A SEARCH FOR CHARGED SCALAR PARTICLES PAIR PRODUCED IN e^+e^- ANNIHILATION

JADE Collaboration

W. BARTEL, D. CORDS, P. DITTMANN, R. EICHLER [1], R. FELST, D. HAIDT, H. KREHBIEL, K. MEIER, B. NAROSKA, L.H. O'NEILL [2], P. STEFFEN, H. WENNINGER [3]
Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

E. ELSEN, A. PETERSEN, P. WARMING, G. WEBER
II. Institut für Experimentalphysik der Universität Hamburg, Germany

S. BETHKE, J. HEINTZE, G. HEINZELMANN, K.H. HELLENBRAND, R.D. HEUER, S. KAWABATA [4], S. KOMAMIYA, J. von KROGH, P. LENNERT, H. MATSUMURA, T. NOZAKI, J. OLSSON, H. RIESEBERG, A. WAGNER
Physikalisches Institut der Universität Heidelberg, Germany

A. BELL, F. FOSTER, G. HUGHES, H. WRIEDT
University of Lancaster, England

J. ALLISON, A.H. BALL, G. BAMFORD, R. BARLOW, C. BOWDERY, I.P. DUERDOTH, J.F. HASSARD [5], B.T. KING [6], F.K. LOEBINGER, A.A. MACBETH, H. McCANN, H.E. MILLS, P.G. MURPHY, K. STEPHENS
University of Manchester, England

D. CLARKE, M.C. GODDARD, R. MARSHALL, G.F. PEARCE
Rutherford Appleton Laboratory, Chilton, England

and

J. KANZAKI, T. KOBAYASHI, M. KOSHIBA, M. MINOWA, M. NOZAKI, S. ODAKA, S. ORITO, A. SATO, H. TAKEDA, Y. TOTSUKA, Y. WATANABE [4], S. YAMADA and C. YANAGISAWA [7]
Lab. of Int. Coll. on Elementary Particle Physics and Department of Physics, University of Tokyo, Japan

Received 29 April 1982

We have searched for unstable charged scalar particles ($S^\pm$) such as technipions or charged Higgs particles pair produced in high energy e^+e^- annihilation. No evidence for such particles was observed in both decay modes $e^+e^- \to S^+S^- \to (\tau\nu)$ (hadrons) and $\to (\tau\nu)(\tau\nu)$. Upper limits of 4 to 11% are obtained for the branching ratio $S^\pm$ mass range between 4 to 12 GeV.

[1] Present address: ETH Zürich, Switzerland.
[2] Present address: Bell Laboratories, Whippany, NY, USA.
[3] On leave from CERN, Switzerland.
[4] Present address: National Laboratory for High Energy Physics (KEK), Ibaraki, Japan.
[5] Present address: Harvard University, Cambridge, MA, USA.
[6] Present address: University of Glasgow, Scotland, UK.
[7] Present address: Rutherford Appleton Laboratory, Chilton, England.

e^+e^- annihilation is an efficient way of searching for heavy point-like particles. Any charged particles with arbitrary spin can be pair-produced via a virtual photon. We report ‡1 in this paper on a search for unstable charged scalar particles (spin zero, with plus or minus parity, denoted as $S^\pm$ generically) using the JADE detector at the e^+e^- colliding machine PETRA.

The existence of such charged scalar particles is predicted in various models. Hyper(techni)-color models [3] require the technipions ($p^\pm$) as the pseudo-Goldstone bosons with masses possibly as low as several GeV. Although the technipions are composite particles, their sizes are expected [3] to be around $(1\ \mathrm{TeV})^{-1}$ and therefore they should behave almost point-like at PETRA energies. The technipions are expected to decay rapidly (in 10^{-20} to 10^{-18} s), predominantly into heavy fermion pairs such as $(\tau\nu)$, (cs) or possibly (cb) as compared to other possible decay channels like $(e\nu)$, $(\mu\nu)$ or (ud). The quark pairs (cs), (cb), or (ud) then fragment into hadrons. Charged Higgs ($H^\pm$) particles [4] and heavy axions [5] are also conceivable with dominant branching ratios into the heavy fermion pairs.

