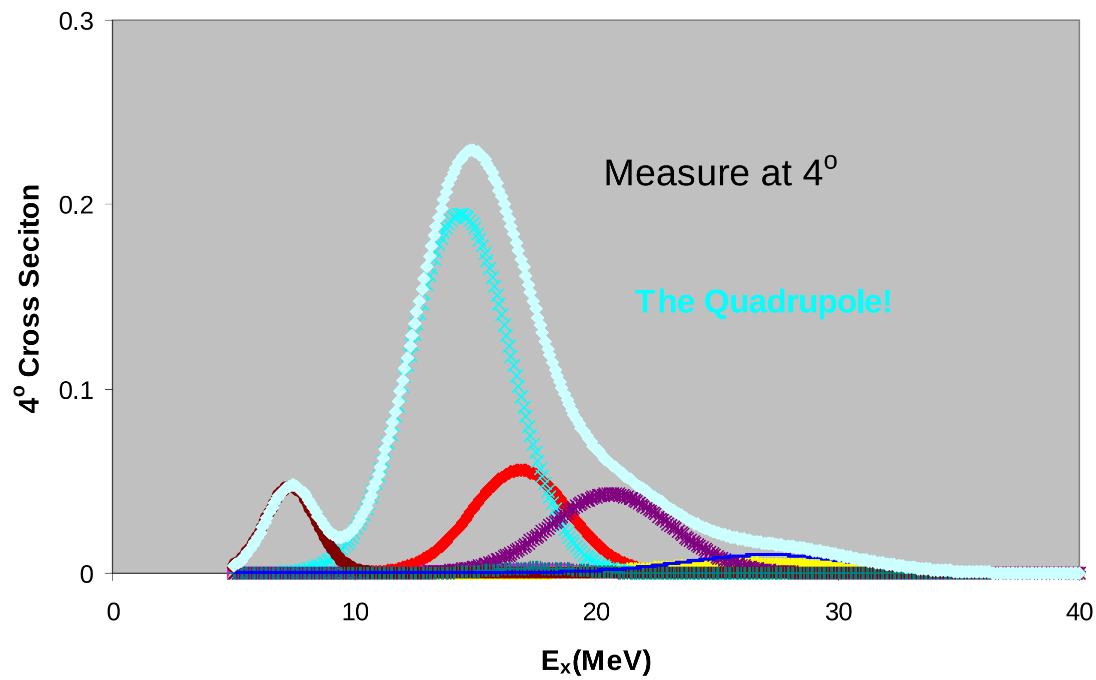
Measure at different scattering angles!

Could separate Monopole from Quadrupole

by measuring 1.5^o to 4^o

Monopole Enhanced at 0°.



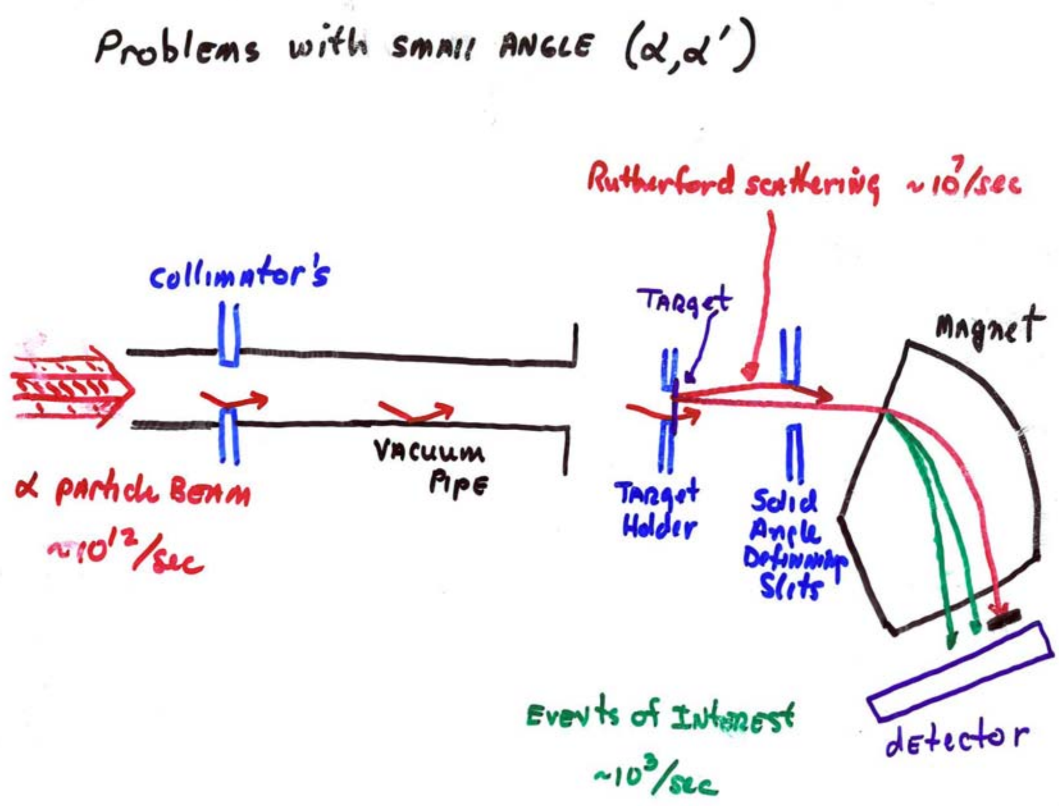


At Small angles

Beam would destroy detectors.

Use Magnet to separate beam from inelastic scattering

BUT!



Beam must be transported without hitting anything!

Nobody had done 0^o inelastic scattering.

Measure over the minimum in the monopole.

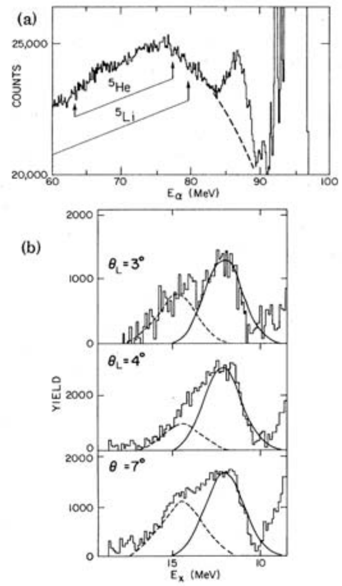


FIG. 1. (a) A ^{208}Pb(α, α') spectrum taken at $\theta_L = 4°$. The dashed line indicates the background chosen. (b) A portion of ^{144}Sm(α, α') spectra ($E_\alpha = 96$ MeV) taken at 3°, 4°, and 7° are shown after subtraction of the continuum background. Gaussian peaks are shown for both components utilizing positions and widths from Table I.

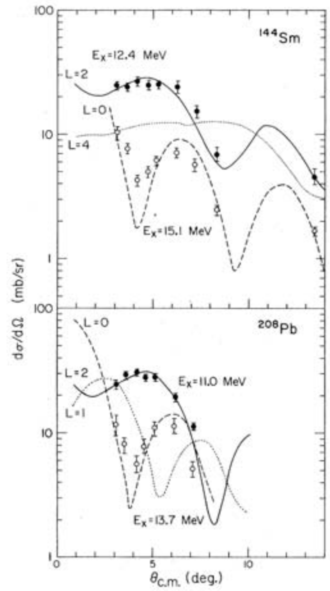


FIG. 2. Angular distributions obtained for both components of the giant resonance peaks in ^{144}Sm and ^{208}Pb. DWBA calculations are shown for several L transfers. The normalizations for the $L = 1$ and $L = 4$ calculations are arbitrary.

^{208}Pb by Harakeh *et al.*[6] The angular distribution obtained for the two broad components for both ^{144}Sm and ^{208}Pb are shown in Fig. 2. In each case the angular distributions for the two GR components are different as is apparent from the spectra shown in Fig. 1.