This search is based on the $(\tau\nu)$ decay of the scalar particles: We looked for events of the type $e^+e^- \to S^+S^- \to (\tau\nu)$(hadrons) or $(\tau\nu)(\tau\nu)$, and thus are sensitive to the products of the branching ratios $B_{\tau\nu}B_{\text{had}}$ and $B_{\tau\nu}B_{\tau\nu}$.

The JADE detector and the trigger condition have been described elsewhere [6]. Features of the detector essential to this analysis are summarized below: The cylindrical drift chamber (JET-chamber) situated in a solenoidal magnetic field of 4.8 kG covered 97% of the solid angle and measured the momenta of the outgoing charged particles. The energies of γ rays were measured with barrel- and end cap-arrays of a total 2712 leadglass shower counters covering 90% of the solid angle.

Data used here were accumulated in the period of July '79 to August '81 and amount to a total integrated luminosity of $2.03 \times 10^{37}\ \mathrm{cm}^{-2}$ ($20300\ \mathrm{nb}^{-1}$) at total c.m. energies ($\sqrt{s} = 2E_{\text{beam}}$) between 26.7 GeV and 36.7 GeV, with 86% of luminosity above 32.4 GeV.

The raw data, consisting of 26 million triggers, were first reduced to high- and low-multiplicity samples according to the following procedures. For the "high multiplicity sample" we required:

– At least two tracks ‡2 from the interaction region, and the barrel shower energy to be more than 3 GeV or each end cap shower energy more than 0.4 GeV. These conditions were to reject dominant backgrounds originating from beam–wall interactions.

Surviving events were scanned by physicists and a further selection of at least 4 tracks was made to reduce $\tau^+\tau^-$ background, which was further minimized by rejecting events with "(1–3) track configuration", i.e. those 4 track events with three tracks recoiling against the fourth.

The surviving 12600 events comprised the "high multiplicity sample" and consists of ordinary multihadron (~two thirds) and hadronic two-photon (~one third) and $\tau^+\tau^-$ (~1%) events.

The "low multiplicity sample" on the other hand was selected requiring:

– At least one track with a momentum over 0.3 GeV/c and a polar angle larger than 37° from the $e^\pm$ beam directions.

– $E_{\text{vis}} > 0.1\sqrt{s}$, where E_{vis} is the total visible energy of the event.

– Number of charged tracks of at least 4 and at most 8.

Events with the (1–3) track configuration were not excluded. The resulting sample (41700 events) consists mainly of two-photon, $\tau^+\tau^-$, and multihadron events. The low and high multiplicity samples have considerable overlap to each other.

Independent analyses were performed for $(\tau\nu)$ (hadrons) and for $(\tau\nu)(\tau\nu)$ modes. These analyses are described separately below.

(A) $(\tau\nu)$(hadrons) mode. Candidates for this mode were sought among the "high multiplicity sample" in which more than 90% of $(\tau\nu)$(hadrons) events, if they exist, were expected to survive for an $S^\pm$ mass (m_s) over 4 GeV.

The dominant event topology of the $(\tau\nu)$(hadrons)-

‡1 Preliminary results of this work were reported at the German Physical Society meeting (March '81) and at the Symposium on Lepton and photon interactions at high energies (Bonn, August '81), and were described in theses by Sato [1] and by Nozaki [2].

‡2 Throughout this paper, a "track" refers always to the trajectory of a "charged" particle.

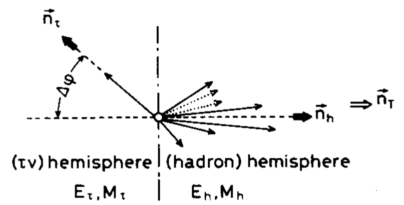

Fig. 1. A typical $(\tau\nu)$(hadrons) event seen in the view normal to the $e^{\pm}$ beam, and the definition of quantities: The full and the dotted lines represent the momentum vectors of charged particles and the γ rays respectively.

mode is one or three tracks from the τ decay with or without neutrals recoiling against a jet of hadrons (fig. 1). The $\tau\nu$-side should show a large missing momentum and energy due to the emission of at least two neutrinos while the hadron-side should have almost the full energy. Further selection relied on this characteristic event topology. For this purpose, the thrust direction $\boldsymbol{n}_{\mathrm{T}}$ was obtained for each event by maximizing the thrust:

$$T = \sum_i \boldsymbol{p}_i \boldsymbol{n}_{\mathrm{T}} \Big/ \sum_i |\boldsymbol{p}_i| ,$$

where $\boldsymbol{p}_i$ are the momentum vectors of charged and neutral particles detected. The resulting thrust direction $\boldsymbol{n}_{\mathrm{T}}$ is expected to point in the approximate direction of the S^+ or S^-. The event was then cut into two hemispheres by the plane perpendicular to $\boldsymbol{n}_{\mathrm{T}}$. The part with the larger energy was defined as the "hadron-hemisphere" and the other as the "$\tau\nu$-hemisphere" (fig. 1). The momentum four vectors $P_{\mathrm{h}} = (E_{\mathrm{h}}, \boldsymbol{P}_{\mathrm{h}})$ and $P_\tau = (E_\tau, \boldsymbol{P}_\tau)$ were defined as the sums of neutral and charged momenta in the hadron- and $\tau\nu$-hemispheres respectively.

The following cuts were then applied to enrich the expected type of event in the sample.

(1) $|\cos\theta_{\mathrm{T}}| < 0.65$, where θ_{T} is the angle between $\boldsymbol{n}_{\mathrm{T}}$ and the initial e^+ beam direction.

(2) Existence of at least one track on the $(\tau\nu)$ side inside a 70° cone around the thrust axis.

(3) $E_{\mathrm{h}} > 0.6E_{\mathrm{beam}}$ and $E_\tau < 0.4E_{\mathrm{beam}}$.

The cut (1) was to reduce the background from the two photon processes which tend to have the thrust vector in the beam direction. The cut (3) eliminated the remaining two photon background and reduced the multihadron events which usually have E_τ and E_{h} approximately equal to the initial beam energy.

The selection criteria (1) to (3) were designed to be rather insensitive to the velocity or the mass of $S^{\pm}$ produced. For further selection two different sets of criteria were applied in addition to cuts (1) and (3), one efficient for low and the other for high m_s.

(A1) $(\tau\nu)$(hadrons)-mode, low m_s.

(4) All tracks other than the one on the $\tau\nu$-side must be on the hadron-side within a cone of 60° from $\boldsymbol{n}_{\mathrm{T}}$, i.e. an isolated track with or without neutrals recoiling against a narrow hadron jet.

(5) The invariant mass of the $\tau\nu$-hemisphere (M_τ) must be less than 2 GeV.

(6) The invariant mass of the hadron-hemisphere (M_{h}) must be larger than 2.5 GeV.
The cuts (4) and (5) were to detect the τ-candidates and the cut (6) eliminated the backgrounds from $e^+e^- \to \tau^+\tau^-$. No event survived these cuts.

(A2) $(\tau\nu)$(hadrons)-mode, high m_s. For a high m_s, i.e. for slow $S^{\pm}$ produced near threshold, the decay hadron jet becomes increasingly wide and could even diffuse into the $\tau\nu$-hemisphere, thus destroying the effectiveness of the cuts (4) to (6). In such events however the neutrino is likely to carry a large missing transverse momentum of up to about $m_s/2$, which should normally result in a large acoplanarity between the τ decay products and the hadrons.

To select possible $(\tau\nu)$(hadrons) events originating from a high mass S^+S^-, we require after the cut (3):

(4′) A high invariant hadron mass: $M_{\mathrm{h}} > 0.3E_{\mathrm{beam}}$.
For each surviving event, "acoplanarity" $(\Delta\phi)$ between $\boldsymbol{P}_\tau, \boldsymbol{P}_{\mathrm{h}}$ and the beam direction was defined by (fig. 1),

$$\cos(\Delta\phi) = \frac{(\boldsymbol{n}_\tau \times \boldsymbol{z}) \cdot (\boldsymbol{n}_{\mathrm{h}} \times \boldsymbol{z})}{|\boldsymbol{n}_\tau \times \boldsymbol{z}|\,|\boldsymbol{n}_{\mathrm{h}} \times \boldsymbol{z}|} ,$$

where $\boldsymbol{n}_\tau, \boldsymbol{n}_{\mathrm{h}}$ and $\boldsymbol{z}$ are the unit vectors pointing to the directions of $\boldsymbol{P}_\tau, \boldsymbol{P}_{\mathrm{h}}$ and the e^+ beam respectively.