Distorted-wave Born-approximation (DWBA) calculations were performed using the computer code DWUCK.[8] The calculations used were performed with the parameters listed in Ref. 1

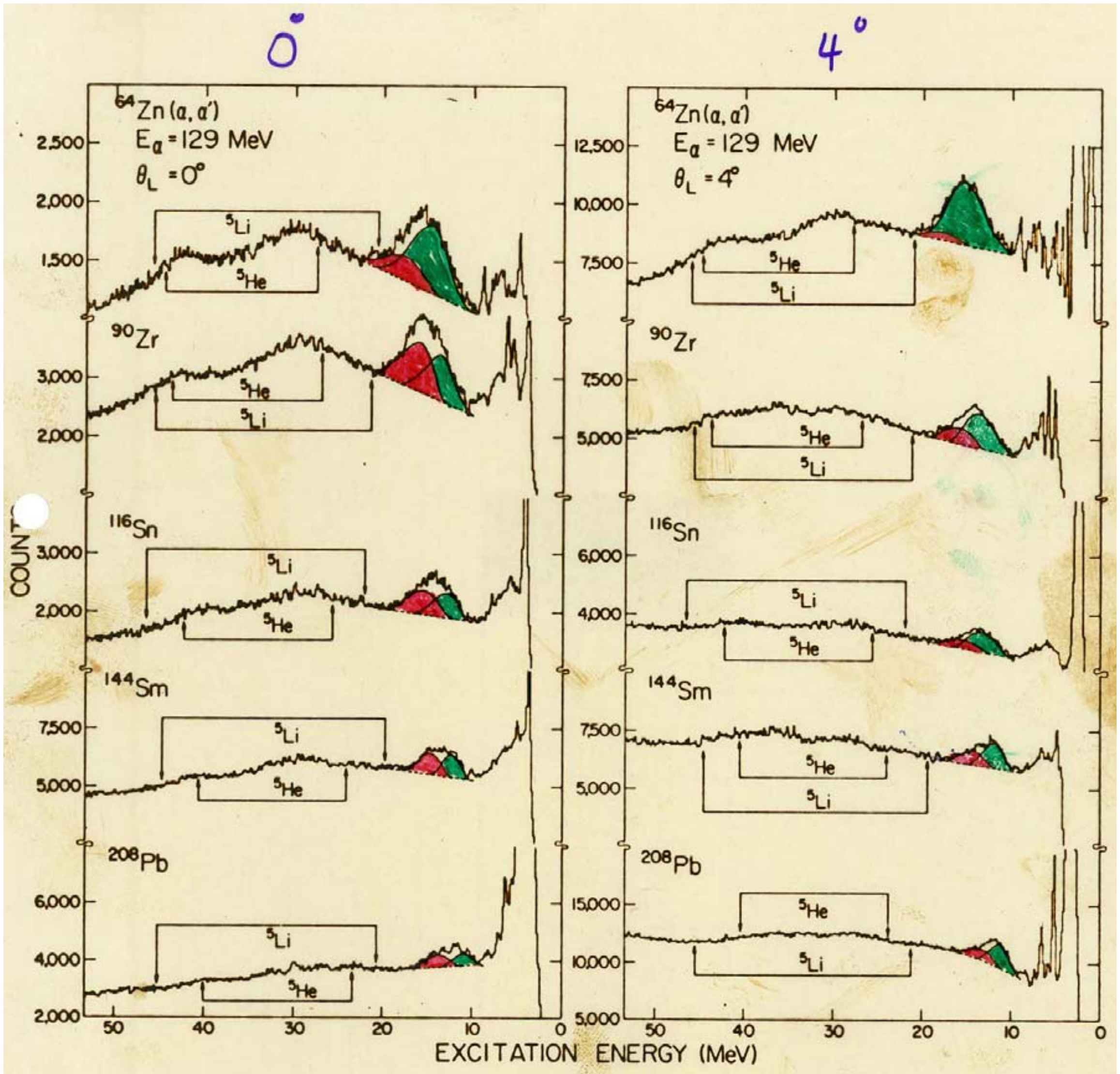
TABLE I. Parameters obtained for the two components of the GR peak.

	E_x (MeV)	Γ (MeV)	J^π	$\beta^2 R^2$	EWSR (%)
^{144}Sm	12.4 ± 0.4	2.6 ± 0.4	2^+	0.43	85 ± 15
	15.1 ± 0.5	2.9 ± 0.5	0^+	0.22	100 ± 20
^{208}Pb	11.0 ± 0.2	2.7 ± 0.3	2^+	0.35	90 ± 20
	13.7 ± 0.4	3.0 ± 0.5	0^+	0.17	105 ± 20

(^{148}Sm parameters were used for ^{144}Sm). Several optical-potential-parameter sets from the literature were tried, but the results were roughly independent of optical parameters. Monopole calculations were performed using both Satchler's[9] version-1 and -2 form factors. The other form factors and sum rules used are discussed in Ref. 1. The magnitudes of the DWBA predictions changed somewhat with differing optical potentials, differing form factors (for the monopole), and differing Coulomb-excitation parameters; however, the shapes of the angular distributions were essentially unchanged. The predictions for a monopole state, the isovector-dipole state, a quadrupole state, and a hexadecapole state are shown superimposed on the data in Fig. 2. It is readily seen that the lower-excitation component is relatively well fitted by the quadrupole calculation, while the higher-excitation component is fitted adequately by the monopole calculation. In particular, the predicted signature of a monopole state, a sharp minimum around 4°, is very appar-

later we succeeded at 0°.

BUT average angle ~2°.



A Few Facts About the GMR

$E_x = \hbar\omega \sim 15\,\text{MeV} \Rightarrow \quad f \sim 4\times10^{21}/s$

$\Gamma \sim \hbar/\Gamma \sim 3\,\text{MeV} \Rightarrow \quad \tau \sim 6\times10^{-22}\,s$

Thus it "lives" for at most a few oscillations!

Oscillation amplitude: $\quad \frac{\delta\rho}{\rho} \sim 0.05$

Interesting Numbers from $K_{nm} \approx 230\,\text{MeV}$

Compressibility $\chi_{nm} = \frac{9}{n K_{nm}} \Rightarrow \chi_{nm} \sim 1.5\times10^{-32}\left[\frac{N}{m^2}\right]^{-1}$

n = nucleon density $\qquad \chi_{water} \sim 5\times10^{-10}\left[\frac{N}{m^2}\right]^{-1}$

Velocity of Sound in nuclear matter

$$c_s = \sqrt{B/\rho}$$
$$= \sqrt{1/\chi_{nm} m n}$$
$$= \left[\frac{K_{nm}}{9mc^2}\right]^{1/2} c$$

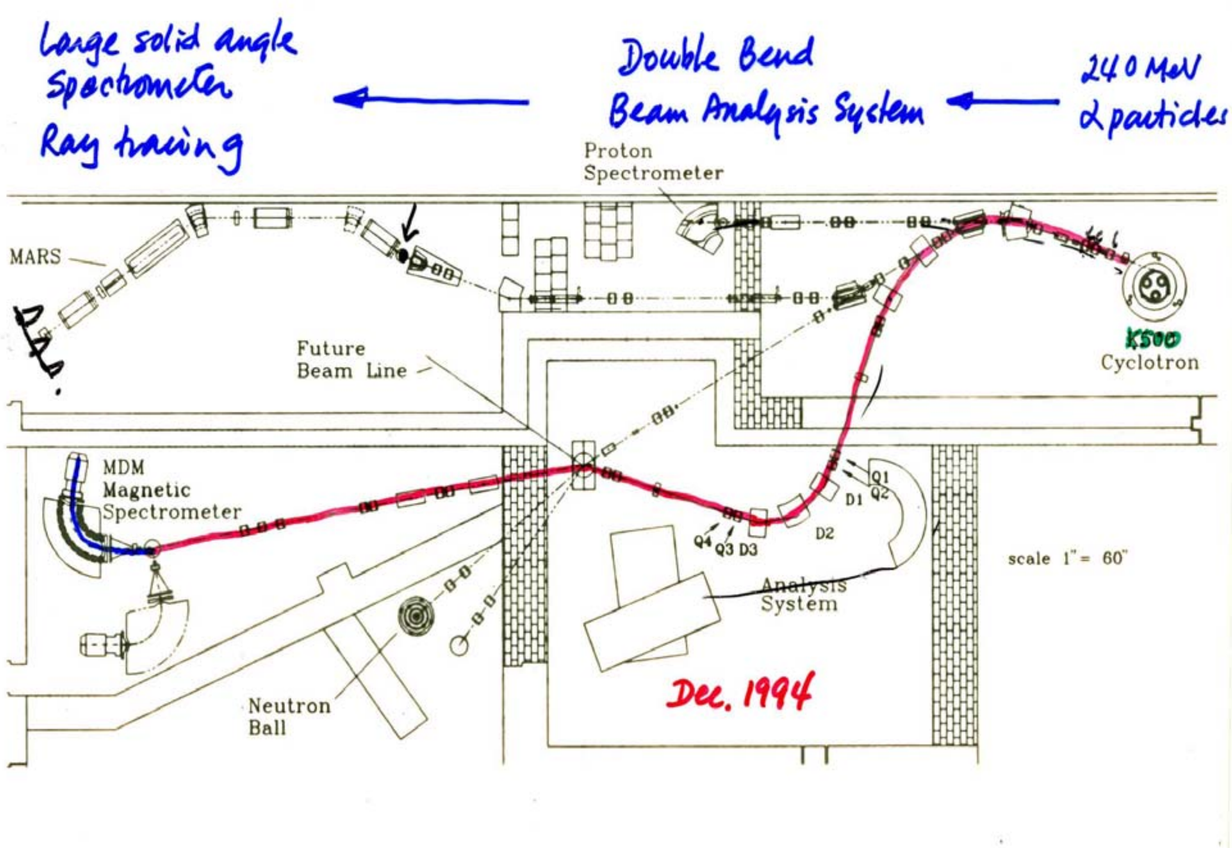
$c_s = 0.15\,c$

Built:

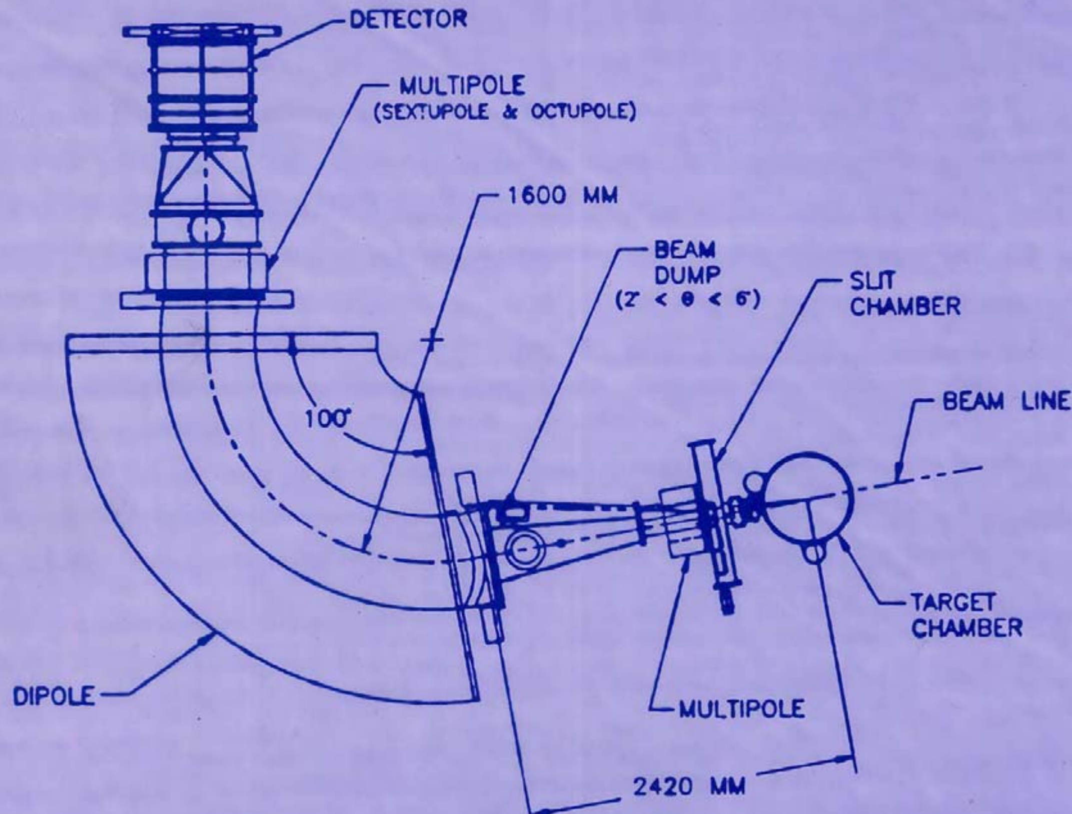
New cyclotron - higher energy.

New beam analysis/transport system - Clean beams.

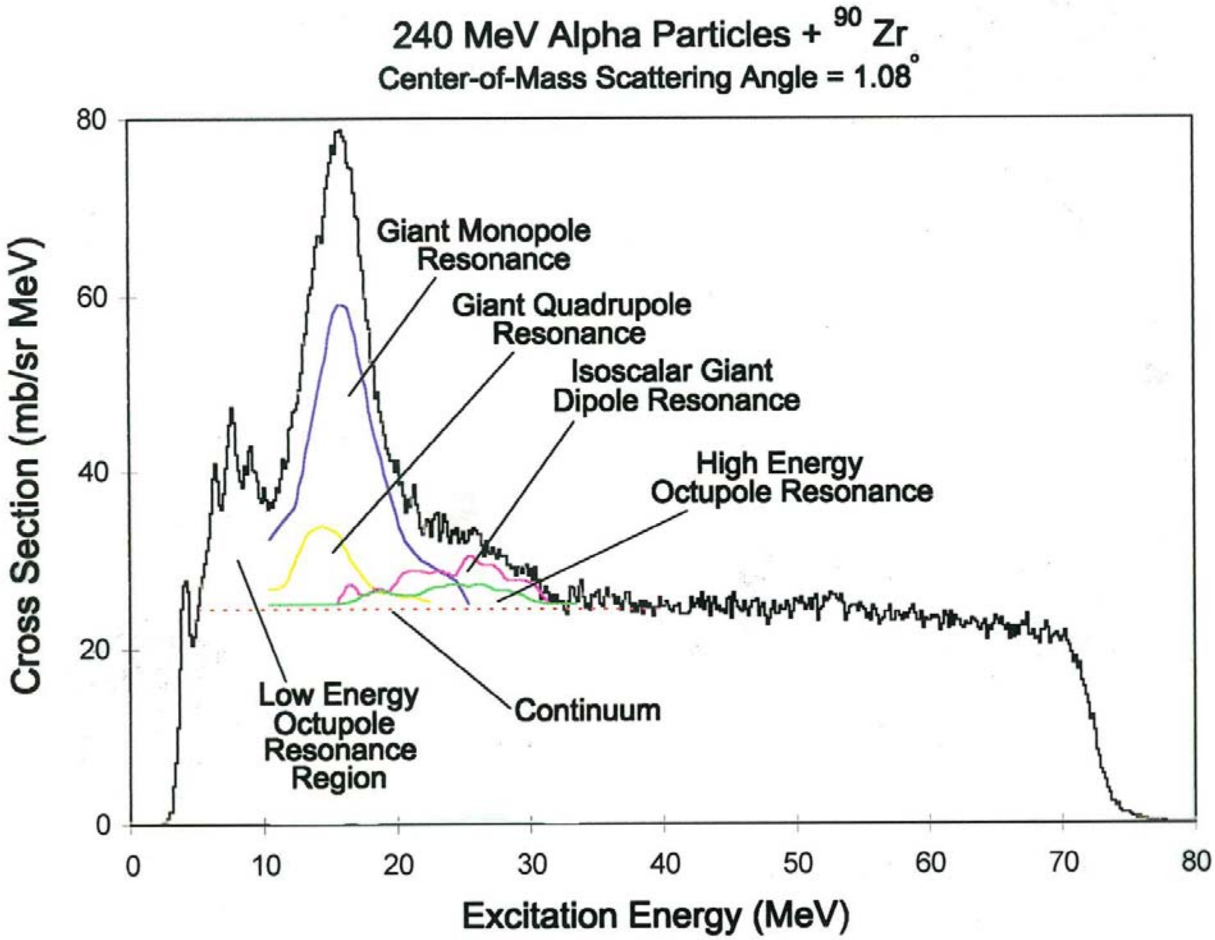
MDM spectrometer



MDM Spectrometer



K	**315–400 (315 alphas, 78 MeV/A)**
Vertical Acceptance	**+-50 mrad**
Horizontal Acceptance	**+-40 mrad**
Solid Angle	**8 msr**
E_{max}/E_{min}	**1.31 (E_x up to 50 MeV @ 200 alphas)**
Resolving Power delE/E	**4500**

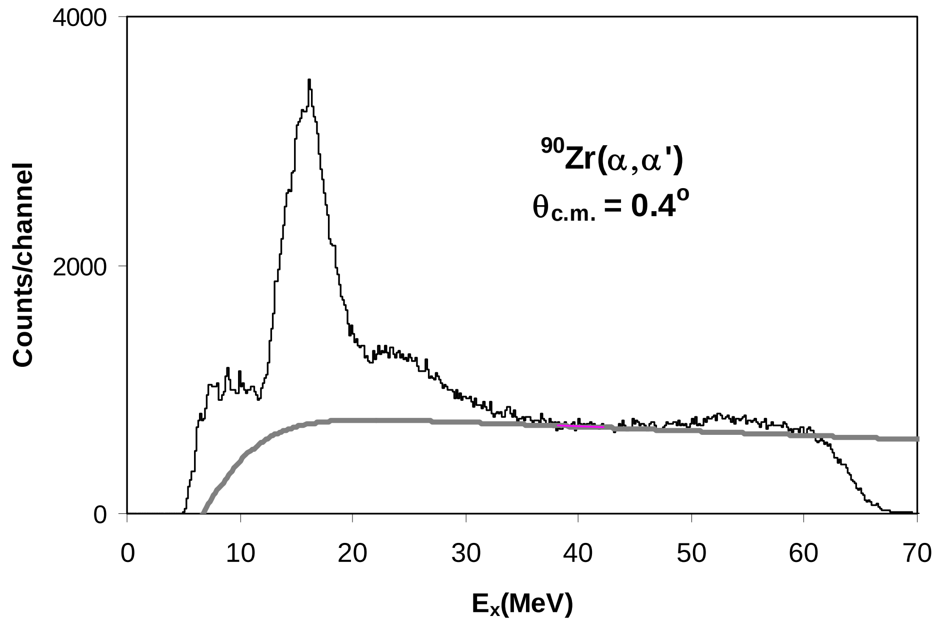


Measuring only horizontal angle.

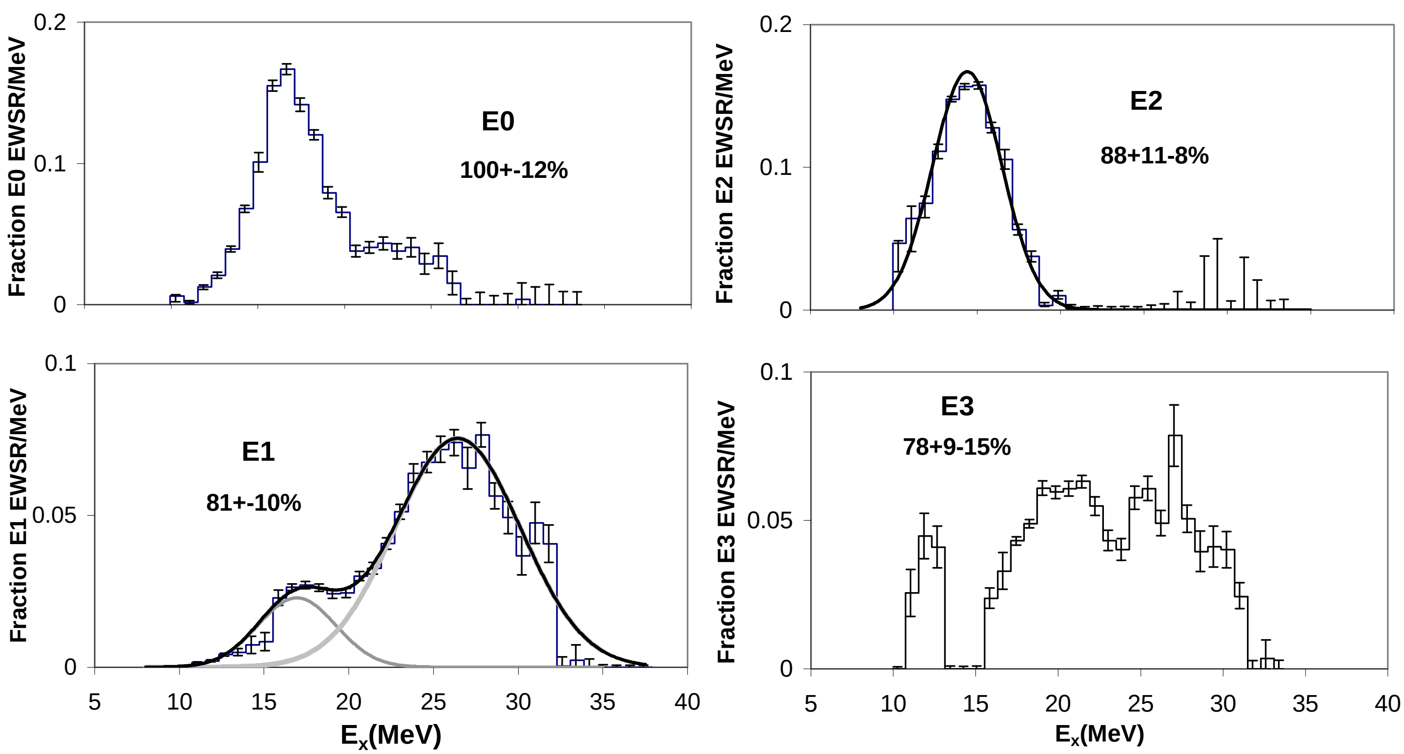
Average over vertical angle.

Added measurement of vertical angle

^{90}Zr Spectrum



Multipole Distributions



We can separate multipoles!

An Experimentalist's View of Nuclear Compressibility

Important Quantities which characterize Nuclear Matter are:

(1) Binding Energy per particle: ~16MeV/particl
obtained from a semi-emperical mass formula
with fits to nuclear masses.

(2) Density $\rho_0 \sim 0.17$ nucleons/fm^3 - or -
Fermi momentum $k_F \sim 1.36\ fm^{-1}$
obtained from central density of heavy nuclei measured by electron scattering

(3) Compression Modulus (Incompressibility)

$$K \equiv \left(k_F^2 \frac{d^2 E/A}{d k_F^2} \right)_0$$

obtained from energy of the breathing mode state.

$$E_{BM} = \frac{\hbar}{r_0} \sqrt{\frac{K_A}{m}}$$

$$K_A = r_0^2 \frac{d^2 E/A}{d r_0^2} \quad \left[\text{for a finite nucleus} \right]$$

$$E_{GMR}=\hbar\,(K_A/m\langle r^2\rangle)^{1/2}$$

$\langle r^2\rangle$: mean square nuclear radius
m: nucleon mass
K_A: compressibility of nucleus

Compressibility of Nuclear Matter

Simple Picture: Leptodermous Expansion

$$K_A=K_{NM}+K_{Surf}A^{-1/3}+K_{vs}((N-Z)/A)^2+K_{Coul}*Z^2/A^{4/3}$$

$$K_{vs}=K_{Sym}+L(K'/K_v-6)$$

Where K_{NM}: curvature of E/A around ρ_o
K_{Sym}: curvature of symmetry energy

Note that E_{GMR} depends on K_{NM} AND K_{Sym}!

The Right Way to get K_{NM}

Calculate E_{GMR} using effective interactions
(each results in a specific K_{NM})

Compare to experiment!

Vretenar et al. PRC 68,024310(2003).
Agrawal et al. PRC 68,031304(2003).
Colò et al. PRC 70,024307(2004).

Role of K_v and K_{Sym} in Infinite nuclear matter.

Microscopic Calculations:

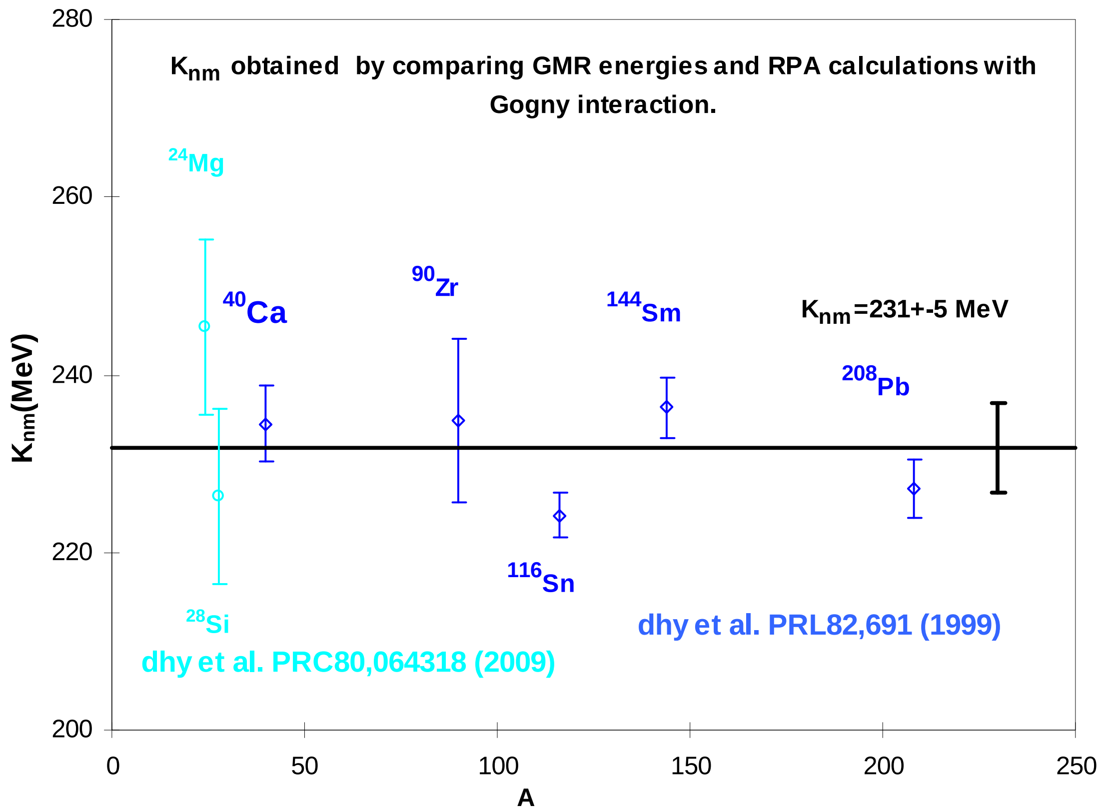
Non_Relativistic:

Skyrme, Gogny effective interactions.