Fig. 2a shows the observed acoplanarity distribution compared with the one obtained from simulated ordinary multihadron events generated by the Lund Monte Carlo programme and passed through the same selection criteria. The same Lund-simulation [7] reproduces [8] well the observed detailed characteristics of the multihadron events such as the multiplicity, momentum spectra of $\pi^{\pm}$, $K^{\pm}$ and K^0's, and the particle angular distributions around jets [9] etc. As seen in fig. 2a the rate and the shape of the observed acoplanarity distribution agree with the ones expected from normal multihadron events, and there is no evidence for extra

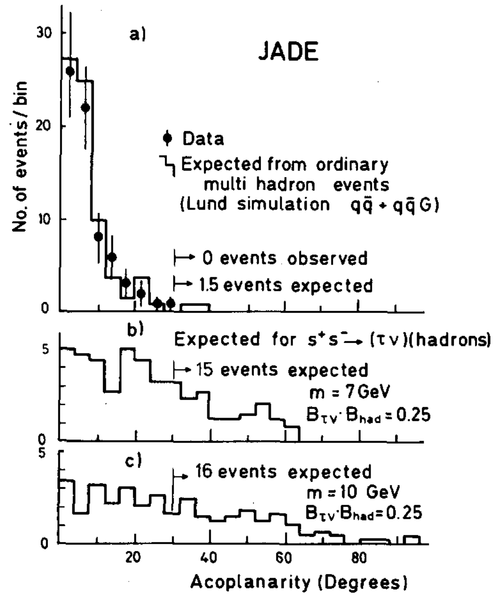

Fig. 2. The observed and expected acoplanarity ($\Delta\phi$) distributions for the ($\tau\nu$)(hadrons) mode after cut (4′) of criteria A2.

events with a large acoplanarity as expected from the ($\tau\nu$) (hadron) events (figs. 2b and 2c).

In fact no event has survived the final cut:

(5′) $\Delta\phi > 30°$.

The significance of these null results was assessed using Monte Carlo simulation of the process $e^+e^- \to S^+S^- \to (\tau\nu)$(hadrons). In the simulation, a pair of S^+S^- was created according to the point-like differential cross section [10];

$$d\sigma/d\Omega = (\alpha^2/8s)\,\beta^3 \sin^2\theta \ ,$$

folded with the radiative corrections up to α^3, where α is the fine structure constant, β the velocity and θ the polar angle of $S^\pm$ to the e^+ beam direction. The S^+ and S^- produced were then allowed to decay into ($\tau\nu$) and (cs). The τ decayed according to the branching ratios listed in table 1, mostly based on existing data [11]. The quark pair fragmented into hadrons through the Lund-scheme [7,8]. A zero decay length was assumed, although the criteria for the track vertices were such that a decay length up to one cm should not change the results significantly. For each simulated ($\tau\nu$)(hadrons) event, an event format exactly the same as the real data was then created through detector simulators which took into account detailed features of the detector such as multiple scattering, nuclear interactions and resolution. The simulated events went through the trigger checking routine and the same analysis program as the real data to determine the efficiencies of the selection criteria.

Table 1
Assumed branching ratios of the τ used in the Monte Carlo simulation.

$\tau \to e\nu\nu$	18.0%
$\mu\nu\nu$	17.5%
$\pi\nu$	10.6%
$K\nu$	0.4%
$\rho\nu$	23.5%
$A_1\nu$	9.0%
π + more than $2\pi^0 + \nu$	5.5%
3 charged $\pi + \pi^0$'s $+ \nu$	14.3%
5 charged $\pi + \nu$	1.0%
5 charged $\pi + \pi^0$'s $+ \nu$	0.2%

The efficiencies of the criteria A1 and A2 for the ($\tau\nu$)(hadrons) events thus obtained are summarized in table 2 for various values of m_s, together with the expected number of S^+S^- events produced. For m_s above 7 GeV the same procedure was repeated on A2 criteria using (cb) quark pairs instead of (cs). The resulting efficiencies were the same within 10% relative to each other, thus demonstrating that the criteria A2 are rather insensitive to the detailed nature of the hadron jet.

Upper limits on $B_{\tau\nu}B_{\rm had}$ can be calculated from the number of S^+S^- events produced, the efficiencies and the upper limits on the number of events (3.0 events with 95% confidence level for zero observed events). To be safe against possible systematic errors in obtaining efficiencies, the lower limits of the efficiencies were obtained by dividing the efficiencies in table 2 by "systematic" factors 1.9 and 1.3 for the criteria A1 and A2 respectively. These factors correspond to three times the estimated systematic errors, which are mainly due to uncertainties in the hadron fragmentation.

The upper limits of $B_{\tau\nu}B_{\rm had}$ (95% confidence level) were calculated by using these lower limits of efficiencies and are shown in fig. 3 (right hand scale) as functions of m_s. The left hand side scale of fig. 3 corresponds to the upper limit of $B_{\tau\nu}$ calculated from $B_{\tau\nu}B_{\rm had}$ assuming negligible branching ratios into channels other than the ($\tau\nu$) and (hadrons), as expected for technipions or charged Higgs particles.

Table 2
Expected number of produced $e^+e^- \to S^+S^-$ events and the efficiencies of the selection criteria for specific decay modes as functions of the mass of the scalar particle.

m_s (GeV)	Expected no. of S^+S^- events produced	Efficiencies for specific decay modes		
		$(\tau\nu)$(hadrons)		$(\tau\nu)(\tau\nu)$
		A1	A2	B
3	452	4.8%	0%	0%
4	423	17.3%	0%	1.1%
6	360	22.8%	5.6%	4.9%
8	285	14.3%	12.3%	7.2%
10	212	7.5%	15.2%	7.5%
12	132	3.4%	15.5%	6.9%
14	62	1.2%	14.7%	6.7%
15	34	0%	13.9%	6.3%

(B) $(\tau\nu)(\tau\nu)$ mode. A typical event topology of this mode is (1–3) or (1–5) track configuration with almost all observed energy inside two narrow cones. To select such events, the following criteria were applied on the "low multiplicity" sample.

(1) Existence of a track which was separated from other tracks by at least 90°.

The event was then divided into two hemispheres by the plane perpendicular to the isolated track. Two cones with opening angles of 45° were then drawn around two axes n_1 and n_2, which were defined as the directions of the momentum sums of the charged and neutral particles in the two hemispheres.

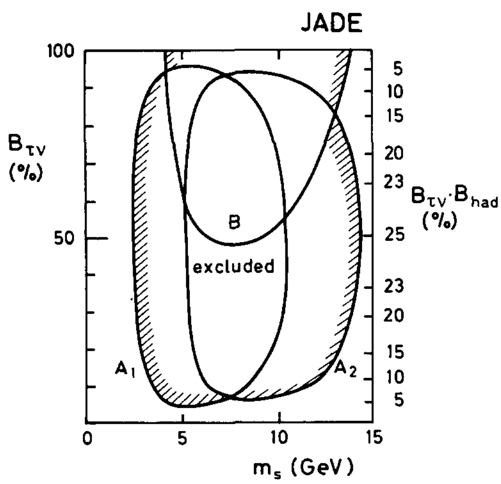

Fig. 3. Limits on the branching ratio $S \to \tau\nu$ as a function of m_s. The curves A1, A2 and B represent the limit obtained from the criteria A1, A2 and B respectively. Combining these limits, the shaded area is excluded with 95% confidence.

(2) Each cone must contain: the isolated track or all the remaining tracks, at least 5% of $\sqrt{s}$ and at least 90% of the energy in the corresponding hemisphere.

(3) $|\cos\theta_1|$ and $|\cos\theta_2|$ less than 0.75, where θ_1 and θ_2 are the polar angles of n_1 and n_2 to the e^+ beam.

The surviving events were dominated by the (1–3) track configuration with the invariant mass of particles in each cone (M_1, M_2) peaked below m_τ, suggesting that most of the events contain a pair of $\tau^+\tau^-$. The following cuts (4) and (5) then eliminated the background from multihadron and two-photon $\tau^+\tau^-$ [‡3] events respectively.

(4) M_1 and M_2 below 2.5 GeV.

(5) E_{vis} larger than 0.3 times $\sqrt{s}$, where E_{vis} is the total visible energy of the event.

For each surviving event, the acoplanarity between n_1, n_2 and the beam direction was calculated. The resulting acoplanarity distribution is sharply peaked toward zero degree as expected from the remaining $e^+e^- \to \tau^+\tau^-$ background, which was eliminated by the following cut:

(7) Acoplanarity larger than 20°.