Relativistic:

NL1, NL3, etc. parameter sets.

Compare calculated to experimental E_{GMR}



^{24}Mg, ^{28}Si Péru, Goutte, Berger, NPA788, 44 (2007)

QuasiParticle RPA-HFB Gogny D1S

K_{NM} interaction dependent.

Symmetry Energy ρ dependence.

Present: K_{NM}~ 220-240 MeV

Nuclear Matter Equation of State

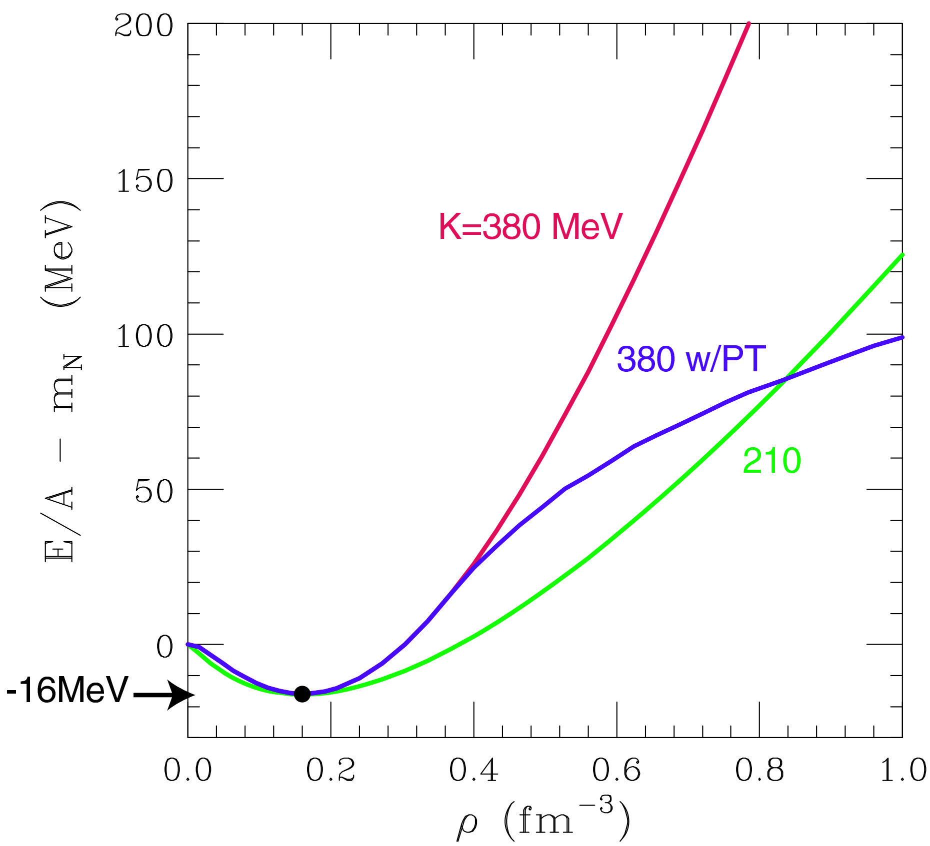
A parametrization of the EOS to order ε^2:

(M. Farine et al. NPA 615,135(1997))

$$E/A = A_v + (K_{NM}/18)\varepsilon^2 + [(\rho_n - \rho_p)/\rho]^2 \{J + (L/3)\varepsilon + (K_{Sym}/18)\varepsilon^2 + ..\} + ..$$

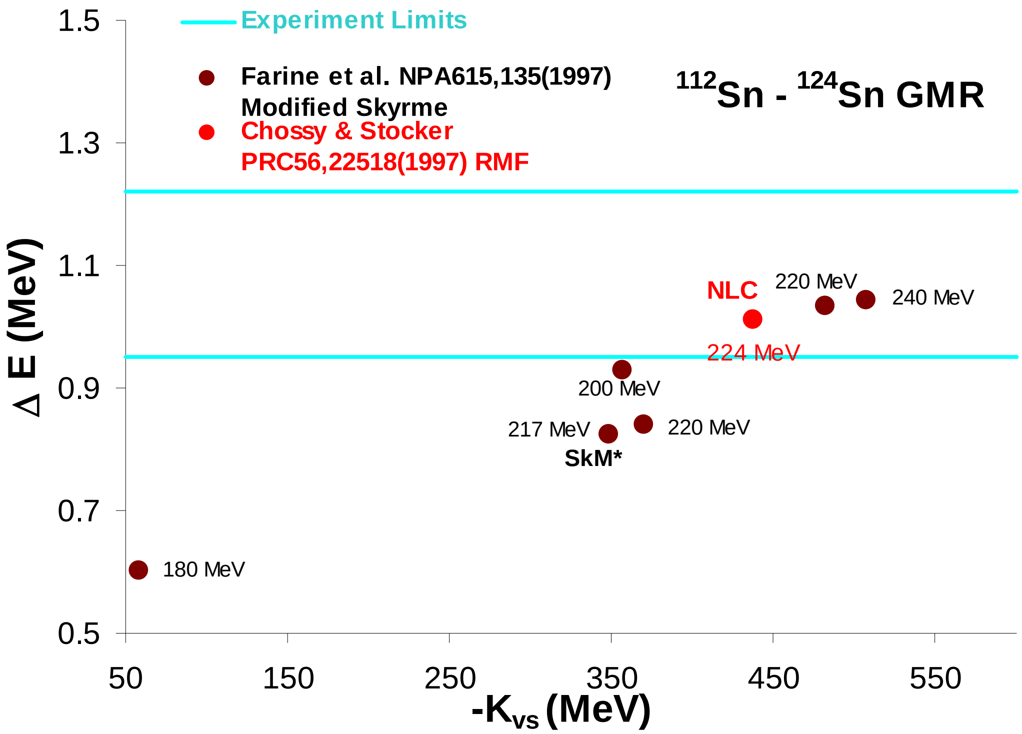
Where $\varepsilon = (\rho - \rho_o)/\rho_o$ and $(\rho_n - \rho_p)/\rho \sim (N-Z)/A$

Second derivative leaves K_{NM} and K_{SYM}.

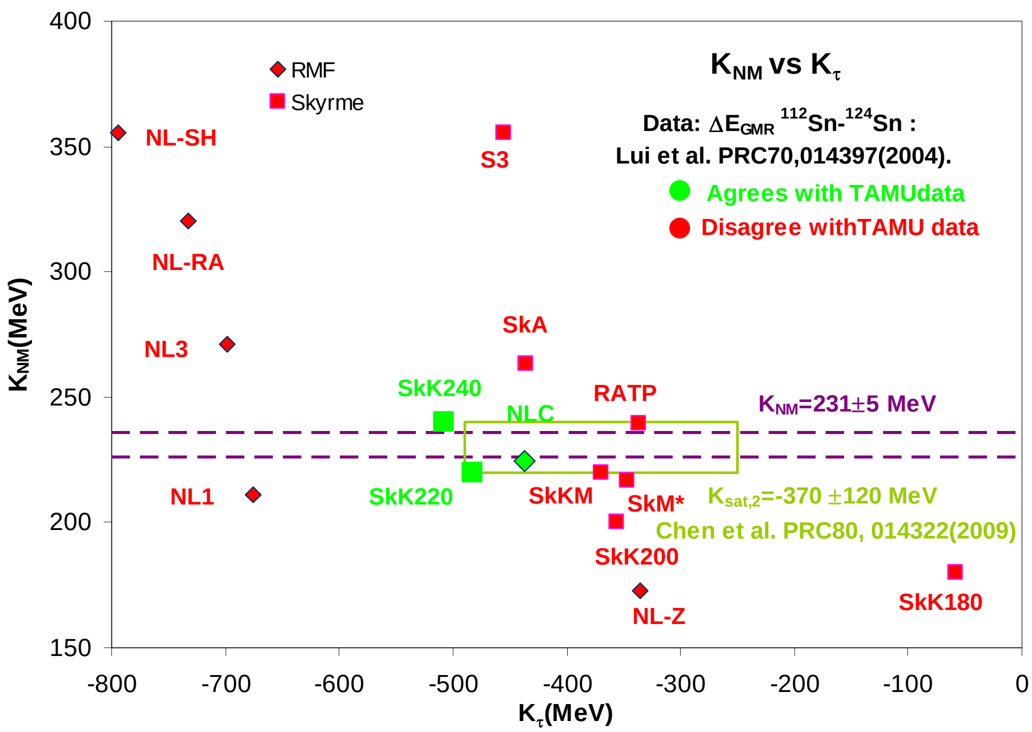


K_{SYM} goes as $((N-Z)/A)^2$

To get K_{SYM}: Change (N-Z)/A $^{112-124}Sn$



$$K_{vs} = K_\tau = K_{Sym} + L(K'/K_v - 6) \qquad K_\tau < -375 \text{ MeV}$$



Increase (N-Z/A) for K_{sym}

Move away from stable nuclei

Present Research

D.H. Youngblood
Y.-W.Lui
Jonathon Button(thesis project)
Will McGrew (REU)
Yi Xu (post doc joins 8/30/12)
Hanyu Li (undergrad joins 9/1/12)

Use unstable nuclei as beams:
upgraded Cyclotron facility.

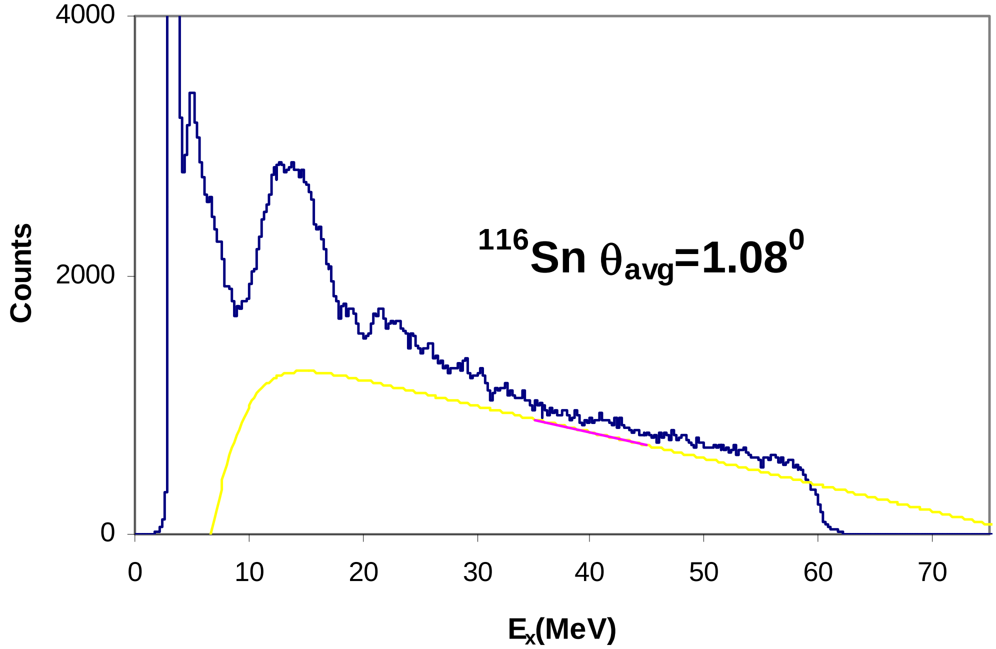
Inverse reactions – Problem: Helium target
Solution: Use ^{6}Li target

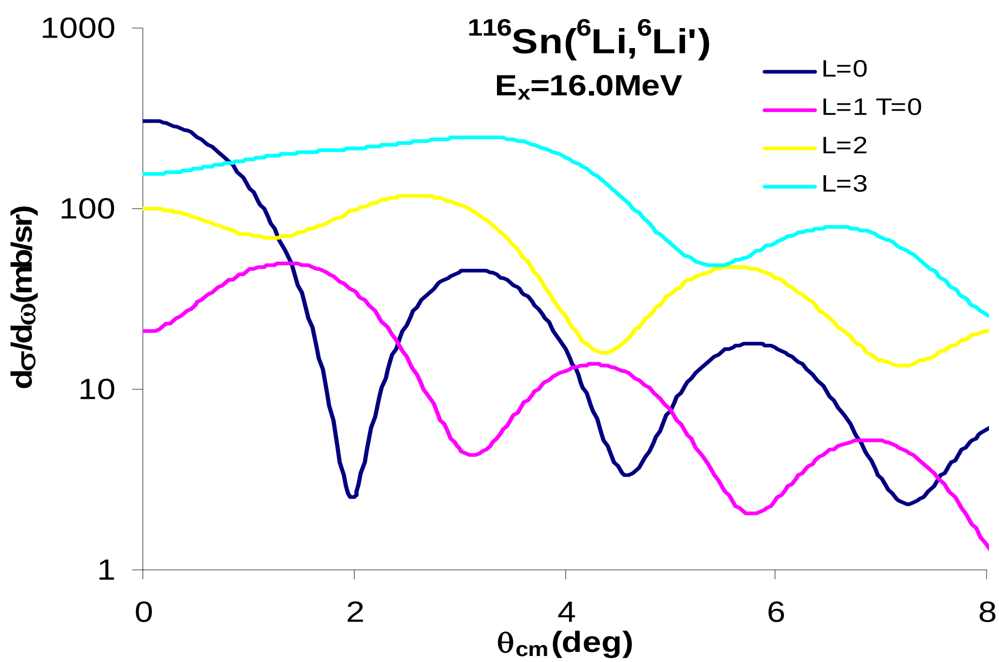
X. Chen's Thesis: 240 MeV ^{6}Li on ^{24}Mg, ^{28}Si, ^{116}Sn.

Prove ^{6}Li scattering good for GMR.