No event survived this final cut.

The efficiency of the above criteria B was obtained from Monte Carlo simulations and listed in table 2 as a function of m_s. The upper limit on $B_{\tau\nu}$ was then obtained by taking into account the maximum system-

[‡3] $e^+e^- \to e^+e^-\tau^+\tau^-$ with undetected final e^+ and e^-.

atic uncertainties of 60% which correspond to three times the estimated systematic error in obtaining the efficiency. The resulting 95% confidence level limit is shown as the curve B of fig. 3.

Combining the limits obtained from the criteria A1, A2 and B, the shaded area in fig. 3 is excluded with 95% confidence.

In conclusion, no evidence is found for the events of the type either $e^+e^- \to (\tau\nu)$(hadrons) or $(\tau\nu)(\tau\nu)$. Limits of the $\tau\nu$ branching ratio are obtained for charged scalar particles such as technipions or charged Higgs particles assuming a point-like production cross section and a decay length of up to one cm: Charged scalar particles with more than 11% branching ratio into $\tau\nu$ are excluded for the mass range between 4 and 12 GeV with 95% confidence [‡4].

We acknowledge the efforts of the PETRA machine group, who provided us with the opportunity of doing this experiment, and also the efforts of the technical support groups of the participating institutes in the construction and maintenance of our apparatus. This experiment was supported by the Bundesministerium für Forschung und Technologie, by the Education Ministry of Japan and by the UK Science and Engineering Research Council through the Rutherford Appleton Laboratory. The visiting groups at DESY wish to thank the DESY Directorate for their hospitality.

‡4 After writing this paper, we learned that the Cello Collaboration made an analysis of the $(\tau\nu)(\tau\nu)$ mode and obtained an upper limit for $B_{\tau\nu}$ [12], and that the Mark-J-Collaboration performed a similar analysis [13].

References

[1] A. Sato, UTLICEPP 82-03, University of Tokyo.
[2] M. Nozaki, UTLICEPP 82-02, University of Tokyo.
[3] S. Weinberg, Phys. Rev. D13 (1976) 974; D19 (1979) 1277;
L. Susskind, Phys. Rev. D20 (1979) 2619;
S. Dimopoulos and L. Susskind, Nucl. Phys. B155 (1979) 237;
E. Eichten and K.D. Lane, Phys. Lett. 90B (1980) 125;
M.A.B. Beg, H.D. Politzer and P. Ramond, Phys. Rev. Lett. 43 (1979) 1701;
S. Dimopoulos, Nucl. Phys. B168 (1980) 69;
M.E. Peskin, Nucl. Phys. B175 (1980) 197;
S. Dimopoulos, S. Raby and P. Sikivie, Nucl. Phys. B176 (1980) 449;
S. Dimopoulos, S. Raby and G.L. Kane, Nucl. Phys. B182 (1981) 77;
G. Barbiellini et al., DESY 81-064, and references therein.
[4] E. Golowich and T.C. Yang, Phys. Lett. 80B (1979) 245;
L.N. Chang and J.E. Kim, Phys. Lett. 81B (1979) 233;
H.E. Haber, G.L. Kane and T. Sterling, Nucl. Phys. B161 (1979) 493.
[5] S.H.H. Tye, Phys. Rev. Lett. 47 (1981) 1035.
[6] W. Bartel et al., Phys. Lett. 88B (1979) 171; 92B (1980) 206; 99B (1981) 277.
[7] B. Andersson, G. Gustafson and T. Sjostrand, Phys. Lett. 94B (1980) 211, and earlier references therein; for details, see: T. Sjostrand, LUTP 80-3 (April 1980), and Errata to LUTP 80-3.
[8] S. Komamiya, thesis, UTLICEPP 82-01, University of Tokyo, to be published.
[9] W. Bartel et al., Phys. Lett. 108B (1982) 140.
[10] N. Cabibbo and R. Gatto, Phys. Rev. 124 (1961) 1577.
[11] R. Kirkby, Proc. Intern. Symp. on Lepton and photon interactions at high energies (FNAL, 1979), and references therein.
[12] Cello Collab., to be published in DESY 82-021.
[13] Mark-J-Collab., to be published in MIT, Laboratory of Nuclear Science Report 125.