Inelastic Scattering to Giant Resonances

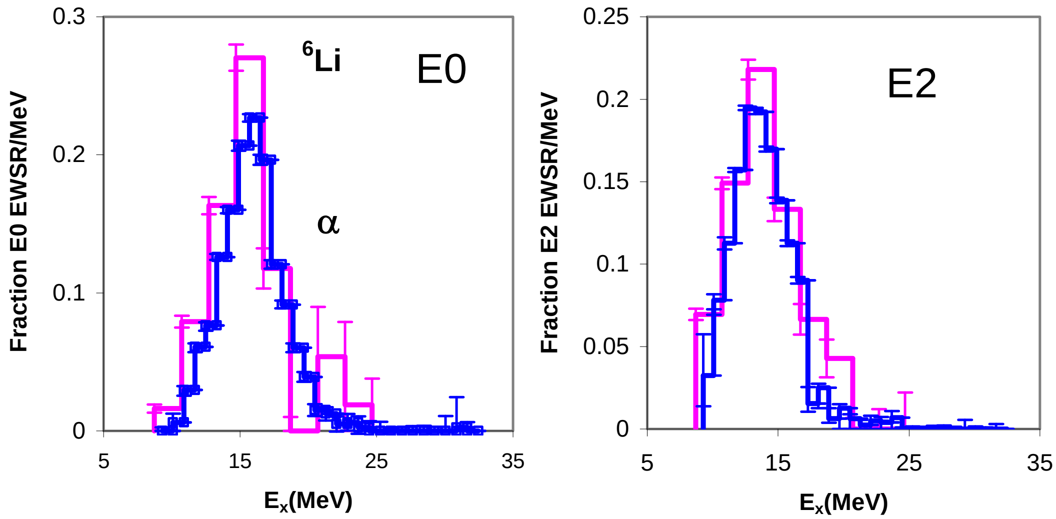
240 MeV $^{6}Li + ^{116}Sn$



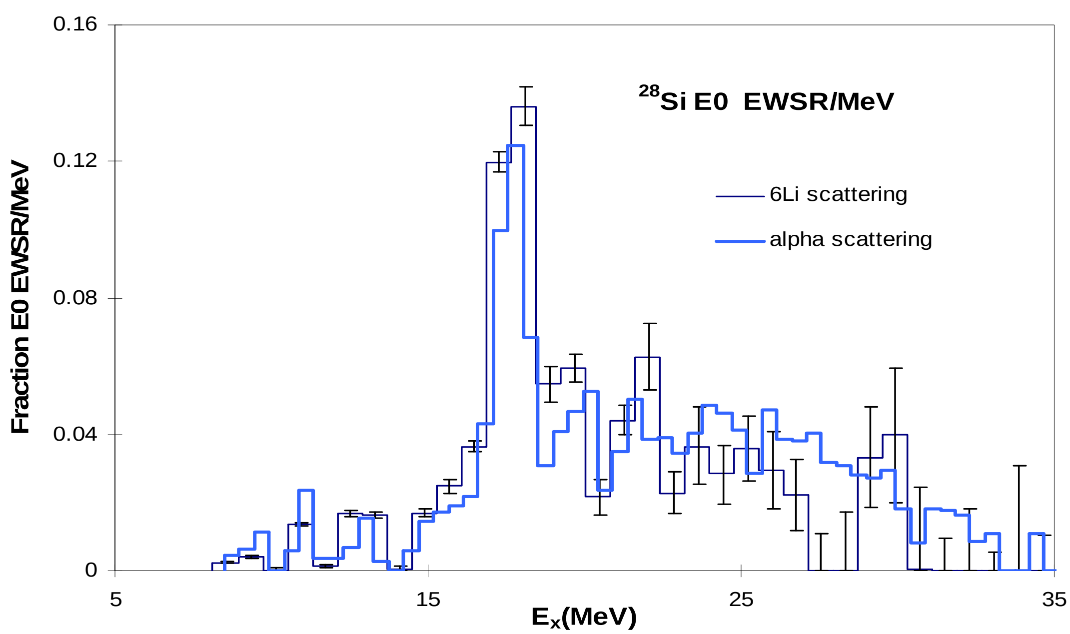


Multipole Distributions

^{116}Sn

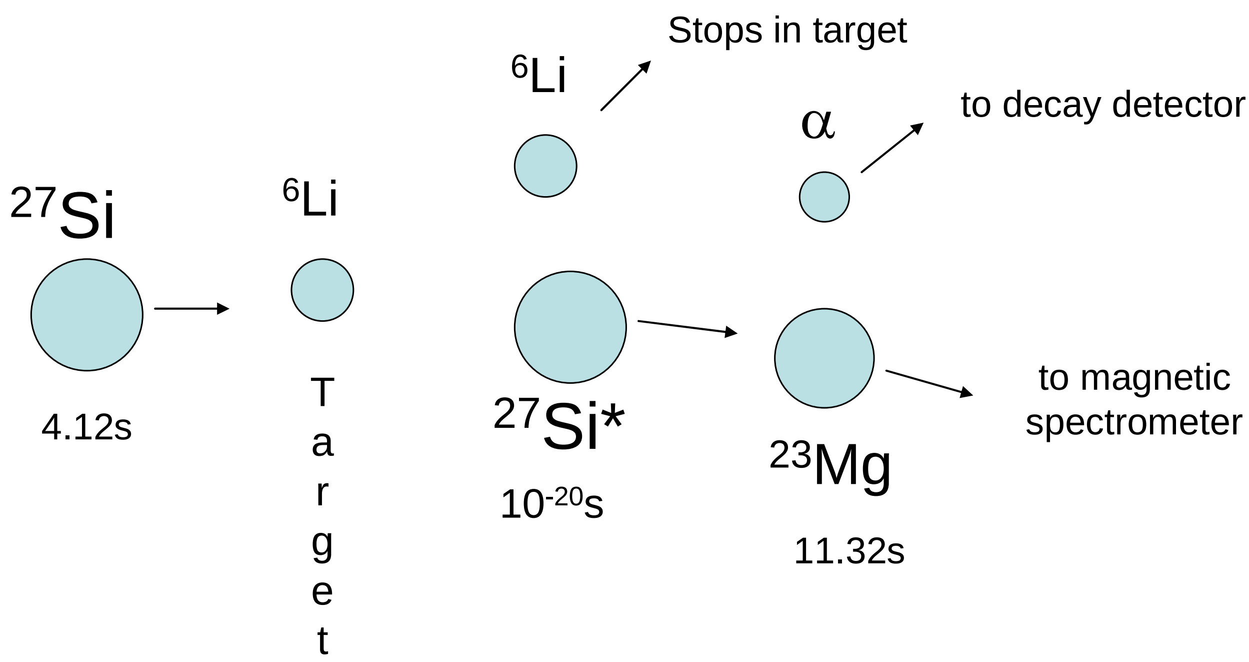


^{28}Si GMR

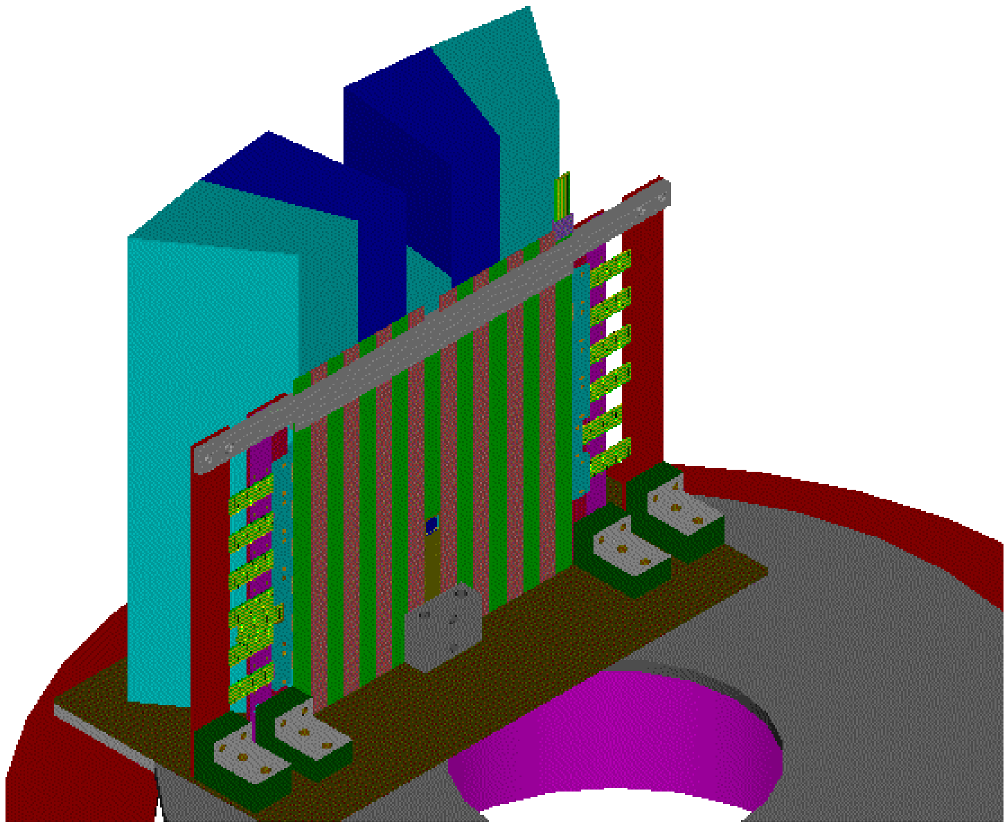


^{6}Li, α agree for GR's ^{116}Sn, ^{28}Si, ^{24}Mg.

To study GMR in ^{27}Si



Decay detector – Jonathan Button thesis



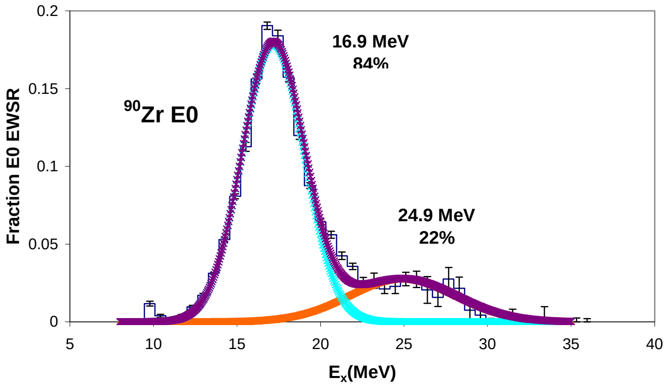
Will McGrew: Analyzing data

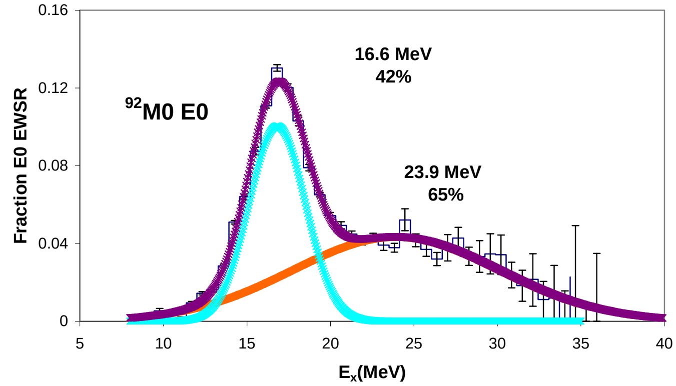
Test run

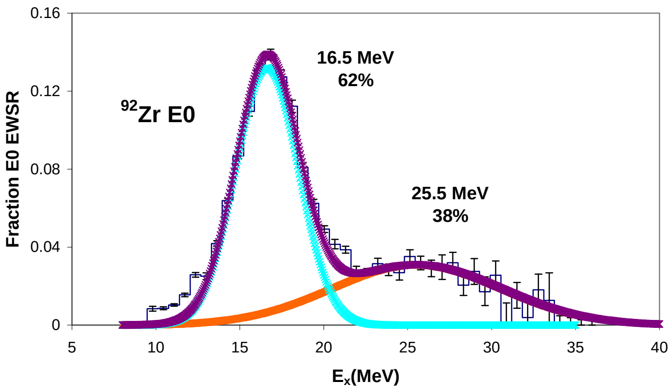
Calibration

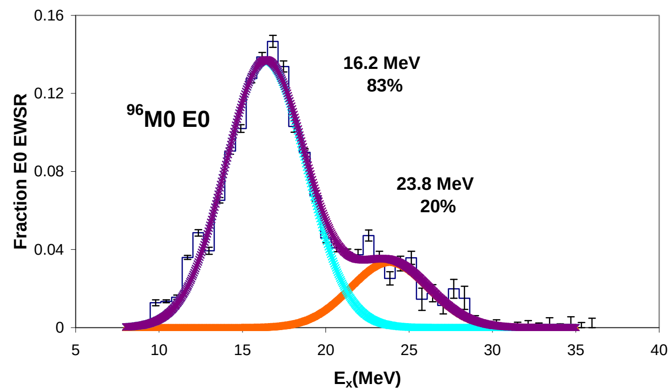
Designing Faraday Cup/Beam Stop

Other Monopole Things

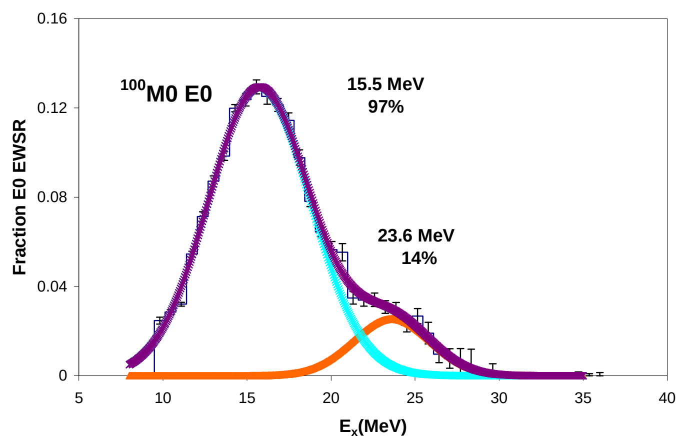






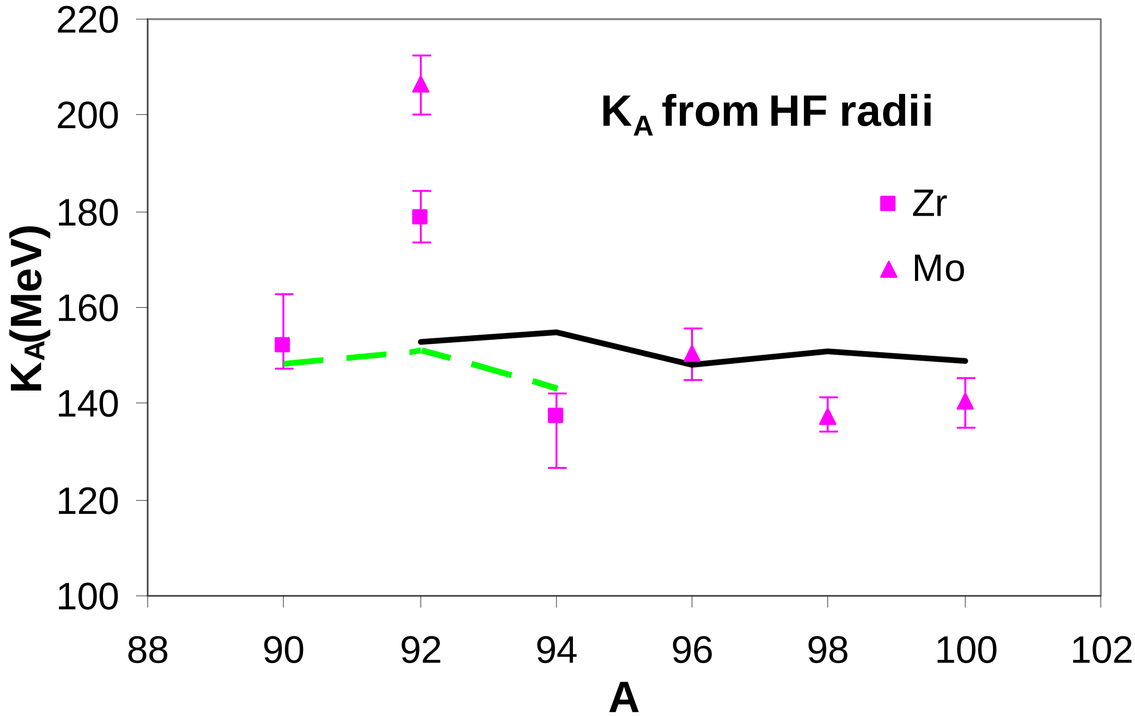


	m1/m0
^{90}Zr	17.87 MeV
^{92}M0	19.62 MeV



E_{GMR} ^{92}Mo should be below ^{90}Zr??

K_A for Mass 92 very different.



^{92}Mo

K_A 5σ from expected value!

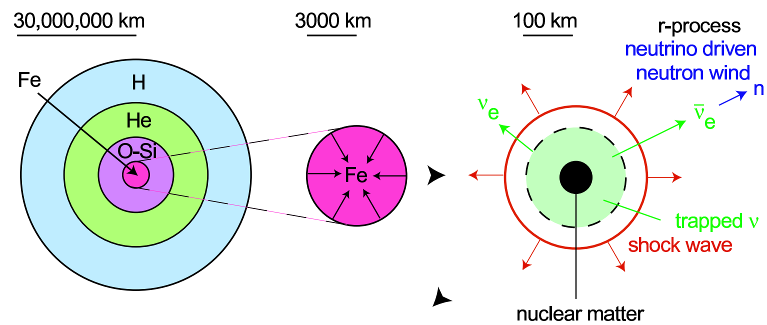
Nuclear equation of state influences many astrophysical processes

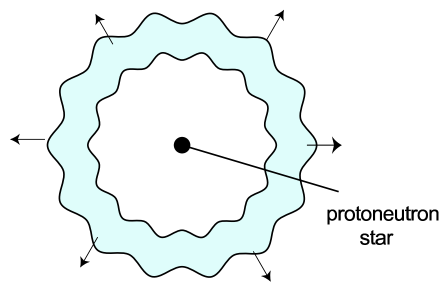
Double pulsar rotation (astro-ph 0506566)

Binary mergers (astro-ph 0512126)

Neutron star formation:

Life of a type II supernova





Protonneutron star has about the same density as nuclei

Stolen from :

C. Hartnack and J. Aichelin
Subatech/University of Nantes
H. Oeschler
Technical University of Darmstadt

Sum Rules

Electromagnetic Operator $Q_L = \sum_i r_i^L Y_{Lm}(\theta_i)$

Show $\sum_n E_n |\langle n | Q_L | 0 \rangle|^2 = \langle 0 | [[Q_L, H], Q_L] | 0 \rangle = S_L$

Assumes $[Q_L, V] = 0$

Then evaluate $\langle 0 | [[Q_L, H], Q_L] | 0 \rangle$ using commutator relations

Result $S_L = \sum_n E_n B(E_L \uparrow) = \dfrac{\hbar^2 (L)(2L+1) A}{8\pi m} \langle r^{2L-2} \rangle$ (for $L \geq 2$)

A "giant resonance" is a state carrying a significant fraction of this Sum.

For Inelastic α scattering

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = \beta^2 \left(\frac{d\sigma}{d\Omega}\right)_{DWBA}$$ β - deformation parameter

$$B(E2 \uparrow) = \beta^2 R^4 \left(\frac{3Z}{4\pi}\right)^2$$

$\beta_Z R_Z = \beta_m R_m$

Deformed optical potential used for form factor in DWBA.

R^2 evaluated for a fermi distribution

Definition of β

$$R(\theta, \phi) = R\left[1 + \sum_{lM} \alpha_{lM} Y_{LM}(\theta, \phi)\right]$$

$$\beta_L(n) = (2L+1)^{1/2} \langle n, M | \alpha^*_{LM} | 0, 0 \rangle$$